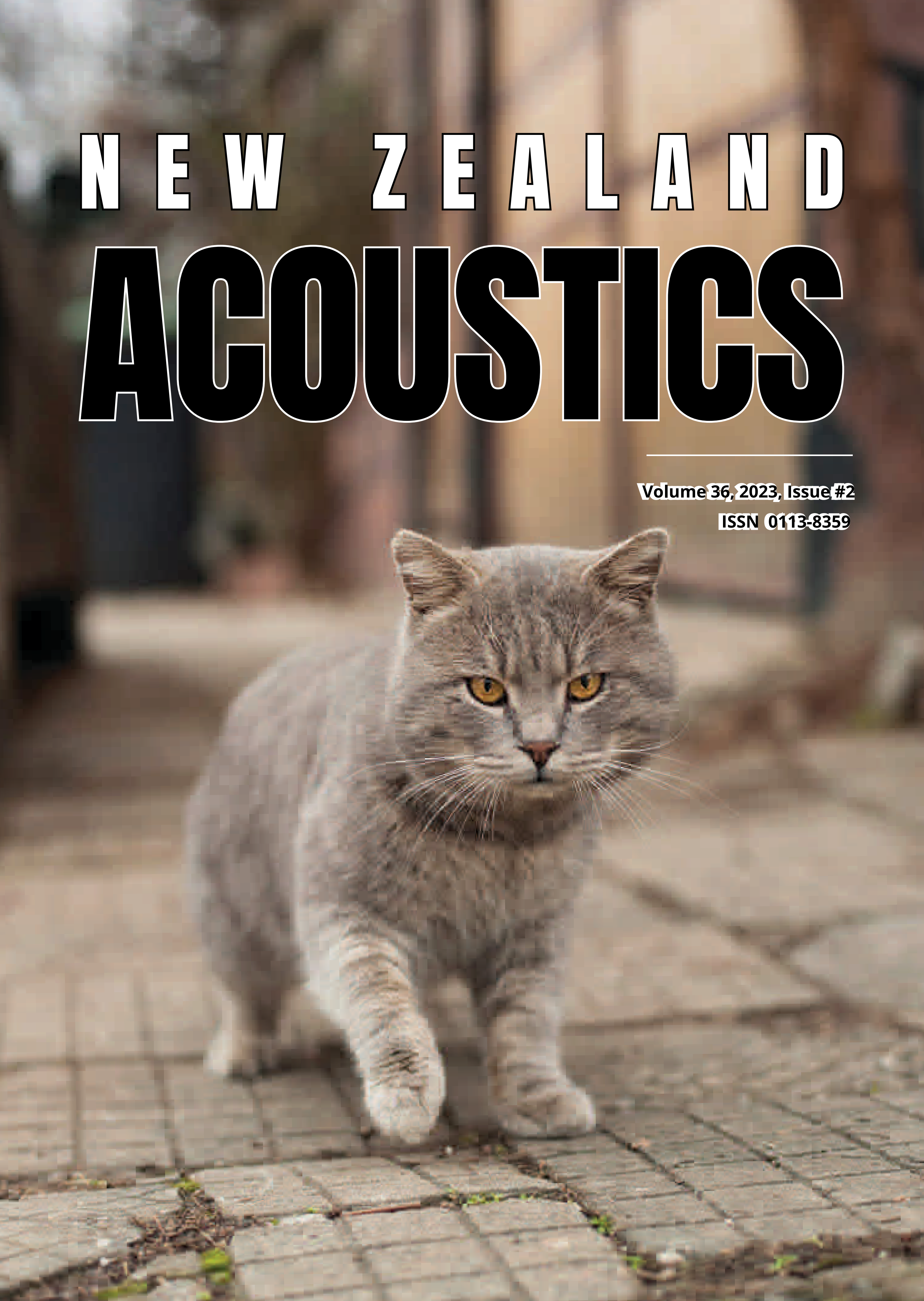
NEW ZEALAND ACOUSTICS

Volume 36, 2023, Issue #2
ISSN 0113-8359



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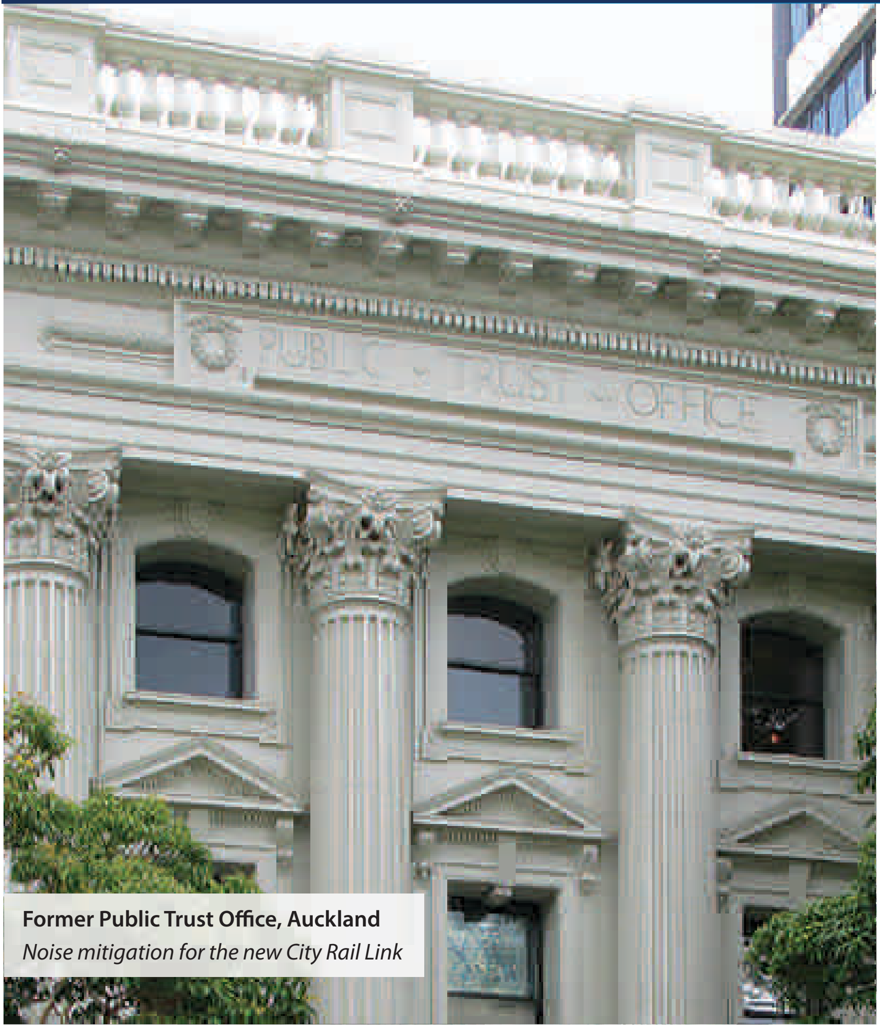

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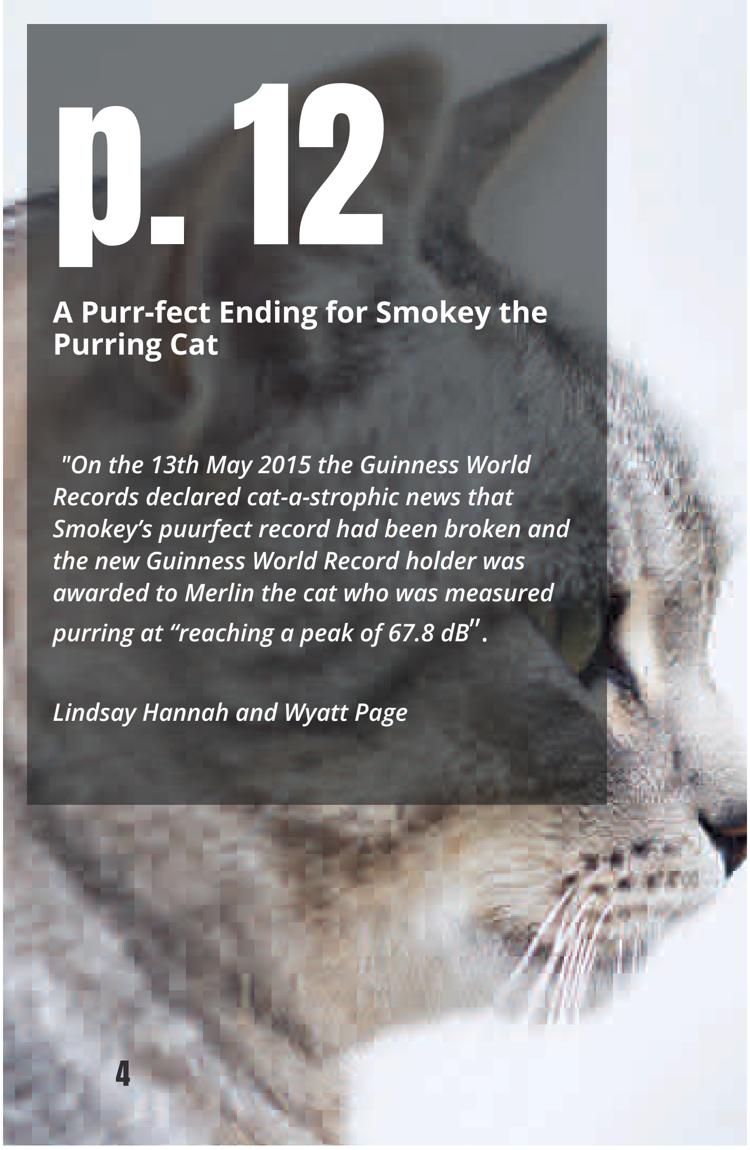

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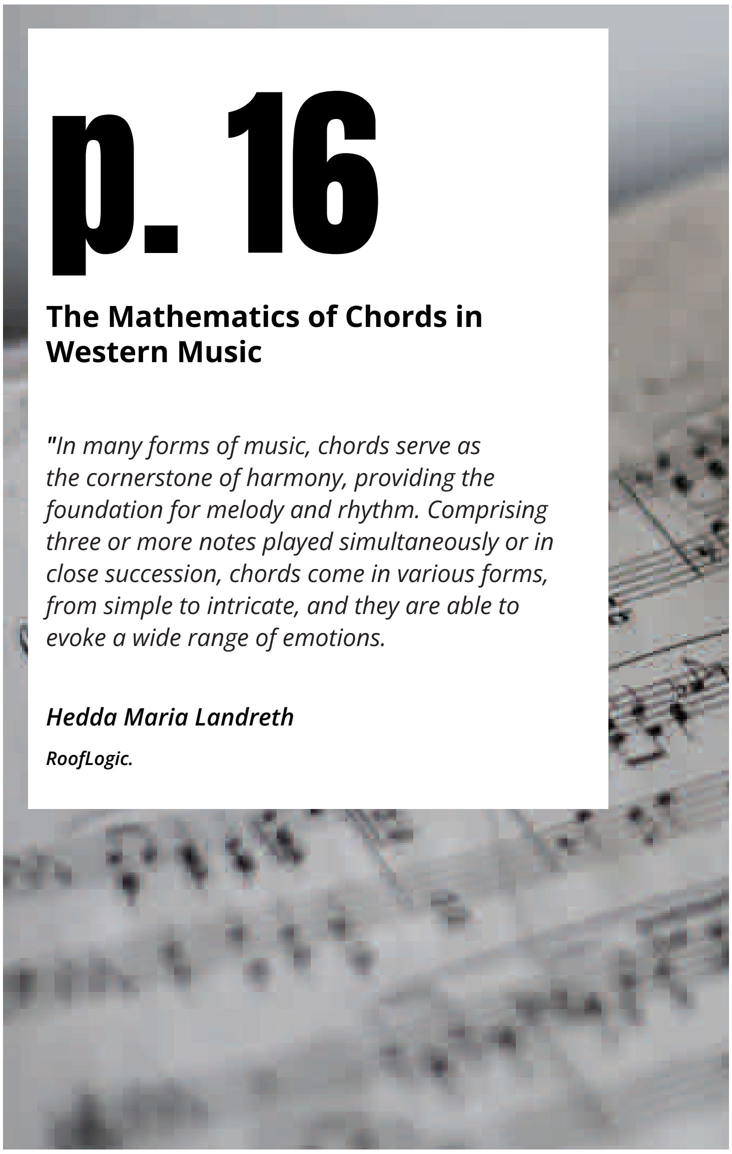
A Purr-fect Ending for Smokey the Purring Cat

"On the 13th May 2015 the Guinness World Records declared cat-a-strophic news that Smokey's puurfect record had been broken and the new Guinness World Record holder was awarded to Merlin the cat who was measured purring at "reaching a peak of 67.8 dB".

Lindsay Hannah and Wyatt Page



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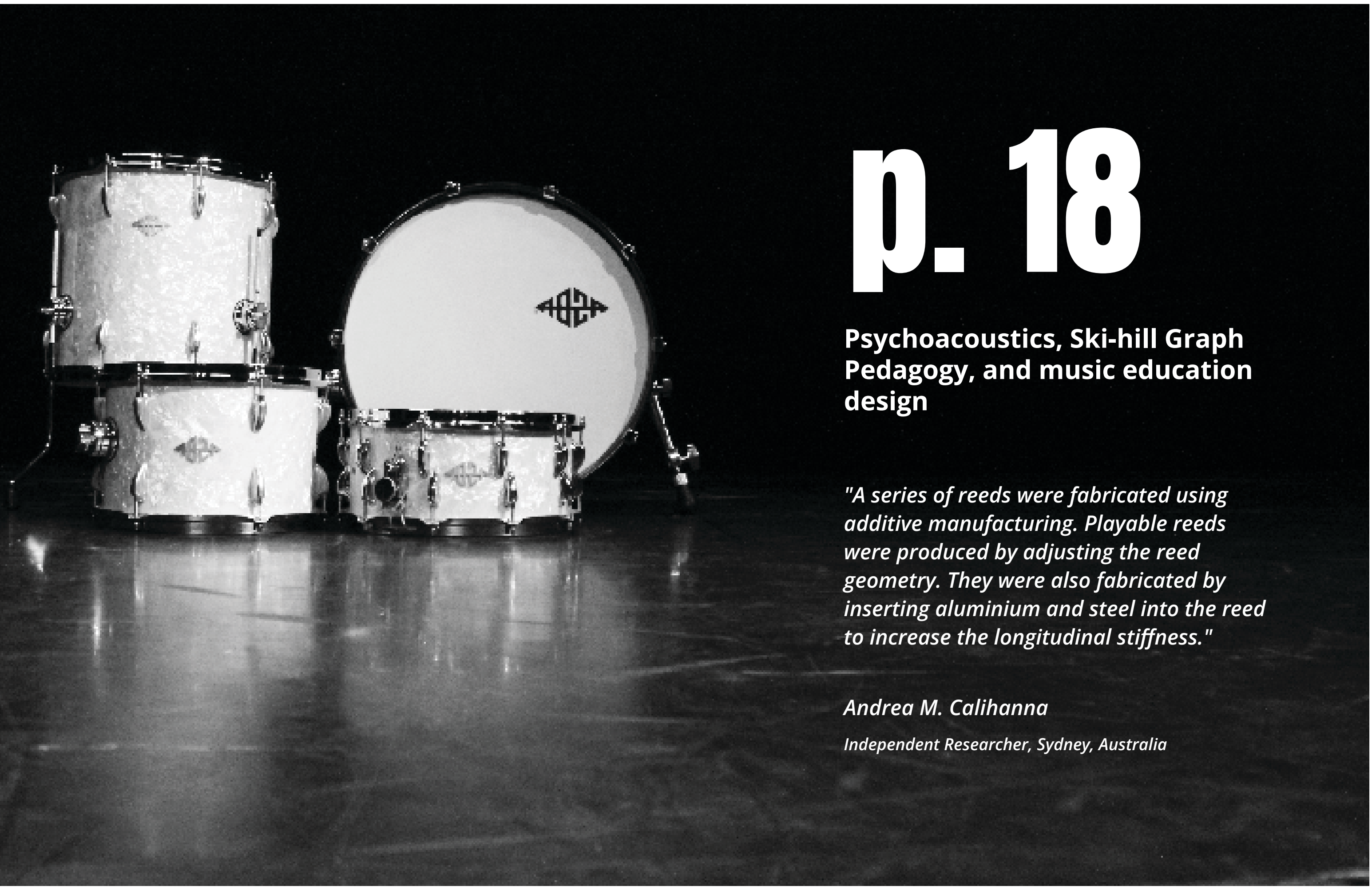
The Mathematics of Chords in Western Music

"In many forms of music, chords serve as the cornerstone of harmony, providing the foundation for melody and rhythm. Comprising three or more notes played simultaneously or in close succession, chords come in various forms, from simple to intricate, and they are able to evoke a wide range of emotions.

Hedda Maria Landreth

RoofLogic.



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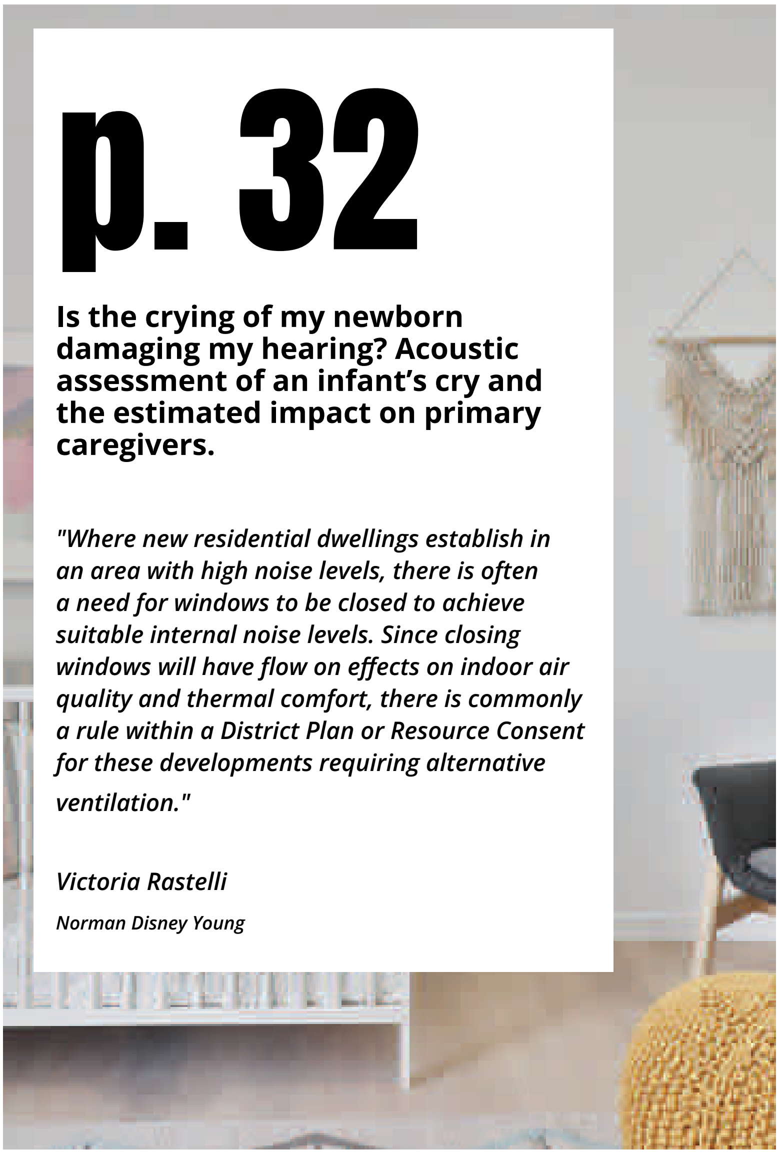
Psychoacoustics, Ski-hill Graph Pedagogy, and music education design

"A series of reeds were fabricated using additive manufacturing. Playable reeds were produced by adjusting the reed geometry. They were also fabricated by inserting aluminium and steel into the reed to increase the longitudinal stiffness."

Andrea M. Calihanna

Independent Researcher, Sydney, Australia



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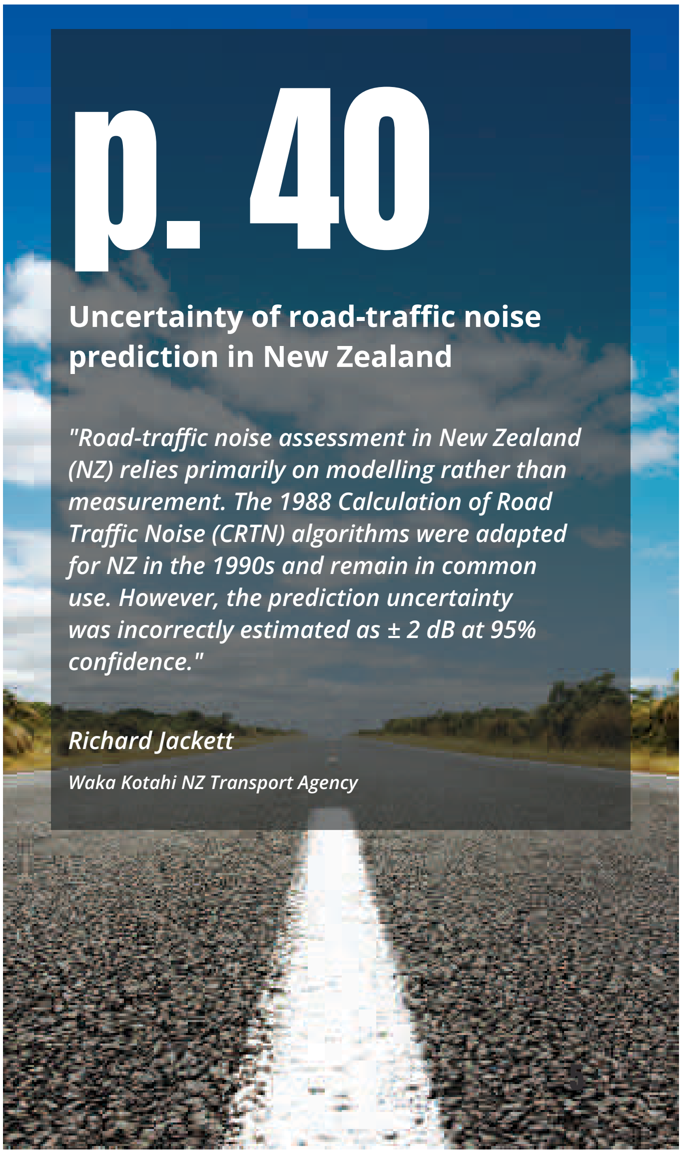
Is the crying of my newborn damaging my hearing? Acoustic assessment of an infant’s cry and the estimated impact on primary caregivers.

"Where new residential dwellings establish in an area with high noise levels, there is often a need for windows to be closed to achieve suitable internal noise levels. Since closing windows will have flow on effects on indoor air quality and thermal comfort, there is commonly a rule within a District Plan or Resource Consent for these developments requiring alternative ventilation."

Victoria Rastelli

Norman Disney Young



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Uncertainty of road-traffic noise prediction in New Zealand

"Road-traffic noise assessment in New Zealand (NZ) relies primarily on modelling rather than measurement. The 1988 Calculation of Road Traffic Noise (CRTN) algorithms were adapted for NZ in the 1990s and remain in common use. However, the prediction uncertainty was incorrectly estimated as ± 2 dB at 95% confidence."

Richard Jackett

Waka Kotahi NZ Transport Agency

Kia ora koutou,

It was with great pleasure that we awarded Siiri Wilkening a Fellowship of the ASNZ at an evening event held in her honour. As James Whitlock said in his glowing encomium on the night, “Siiri is one of the most caring, conscientious and capable people I have ever met. Whomever coined the phrase 'if you want something done, get someone busy to do it', they had obviously met Siiri Wilkening. Siiri's career has flourished because of the dedication and unparalleled work ethic she has. She inspires her colleagues, she leads with compassion and consideration, and in my view, there is nobody more deserving of having this honour bestowed upon her by her peers.” Siiri diligently served the Society from 2000 to 2022 in the roles of either Secretary or Treasurer – that’s 23 years without a break! She is our first female Fellow, and deservedly so.

In June, the ASNZ Council met for our first in-person meeting in several years at NDY’s Auckland office, with all 11 Councillors in attendance. It was a highly productive, full day event, concluding with a tour of the University of Auckland’s intriguing acoustic laboratory. High on the agenda were:

- Improvements to the ASNZ (www.acoustic.org.nz) website. You may have already noticed some changes to the layout and the newly updated content
- The next ASNZ Conference 2024, which is expected to be in Christchurch towards the end of the year
- Continued promotion of the Society on our LinkedIn page

In August, I was lucky enough to attend the Inter-noise 2023 conference in Chiba, Japan, along with fellow ASNZ members, Mike Kingan and Yusuke Hioka. It was a precision-run event with 14 concurrent sessions on any topic you could possibly imagine relating to acoustics (land-based acoustics, mind you, not underwater). Being peak summer, with temperatures hitting 35 degrees each day, it was easy to stay indoors and enjoy the conference atmosphere. A particular highlight was the banquet dinner which was in the style of a Japanese street festival, with singing and dancing (delegate participation mandatory), street food stalls and plenty of sake. We rubbed shoulders with presidents Yoichi Haneda (Acoustical Society of Japan) and Jeff Parnell (Australian Acoustical Society) whilst discussing details of the upcoming Acoustics 2023 Sydney conference on 4-8 December. For me, the Chiba conference and preceding days of sightseeing around Tokyo secured Japan as one of my favourite places to be.

In September, the South Island branch hosted an educational evening event at Tonkin + Taylor’s Christchurch office. Organised by our SI Vice President, Tracy Hilliker, the event was themed around acoustics of timber in the construction industry and was well attended.

SoundPrint has been officially endorsed by the ASNZ and replaces our Cafe and Restaurant Index (CRAI) rating system. This world-wide app is easy to use and includes great features for finding your next “quiet place”, including map-based searching, and taking sound level recordings from your smartphone to assist with rating venues. Going forward, a summary of New Zealand ratings will be included in this journal. Please download the app, get involved and submit those SoundPrint ratings! The more data we have, the better. Visit www.soundprint.co for more information.

Lunch Bunches are in full swing on the last day of every month. Attend either in person at the University of Auckland’s facilities or online via Zoom. Recordings of past events are now available through links on the ASNZ website (www.acoustics.org.nz/videos).

Ngā mihi,

Tim Beresford

President of the Acoustical Society of New Zealand

Kia ora koutou,

Welcome to the second issue of New Zealand Acoustics for 2023. This issue is a bit unique; we have a suite of original feature articles that haven’t appeared elsewhere. We begin by finding out how one of our journals previous articles helped restore Smokey (the cat) to be the joint Guinness World Record holder for the loudest purr. This is followed by two educational articles, one on the mathematics of musical chords, and one on psychoacoustics in music education. The fourth article asks the question ‘Is the crying of my newborn damaging my hearing?’. As a parent or caregiver of very young children you may have asked yourself this question, as close to the source, crying babies can reach well over 90 dB L Aeq . The issue is rounded out with a re-examination of the Calculation of Road Traffic Noise (CRTN) in New Zealand and shows that the prediction uncertainty under the best-case scenario is, and has always been, approximately ± 5 dB at 95% confidence, significantly bigger than previously assumed. Enjoy ≥^.^≤

Lindsay Hannah & Wyatt Page

Principal Editors

Submission All Articles

News, Products, Enquiries

journal@acoustics.org.nz

New Zealand Acoustics is published by the Acoustical Society of New Zealand Inc.
PO Box 1181, Shortland Street
Auckland 1140
ISSN 0113-8359

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Tim Beresford

Lindsay Hannah

Wyatt Page

NEWS

Harnessing Acoustic Energy: How to Make a Thermoacoustic Heat Engine

https://www.youtube.com/watch?v=abswNCqnMRQ&list=WL&index=58&t=76s

Can we recover sound from images?

https://www.youtube.com/watch?v=eUzB0L0mSCI&list=WL&index=59

Hear the Otherworldly Sounds of Skating on Thin Ice | National Geographic

This small lake outside Stockholm, Sweden, emits otherworldly sounds as Mårten Ajne skates over its precariously thin, black ice. “Wild ice skating,” or “Nordic skating,” is both an art and a science. A skater seeks out the thinnest, most pristine black ice possible—both for its smoothness, and for its high-pitched, laser-like sounds

https://www.youtube.com/watch?v=v3O9vNi-dkA&list=WL&index=16

Hear the Sounds of a Nuclear Reactor Start Up

https://www.youtube.com/watch?v=JvgF83OHV9c&list=WL&index=46

The Artificial Sounds of EV's

The increase in electric vehicles and hybrids on roads has also increased the risk of collision with pedestrians and cyclists. Since we have become used to the sound of engines alerting us to a car's presence, the silence of electric cars has caused safety concerns. To mitigate this risk the U.S. and Europe have passed a new regulation that requires EV's to emit a sound while driving under 18.6 mph or 30 kph to replace the sound of an engine.

https://www.youtube.com/watch?v=W3JEvecS_fI&list=WL&index=53&t=25s

Sound Mirrors

The Sound Mirrors (pre radar), on Romney Marsh, were built in the late 1920s as a way to amplify the sound from aircraft engines over the English Channel.

https://www.youtube.com/watch?v=04F5osXK4vw&list=WL&index=24

Tom Scott tests the worlds longest echo

The Inchindown oil tanks in Invergordon, Scotland, have the world's longest reverberation, Tom Scott tests a loud noise with some very sensitive microphones.

https://www.youtube.com/watch?v=lLUcOFwZvyY&list=WL&index=23&t=15s

Visualizing the Speed of Light and Speed of Sound

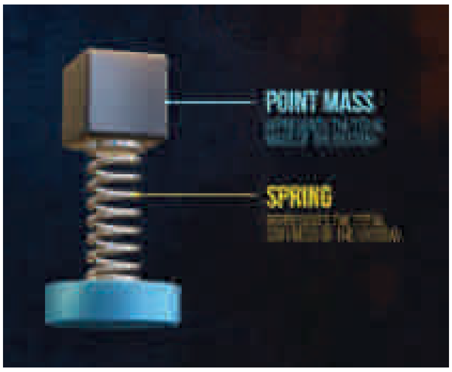
Look at some everyday examples of where the discrepancy between these two speeds are visible

https://www.youtube.com/watch?v=yGZwLFPLB0o&list=WL&index=19

Space Cows

The cows of McGregor, Texas, USA, have nearly become oblivious to the daily barrage of explosions, firings, other projects SpaceX's test facility is known for. Watch as multiple SpaceX Raptor engines are tested to failure while these adorable creatures continue to graze the Texas fields.

https://www.youtube.com/watch?v=4PB9FGbB0-w&list=WL&index=33



Understanding Vibration and Resonance

https://www.youtube.com/watch?v=vLaFAKnaRJU&list=WL&index=72&t=92s

An Off-Road Musical

https://www.youtube.com/watch?v=Ef93WmlEho0&list=WL&index=41

World's Largest Horn?

https://www.youtube.com/watch?v=pFEB0chiuJA&list=WL&index=57

A New Era with SoundPrint

For those of you who have been part of our society for a while will remember CRAI - Café and Restaurant Acoustic Index. Conceived by Stuart Camp in the early 2000s, CRAI was an acoustic rating system tailored specifically for dining establishments. It played a pivotal role for nearly a decade and a half, starting in the late 90s. During this period, CRAI ratings were prominently featured in the NZ Acoustics Journal, serving as a valuable resource to aid our members in selecting venues for a peaceful dining experience.

Over time, our commitment to enhancing the acoustic dining experience led the Society to develop the CRAI app. However, despite our efforts, it struggled to gain the traction we had hoped for.

A New Era with SoundPrint

Today, we are excited to announce a new chapter in our pursuit of quieter dining experiences. We have partnered with SoundPrint (www.soundprint.co), aN app developed by Greg Scott and his team in the USA. SoundPrint essentially carries on the legacy of CRAI, but with a range of additional features, including sound level recording capabilities for users with iPhones or approved Android devices.

At ASNZ we are proud to be designated as SoundPrint ambassadors, aligning our mission with this global movement for quieter dining environments. We believe that our members will find immense value in what SoundPrint offers.

The 3rd Annual Find Your Quiet Place Challenge

As part of our collaboration with SoundPrint, we invite all ASNZ members to download the SoundPrint app and engaging with this exciting international movement.

Currently, SoundPrint is running its 3rd annual "Find Your Quiet Place Challenge," an initiative that aligns perfectly with our shared vision. To participate and learn more about this challenge, visit: Find Your Quiet Place Challenge 2023 (https://www.soundprint.co/fyqp-challenge-2023)

We look forward to seeing our members actively involved in this.

SOUNDPRINT

The ASNZ has teamed up with **SoundPrint** to provide this curated list of acoustic ratings for food and beverage venues across Aotearoa (replacing the previous **CRAI** ratings). This data is collated from submissions made by users of the SoundPrint app, which rates venues based on the ambient noise levels present at the time of review and a subjective impression of how easy it was to hold a conversation.

SoundPrint ratings follow a decibel scale, and these correspond with our awarded star ratings as follows:

QUIET		MODERATE	LOUD	VERY LOUD
70 dBA or below + subjectively “great” for conversations	70 dBA or below	70 - 75 dBA	75 - 80 dBA	80 dBA or above
★★★★★	★★★★	★★★	★★	★

The list below contains submissions from the past 4 years only. The numbers in parentheses are the total reviews over this period.

AUCKLAND

Birkenhead Brewing Company, Birkenhead	★	(1)
Brickhouse Espresso Bar, Auckland	★★★	(1)
Brothers Beer, Auckland	★★★	(1)
Chamate, Auckland	★★★	(2)
Copia, Remuera	★★★★★	(1)
Corner Bar, Auckland	★★★★	(1)
Dear Jervois, Herne Bay	★★★	(1)
Dizengoff, Ponsonby	★	(1)
Fabric Cafe Bistro, Hobsonville	★★★★★	(1)
Ginger, Remuera	★★★★	(1)
Kind Cafe & Eatery, Auckland	★★★★	(1)
Lieutenant, Auckland	★★	(1)
Little Creatures Hobsonville, Hobsonville	★★★	(1)
Little Culprit, Auckland	★★★★	(1)
Masala Indian Restaurant, Pukekohe	★★★	(1)
Pasta & Cuore, Auckland	★★★★★	(1)
Seoul Night, Auckland	★★★	(1)
Siso Bar And Eatery, Auckland	★	(1)
St Pierre's Sushi & Seafood, Auckland	★★★★★	(1)
Sumthin Dumplin, Auckland	★★★★	(1)
The Brewers Co-operative, Auckland	★★★★★	(1)
The Chamberlain, Auckland	★★	(1)
The Dark Horse, Auckland	★	(1)
Tok Tok, Hobsonville	★★	(1)
Toto Cucina, Auckland	★★	(1)

BAY OF PLENTY

Ohope Charter Club, Ohope Beach	★★	(1)

CANTERBURY

Black And White Coffee cartel, Christchurch	★★★★	(1)
Coffe Culture, Papanui	★★★★	(1)
Coffee Culture, Christchurch	★★★★★	(1)
Columbus Coffee, Papanui	★★★	(1)
Doubles, Christchurch	★★★	(1)
Kohan Japanese Cuisine, Lake Tekapo	★★★★★	(1)
Kum Pun Thai Restaurant, Christchurch	★★★★	(1)
Little Poms, Christchurch	★★★	(1)
Meshino, Saint Albans	★★	(2)
Poppies Cafe, Twizel	★★★	(1)
Strange Bandit, Burnside	★★★★	(2)
Strawberry Fare, Christchurch	★★★★	(1)
Terrace Tavern, Christchurch	★★★	(1)

HAWKE'S BAY

Mister D, Napier	★★	(1)

NELSON

Columbus Coffee, Nelson	★★★★★	(1)
Sprig & Fern Hardy St, Nelson	★★★	(1)

OTAGO

1876 Bar & Restaurant, Queenstown	★★	(1)
Farelli's Trattoria, Queenstown	★	(1)
Margo’s queenstown, Queenstown	★★★★	(1)
Market Kitchen, Dunedin	★★	(1)
Pier 24, Saint Clair	★	(1)
The World Bar, Queenstown	★★	(1)
Wolf Coffee Roasters, Arrowtown	★★★★★	(1)

WAIKATO

The Vine Eatery, Taupo	★★	(1)

WELLINGTON

Boulcott Street Bistro, Wellington Central	★★	(1)
Caffe L'affare, Te Aro	★★	(2)
Charley Noble, Wellington	★	(2)
Crab Shack, Wellington Waterfront	★★	(1)
Crumpet, Wellington	★★	(1)
D4, Wellington	★	(1)
Dillinger's, Wellington	★★★★	(1)
Dirty Burger, Wellington	★★	(1)
Dragon Fly, Te Aro	★★	(1)
Foxglove, Wellington Central	★★★	(1)
Ivy: Underground, Wellington	★	(1)
Liberty restaurant, Wellington	★★	(1)
Logan Brown Restaurant & Bar, Wellington	★★★	(1)
Maranui Cafe, Wellington	★	(1)
Mexico, Lower Hutt	★★★★★	(1)
Neo Cafe & Eatery, Wellington	★★	(2)
Preservatorium, Wellington	★	(1)
Rosie’s Cantina, Wellington	★★	(1)
Scopa Caffé Cucina, Wellington	★★	(1)
Seashore Cabaret, Petone	★★	(1)
St Johns Bar, Te Aro	★★	(1)
Te Papa Cafe, Wellington	★★★	(1)
Viva Mexico, Wellington	★★	(1)

SoundPrint can be downloaded from the Apple App Store and Google Play Store. More information and reviews are available at the website: https://www.soundprint.co/locations/nz

A Purr-fect Ending for Smokey the Purring Cat

Lindsay Hannah and Wyatt Page

In early February of this year the Editors of 'New Zealand Acoustics' received a letter from Mrs L Ruth Adams of Spring Hill Farm, Harborough Road, Pitsford, Northampton, United Kingdom.

Ruth was the owner of Smokey a British cat who set the original Guinness World Record for purring at 67.7 dB at 1 metre distance. The record was set on 25th March 2011. The story received international publicity featuring on NBC and ABC news in America and radio newspapers and media around the world including across the United Kingdom. Smokey was also one of 9 Guinness World Record Holders that was featured in a documentary about Guinness World Records. As described by Ruth ***"Smokey came to fame for his annoying loud purring when I was helping the local branch of UK Cats Protection charity promote the spaying and neutering of cats".***

On the 13th May 2015 the Guinness World Records declared cat-a-strophic news that Smokey's puurfect record had been broken and the new Guinness World Record holder was awarded to Merlin the cat who was measured purring at "reaching a peak of 67.8 dB".

After receiving this paw-ful news Ruth was not purr-cisely sure what to do. Ruth may have said Paw-don me and how is this paw-ssible and scratch that, but either way Ruth did not pro-cat-stinate !

Ruth contacted the Editors after having read their paper *"An introductory guide to uncertainty in acoustic measurements"* (NZ Acoustics Vol 30, No 3, 2017).

Ruth noted in her letter to the Editors that ***"at the time not knowing much at all about sound measurements she accepted the decision however I randomly recently viewed the official footage of Merlin's Guinness World Record attempt and I became concerned that maybe the recordings were not as accurate as they could have been".***

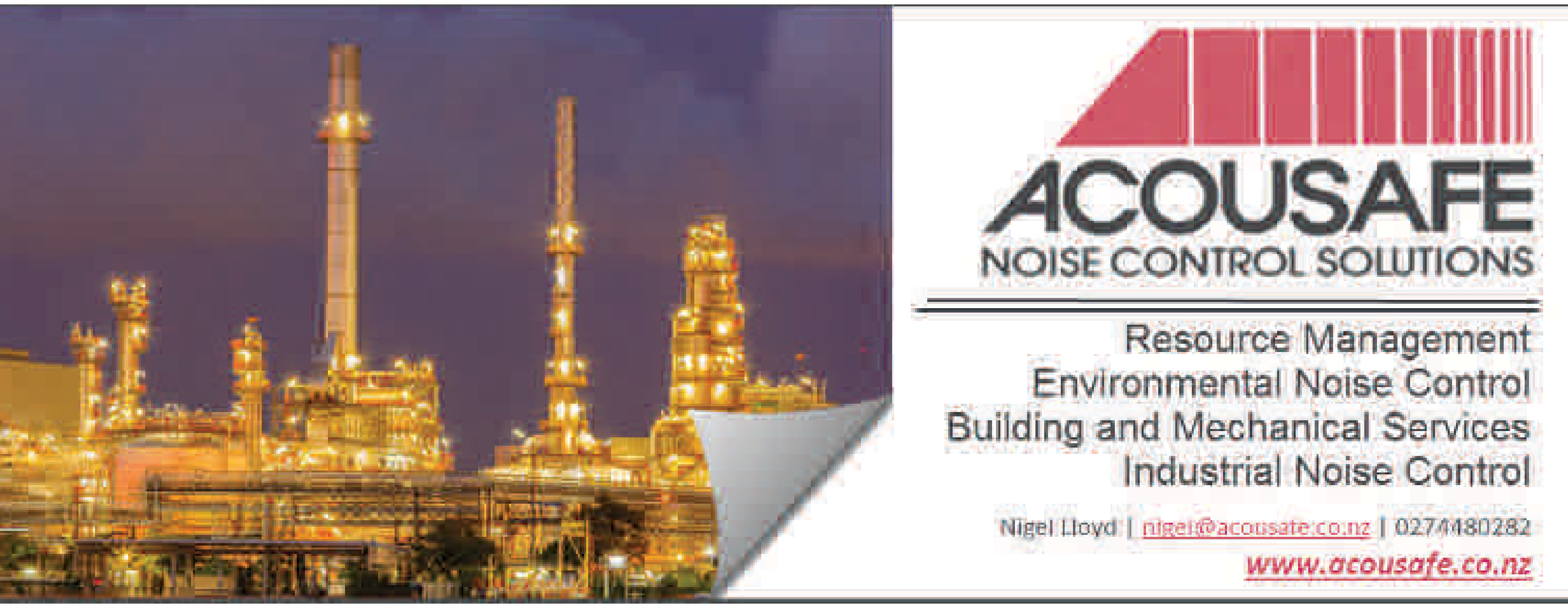
Ruth went on to note that ***"I was concerned that the film showed measuring the height of the decibel reader not the distance from the cats mouth and the cat appears to move forward on the ladies knee during the filming (sic)."***

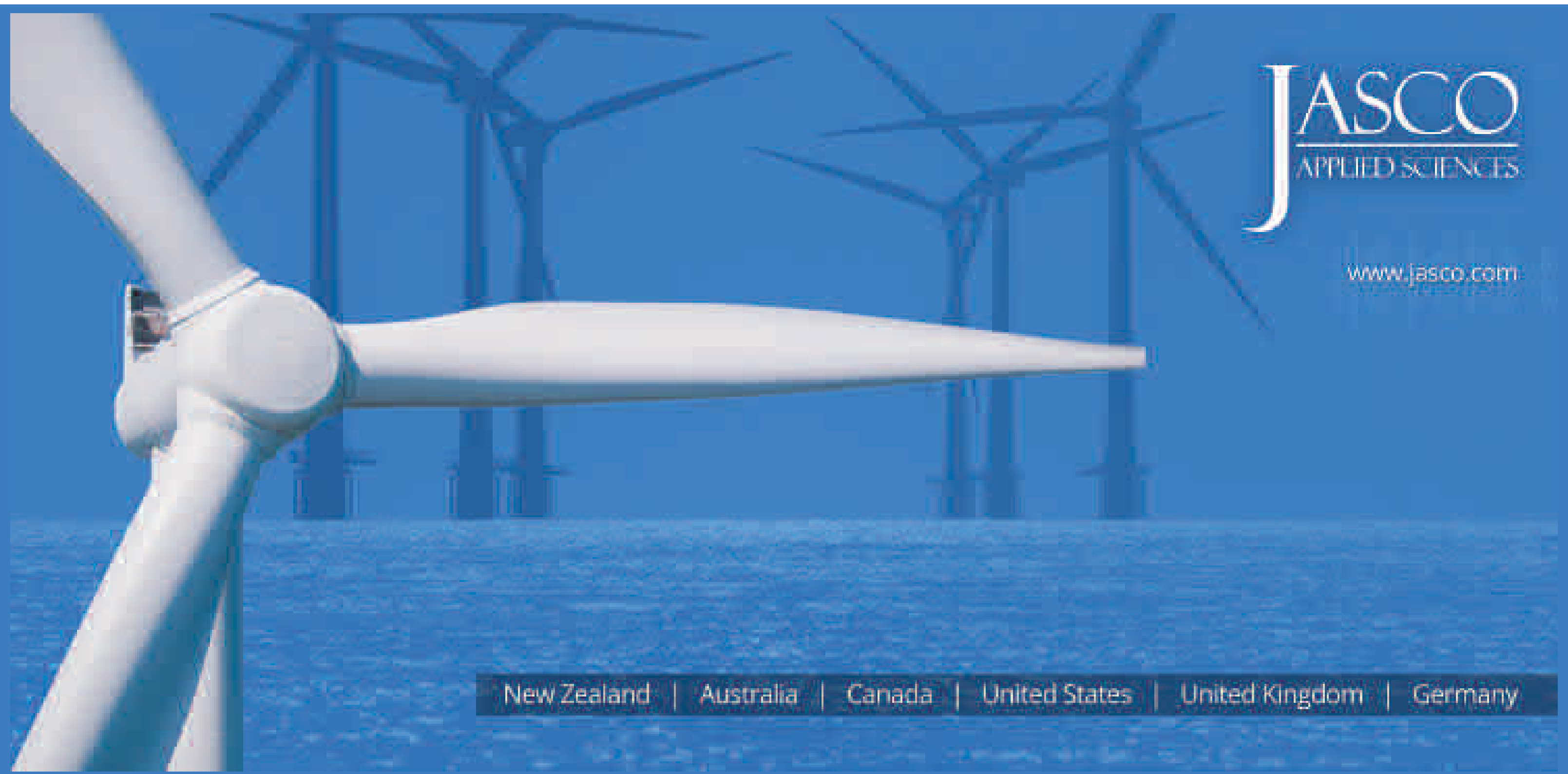
Ruth went on to state in her comms to the Editors ***"I also had concerns about the back ground noise and how this could alter the accuracy of any readings taken for example from road traffic noise as the house in which the recordings were taken appears to be close to the road. In the original GWR guidelines it stressed that background noise must not exceed 20 db. I am also concerned when I looked into the accuracy of decibel readers that they can give an error range of 0.6 to 1 or 2 db. Smokey had his Guinness World Record taken away based on a reading of a tenth of a decibel higher 67.7 db compared to 67.8 db. I read with interest your article on the internet about the accuracy of decibel readings and wondered if you would be able to assist Smokey in his attempt to have the Guinness World Record reviewed (sic)".*** Ruth had formally written to Guinness World Records to raise concerns.

The Editors advised Ruth that the matter was a technical matter. Advice was given to discuss with the Guinness World Record's details around their specific criteria and methodology for measuring records as they did not publish their measurement methodology or have any available guidelines to the public.

The Guinness World Record's web pages states with respect to 'How Measurements are recorded' that ***"As each record is as diverse as our record holders themselves, all titles have a unique set of rules that are specific to that activity. This is why it is crucial to apply to Guinness World Records before your record attempt to get these specific guidelines".***

The Editors advised Ruth that generally speaking, unless one is in a controlled laboratory setting, you cannot measure to 0.1 dB accuracy, and repeatability will be even higher. A standard Class 1 sound level meter when calibrated with a Class 1 calibrator, at best would be within +/- 0.3 dB, and as soon as one takes real-world measurements, things get significantly less accurate. To get better accuracy, one has to use laboratory class instruments in a controlled environment. Seeing that the record has been broken





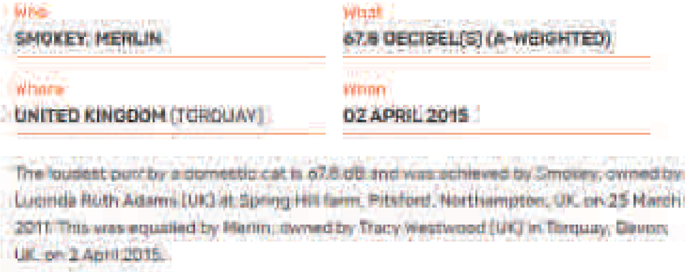
by such a small amount (a 0.1 dB difference at 67.7 dB is tiny, it represents a pressure change of only half a milli-Pascal) one must therefore call into question the measurement process.

Other matters the Editors advised on that may arise from purring sound from cats is the sound is directional, so the positioning and alignment of the sound level meter microphone are likely to introduce significant uncertainty in the measurement. Not controlling for background noise will introduce uncertainty, as will the acoustics of the space in which the measurements are taken.

The outcome was on review of the readings there as simply too many uncontrolled or poorly controlled variables that affect the readings. The Editors advise that the best accuracy we would expect from the measurement procedure that they appear to have used was +/- 1 dB, but it could be higher. So, based on the numbers reported, thus 67.7 dB is deemed indistinguishable from 67.8 dB.

After comms with the Guinness World Record consideration was given and the Editors advised by Ruth that ***"that following the submission of your letter/evidence statement on sound recordings that Smokey has now been awarded a draw so is still the joint Guinness World Records Loudest purring cat (sic).".***

A press release was made and the Guinness World Record web page updated to reflect the draw.



Who
SMOKEY, MERLIN

What
67.8 DECIBEL(S) (A-WEIGHTED)

Where
UNITED KINGDOM (TORQUAY)

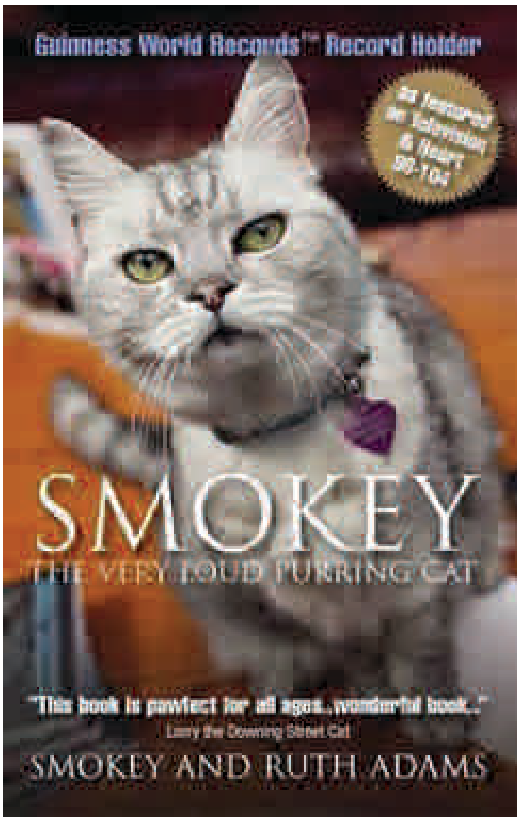
When
02 APRIL 2015

The loudest purr by a domestic cat is 67.8 dB and was achieved by Smokey, owned by Lucinda Ruth Adams (UK) at Spring Hill farm, Pitsford, Northampton, UK on 25 March 2011. This was equalled by Merlin, owned by Tracy Westwood (UK) in Torquay, Devon, UK, on 2 April 2015.

The outcome was as the Guinness World Record's would say was Offically Amazing™

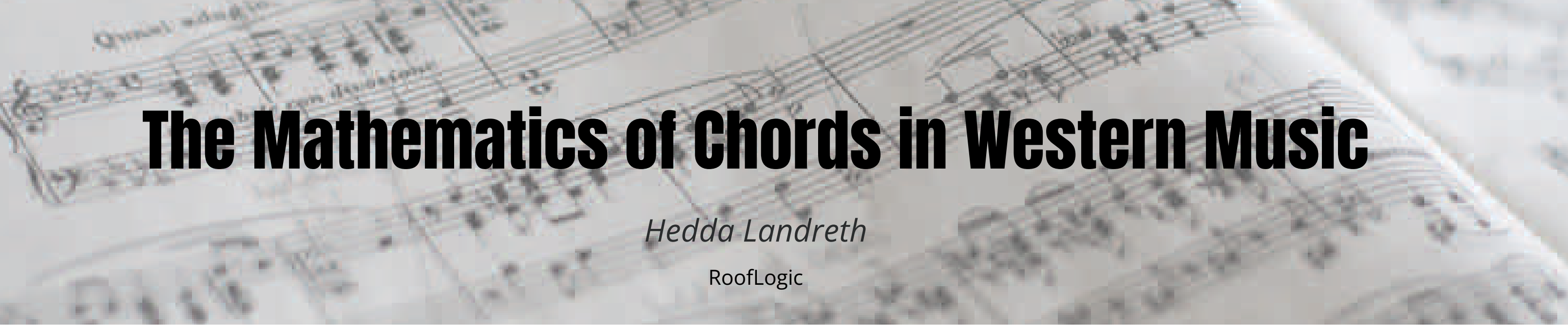
We think it was a puur-fect ending for both Smokey and Merlin.

Reference: Geoff Robinson Photography.



Sound performance: Ruth Adams gets Smokey purring with a breakfast titbit.

Reference Dailymail UK. https://www.dailymail.co.uk/news/article-1384199/Smokey-cats-deafening-purr-wins-place-Guinness-Book-Records.html



The Mathematics of Chords in Western Music

Hedda Landreth

RoofLogic

In many forms of music, chords serve as the cornerstone of harmony, providing the foundation for melody and rhythm. Comprising three or more notes played simultaneously or in close succession, chords come in various forms, from simple to intricate, and they are able to evoke a wide range of emotions. By arranging chords into different sequences with varying durations, they are used as the foundation for a multitude of musical styles, encompassing classical, jazz, rock, electronica, and pop genres etc.

At the heart of a chord lies the root note, which not only gives the chord its name but also serves as its tonal centre. Alongside the root note, additional notes known as intervals contribute to the chord's harmonic texture and colour, shaping its character and overall sound. One of the most common chord structures in Western music is the triad. The intervals of the third and fifth above the root correspond to the strongest and most prominent harmonics -overtones- generated by the fundamental frequency. The relationship between these intervals and the root note is determined by the physics of sound waves.

The notes in the harmonic series shape the foundation of a major chord. In other words, a major triad consists of the root note, the major third, and the perfect fifth all harmonising together. This alignment of frequencies and their mathematical relationship creates consonance and harmony, producing a pleasing and tonally satisfying sound. While a triad is traditionally composed of the root, third, and fifth stacked on top of each other, for a chord, the notes of the triad can be voiced in countless ways, including spreading them across different octaves, using various instruments, and reordering the notes.

This flexibility of voicing and arrangement provides musicians with an infinite number of ways to express a chord. It allows for creativity, experimentation, and the development of unique sonic textures and emotions within a piece of music. Whether it's a close, dense voicing or an open, spacious arrangement, the essence of the chord and its harmonic relationships are preserved, offering composers and performers a rich palette of options for musical expression with just three notes as the starting point.

In contrast to major chords, minor chords bring a different emotional dimension to music. By lowering the third interval by a semitone, a minor chord is formed. The ratio of a minor third interval above the root is 6:5. Minor chords often evoke a sense of sadness or melancholy due to the dissonance created by the minor third interval. However, the presence of the perfect fifth interval (3:1) introduces stability and resolution, contributing to the emotional impact associated with minor chords.

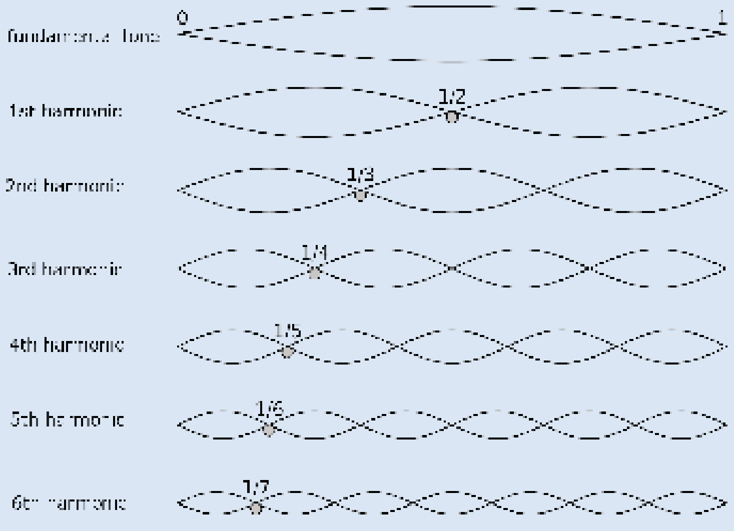
Beyond major and minor triads, extended chords expand on the basic triad structure. Seventh chords, incorporating a seventh interval above the root note, and ninth chords, adding a ninth interval above the root note, offer richer and more complex harmonic possibilities. The ratio of the 7th to the root in a Maj 7th chord is approximately 15:8 in terms of frequency. This ratio contributes to the distinctive dissonant sound of the major seventh chord. When the 7th note is included in the chord, it generates a compelling urge for resolution, essentially longing for the 7th to go up to the 8th, (2:1 which is an octave higher than the root note).

Using Triads as building blocks, chords with different tonal centres -or root notes- can be played consecutively. This sequence of chords forms a chord progression and is a fundamental element in music composition. Chord progressions help establish the overall mood, tension, and release in a piece of music, creating a sense of movement and structure. Musicians and composers use different chord progressions to craft melodies and harmonies that evoke specific emotions and drive the narrative of a musical composition.

In essence, chord progressions are like the building blocks of music, providing a framework upon which melodies and lyrics are built. The interplay between intervals, harmonics, and emotional impact shapes the tonal landscape, allowing musicians to convey a wide range of moods and narratives.

When a string vibrates or an air column resonates, it generates a fundamental frequency, which is the lowest note we perceive. However, sound waves do not vibrate in a "perfect" manner, meaning they are not simple sine waves. Instead, the fundamental frequency vibrates alongside multiple other frequencies that are intertwined. These additional frequencies are referred to as harmonics, and they are exact multiples of the fundamental frequency. To put it simply, they occur at two times, three times, four times, and so forth, the frequency of the fundamental note.

- First Harmonic ; one octave above the fundamental, vibrating at a 2:1 ratio.
- Second Harmonic: one octave and a perfect fifth above the fundamental, vibrating at a 3:1 ratio.
- Third Harmonic: two octaves above the fundamental, vibrating at a 4:1 ratio.
- Fourth Harmonic: two octaves and a major third above the fundamental, vibrating at a 5:1 ratio.
- Fifth Harmonic: two octaves and a perfect fifth above the fundamental, vibrating at a 6:1 ratio



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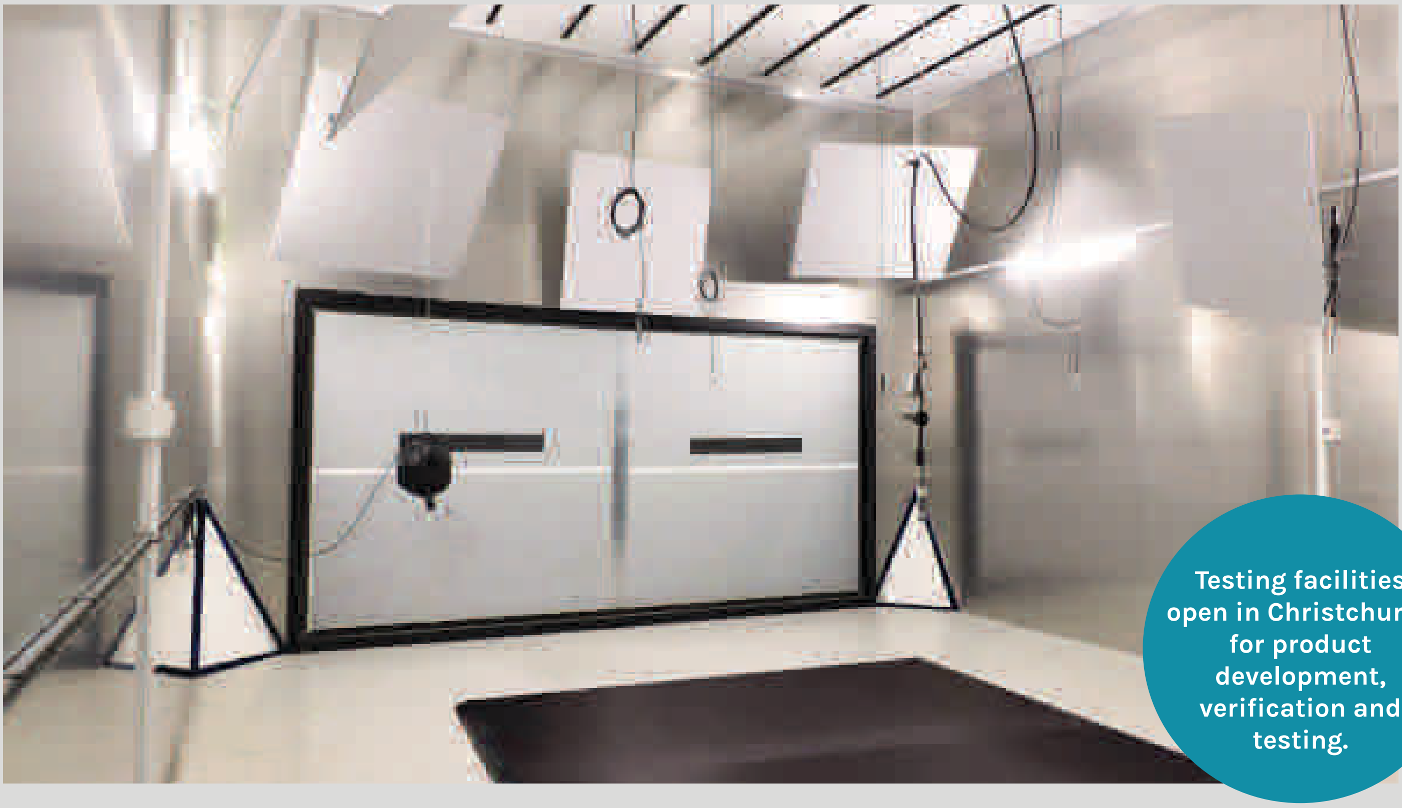

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+64 (0) 21 537 519
mike@acoustic-testing.co.nz

www.acoustic-testing.co.nz

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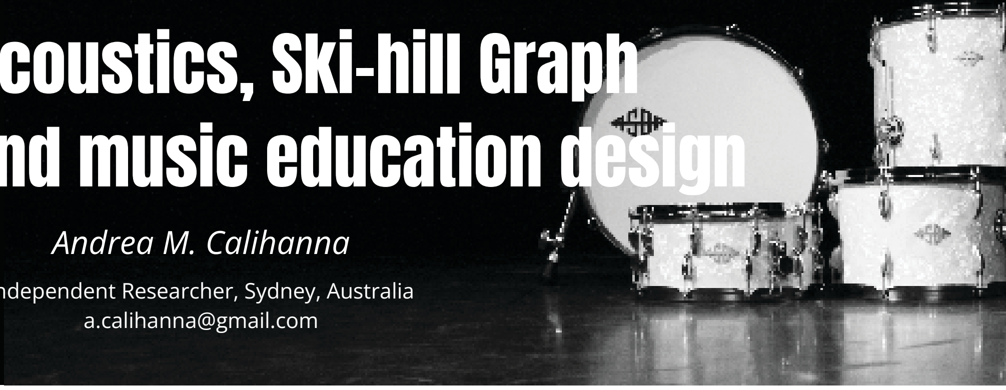

Psychoacoustics, Ski-hill Graph Pedagogy, and music education design

Andrea M. Calihanna

Independent Researcher, Sydney, Australia
a.calihanna@gmail.com

Abstract

Typically, the psychoacoustic experience of listening to music provokes a reaction to meter, rhythm, and pitch frequencies. However, pitch studies dominate the science of sound research in acoustics education. As science investigates how humans experience acoustics as sound and music, the details inform acoustics fields, including psychoacoustics. Educators and education policymakers seek interdisciplinary connections among the areas of music, mathematics, and acoustics. A cognitive gap emerges when listeners represent acoustics as the meter using the mathematics of traditional Western notation-based music theory. The study encourages a re-evaluation of meter theory and the accurate representation of the meter in music pedagogy foundations using the Ski-hill graph to present sound-based mathematical music theory to teach the meter in spectral analysis through listening. As music is sound (acoustics), it is logical to base the foundations of meter theory pedagogy on sound, that is, the subjective response of the listener and their engagement of the human auditory system – the mind and body response to sound. In addition, the computational analysis points to the need for human listening to complement spectral analysis. Until recently a comprehensive theory of the meter based on the experience of sound was not available with the capacity to encompass all the essential parts of a unified psychoacoustic approach to the pedagogy of the meter. As a music educator, I present a solution through the flexible three-step process of Ski-hill Graph Pedagogy inspired by the meter theories of Richard Cohn, Yale.

Introduction

This paper aims to address the area of music listening in the pedagogy of meter theory, specifically the pedagogy of the fundamentals of the meter through Ski-hill Graph Pedagogy inspired by the meter theories of Richard Cohn [1], [2]. The paper provides a psychoacoustic solution for teachers and students to understand the processes of the meter, and to accurately represent the meter [3]. The meter is conceptualised as the experience of acoustics as music and mathematics, rather than as a time signature or groups of beats notated in measures. In other words, the paper is a music educator-researcher practical response to Cohn's comprehensive contemporary sound-based meter theory. The broader purpose of the paper aims to contribute to the interdisciplinary field of Psychoacoustics in music theory pedagogy of the fundamentals of the meter [4].

Developing psychoacoustics skills at an early age such as spectral awareness of meter and tonality is yet to be fully researched, however, it is logical to assume the long-term benefits over the lifespan of humans. Listening to music evokes quantification of pulse, meter, rhythm, and pitch likely the same processes involved in executive function. Studies of music and include spatial-temporal reasoning and other executive functions [5]-[9], motor control [10], and our emotions [11]. Quantification research indicates several benefits for music theory education detailed in the following sections. Connections with auditory, sight, and other senses, that is, experiential and engagement-focused learning through recognition of temporal aspects of music.

Several studies indicate the benefits of learning music towards numeracy and literacy [12], [13]. Results point to the role of music, mathematics, and concepts common to both as beneficial for learning and pedagogical design. Quantification of language rhythms and musical rhythms likely use the same parts of the brain [14] yet rhythm focused research neglects the critical roles of the meter. Scholarship exploring core concepts common to meter and mathematics include interdisciplinary mathematical music theory to approach meter theory pedagogy indicate benefits through learning music through mathematics and mathematics through music [15]-[18].

As students develop mathematical skills through listening to music a benefit of learning music is the development of far transfer (applying skills to new work) [17]. A study critical of benefits of music education conceded including arithmetical notation in music to facilitate learning in other disciplines such as arithmetic is proposed [19]. Graphical visualisations of music notation through the mathematics of Cohn's Ski-hill graph contributes efficacy for teaching mathematical properties common to music and mathematics. Implementing Ski-hill Graph Pedagogy of the meter fundamentals positions this paper in response to the new area of meter pedagogy research and benefits are yet to be further investigated.

Cognitive neuroscience is yet to research quantification thoroughly, the temporal processes pivotal to the benefits of learning music are likely the experience of the meter mathematics. Cohn's theory and Ski-hill Graph Pedagogy may provide significant solutions for meter fundamentals, the implications are immense for education and science. This paper reports on some observations of teaching the meter through the psychoacoustic and visual mathematics approach of Ski-hill Graph Pedagogy in a piano studio setting. Each lesson is taught with a collaborative focus to workshop evidence of the meter from listening, represent the meter through the Ski-hill graph, and apply students' knowledge and skills to performance timing, expression, and insights into structure.

Background

The field of Psychoacoustics is not usually associated with the work of music educators especially those working with primary school age students and the fundamentals of music. In part, this is due to the focus of acoustics research on the science of sound (mainly pitch frequency) [20] rather than the science of music as sound experienced. Physicists, music theorists, cognitive scientists, and music educators, notably those involved in acoustics education outreach projects [21] have begun to explore music as more than wave theory, frequencies, and amplitudes.

The psychoacoustic impact of other aspects involved in the human response (processes) of the meter, includes but is not limited to pulse and resonance [22]; entrainment [23]-[25]; beat and pulse perception [26]-[28]; movement [29]-[33]; rhythm ratios [34]; language and rhythm [14]; harmonic tension [35]; auditory imagery [36]-[38]; timbre [39], [40]; anticipation [41]; social [42]; enjoyment [42]; well-being [43]; surprise [44]; performance [45], [46], [2], [27]; multi-modality [46], [15]; and acoustics producing everyday sound [47]. Although critical, further areas of music listening imbibe the impact music has on our lives and learning.

Medical science, including neuroscience, is exploring human interaction with music including spectral analysis to observe the processes of low meter frequencies [24]. In response to music neural activity including spiking is observed in ratio 2:1 and 3:1 in the human auditory cortex [25], the Psychoacoustic auditory-tactile and embodied reason why we tap our foot and dance to music. Arguably, most people intuit mathematics and music are related and science is pinpointing why they are related and how to maximise this knowledge in teaching and learning [48]-[52].

In other words, the intersection of these related studies has been developing albeit without access to a formal and comprehensive theory of the meter. Cohn's contemporary meter treatise [1] brought together the threads of meter theories adding to them. Scholarship in this area defaults to traditional Western notation-based understandings of the meter [3]. For instance, students are still examined in aural skills based on notation, and music teachers want students to perform well in examinations. The disconnect between what is experienced as the meter and what is taught as the meter continue to be the 'norm'. Teaching inaccurate mathematics to young students is irresponsible and to delegate the problem to 'convention' cowardly.

Several music educator-researchers have contributed to the trend towards more listening (audiation) [53], [54] and focus on sound in music education in studio and school classroom settings [55]. Among those who have sought to improve meter pedagogy introducing contemporary ideas mainly from North America – Komar, Lewin, Schachter, Krebs, Kramer, Hasty, Horlacher, Cohn, Biamonte, and Murphy. And many others connected the fields of music and cognitive science Pressing, Repp and Su, Parncutt, Lerdahl and Jackendoff, Povel and Essens, Imbrie, Fitch, Huron, Large, Deutsch, Temperley, and London.

Ski-hill Graph Pedagogy sources the interdisciplinary scholarship in mathematics and music pioneered in transformational theory by David Lewin, set theory, neo-Riemannian theory, and maximal evenness by Douthett and Clough and applied to psychoacoustic and developed into pitch and beat class mathematical meter theory [1], [56]-[65]. While others focus on sound and mathematics research [66], [67], Cohn has consistently called for a re-think of music education based on the experience of music as sound not notation [60], [62].

Ethnomusicology indicates mathematical music theory to represent music provides critical solutions and significant insights [1], [68]. Bamberger pioneered connections with embodiment, mathematics, and visualisations in music education [69] introducing technology as an intermediary between information and knowledge [70]. Embodiment [71], [51], [52] has serious implications for theories of the meter. The mathematics of the experience of the meter and its ethical representation through listening to music [1]. Conventional and mathematical music theory is yet to be researched further for meter theory education [2].

Researchers are exploring the reasons for these benefits of studying music [42] and where research focused on pitch and harmony, studies increasingly look to meter, rhythm, and quantification. Implications of the significance of the meter [72], beat perception and prediction [73] including in the absence of movement [29]; engagement of all the senses; metacognition; learning; visualising music theory [1], [2], [15], [74] are apparent. Practical consideration of introducing a psychoacoustic approach to acknowledge quantification of the meter in teaching [1], [15], [54], [64], [68], [75] is growing.

Elsewhere scholars aware of the importance of engaged listening to music and making music seeking to improve music education are also looking to solutions through a cross-cultural approach which includes enaction and praxis [75]. Elliott regards music as doing, collaborative, engaging and enacted by the listener and draws on Gestalt theory conceptual frameworks for experiential approaches because the listener may have different experiences of music such as polyrhythms in Ghanaian music.

Interestingly, mathematics is core and key to music and understanding the meter is central to the evolution of music education [76]. Yet there is resistance to change or a notable lack of reference to the mathematical properties of listening and the meter. Close listening to music reveals significant details of cultural identity, aspects overlooked without appropriate music-theoretic instruments with the capacity to capture and record analyses of fine structural elements of the meter and tonality [4], [61].

Temporal acoustical data listeners process then report inaccurately through details, distorts, and marginalises the cultural contributions of whole nations. Colonialisation brought Western music theory and practices without the capacity to capture the fine details of listening experience.

Much music has become extinct, and this paper provides a psychoacoustic solution for this unsustainable problem.

Representing music through visualisations

Humans have included visualisations of data such as music in pedagogy in graphic representations for centuries [77] and the meter is no exception [78]-[80]. Temporal data geometry augments the efficacy of meter pedagogy through the auditory, visual, and kinesthetic senses. The Ski-hill graph, a two-dimensional matrix with the capacity for listeners to represent their temporal data of the meter mathematically, enables wider

audience participation to study the meter and rhythm through practical theories.

Applying notation-based conventional Western music theory to traditional music of cultures around the world is problematic, an example being the traditional music of Igbo people, Nigeria. This unethical practice has led to the underrepresentation and cultural appropriation of Igbo culture and identity [80].

Despite advances in computational analysis and Artificial Intelligence human listening is still required to analyse the meter [81]. Fourier theory in pitch and meter studies provide insights into sound signals and mathematics of sound [82]. However, information is left out of analyses when the psychoacoustic meter process is not analysed, that which is in the imagination and not physically sounded - the pulses in-between onsets of rhythms, and this seriously misrepresents music, musicians, and whole nations. Analysis which does not acknowledge the role of the imagination and include onset intervals of all metric cycles, pulses, and centrally, the meter, over-simplifies and underrepresents music such as the Igbo people, Nigeria. In other words, Ski-hill Graph Pedagogy brings new possibilities to solve these problems through focusing accuracy of representation with correct mathematics (Ski-hill graph) and the psychoacoustic experience of music and mathematics.

Visualising the mathematics from listening to music has been gaining traction in music education and other fields of education such as mathematics, acoustics, engineering, computer science, physics particularly through graphical representation [63]. Time signatures, for instance, are not accurate representations of the experience of the meter through sound, patterns, and symbols. The availability of Cohn's (2020) contemporary psychoacoustic approach to music education is prompting calls for an overhaul of music theory in music education to enable students to accurately articulate music, mathematics, and acoustics [2]. Increasingly, scaffolding for teaching and research to embed in pedagogy conceptual frameworks include multi-sensory and multi-modal educational design and practice. Information technology can provide mainstream school and music studio education potential for engaged learning including a much wider application such as STEAM, transcultural, and health benefits. Questions are being asked – what is music education? What is the purpose of music education? What is the role of listening to music? How should music be represented?

What is the meter and why is it problematic?

Although cognitive neuroscience indicates the meter is not notation [24] inaccurate assumptions of meter theory are the basis of conventional music theory taught at an early age for music theory exams and applied to nearly all fields of science. Yet music analysis, performance, and composition of music requires a great deal of listening (as should music theory exams) and all music is processed through the human auditory system including, critically, the imagination. In other words, listening to music and applying conventional meter theory is problematic and Ski-hill Graph Pedagogy inspired by Cohn's meter theory [1], [61], [64], [65] bridges the gap between what is experienced as the meter and what is taught as the meter [2]. If you were (or are) confused about time signatures, for instance, the denominator (the number on the bottom), you may have concluded that something didn't make sense. You were right. Simply put, the maths is wrong.

Cohn's definition of the meter: A set of two or more pulses in a relation of inclusion in a ratio of 2:1 (duple meter) and or 3:1 (triple meter) is surprisingly simple, and yet it augments conventional meter theories. This paper aims to illustrate some benefits of adopting Cohn's contemporary meter theory and applying it to the pedagogy of the fundamentals of the meter.

It appears music pedagogy is undergoing a re-evaluation of the pedagogy of the fundamentals of the meter. Cohn's comprehensive theory of the meter ushers in a new era of meter analysis because it augments the notation-based based understandings of conventional meter theories and addresses problems, notably, defaults and disconnections. Cohn's definition acknowledges the listener's qualia, that is, the subjective and measurable elements of the listening experience, and enables the listeners to articulate their quantification of the meter through mathematical music theory. Conventional meter theory, on the other hand, a propositional approach with underlying assumptions of the meter as notation, tells the listener what the meter is via the meter signature and notation. Meter theory associated with explaining notation and the notation to express the meter (sound to symbol and symbol to sound), often confuse beginners because of the mismatch with the experience of acoustics as music represented as notation.

The meter isn't notation. Meter is the psychoacoustic experience of acoustics and meter theory requires music theory based on sound, music, mathematics, and acoustics to accurately represent their subjective psychological and physiological experience. Yet conventional meter theories default to the notation as the meter. For instance, the meter is understood as a meter signature and beats in a measure and conventional meter theory maths doesn't make sense. For example, there are no eighths (division of an eighth) or eighth notes 'in' 6/8. Rather, the quavers are a division of a sixth and the meter signature 6/6 accurately represents this one pulse. But how limiting. Why stop with one pulse when many other divisions and pulses are reported by listeners of all ages and musical experience? Cohn's Ski-hill graph and meter theory also solves this problem.

More than just numbers, music also engages the emotions, the 'heart' through all the senses. These two central and complex components of the acoustical experience and pedagogy influence the pragmatical approach to benefit student learning, that is, the pedagogy needs to be sensible yet creative, realistic yet imaginative, robust, practical, and ethical. Therein lies the value and potential of Cohn's meter theory for studying the meter processes from the fundamentals.

Essentially, Cohn's definition is a distillation of centuries of thought and scholarship of the experience of the meter from all over the world, that is, the theory doesn't claim to be Euro-centric nor only applicable to 'World' Music. Terms like Ethnomusicology are becoming antiquated labels from a divided world. Instead, the theories apply wherever the meter is discussed – inclusive meter theory in diverse education.

The Ski-hill Graph

Without appropriate sound-based meter theory, teachers and researchers struggle to include meaningful discussion of the meter because the meter surpasses the capacity of conventional Western music theory, by contrast, Ski-hill Graph Pedagogy provides a solution. Figure 1 illustrates a digitised version of the Ski-hill graph, Stereo Metronome [83] a new beta version application for Android. The Ski-hill graph provides a graphical layout for students to represent a compact summary of meter reported from listening to a piece of music.

Figure 1. The Ski-hill Graph *Stereo Metronome* (Fan and Calihanna, 2021)

In a sense, the purpose of a Ski-hill graph is to orientate the listener, a compass through which to plot the details of each pair of pulses that form a 2:1 relation or duple meter (mapped to the left pathways) and 3:1 relation or triple meter (mapped to the right). Each of these pairs of pulses form a minimal meter and most music initiates more than one set of minimal meters. Students visualise the metric hierarchy for each piece of music: the whole metric space.

Time signatures have the limited capacity to represent groups of a single pulse in notated measure and the accompanying meter theories in music textbooks is not referring to the listening experience, rather, it is an explanation of the notation. By contrast, Ski-hill graphs enable students to keep a record of all the pulses and all the meters they experience from listening and often there are many – too many to remember. These pulses and meters and their mathematics can then be applied to performances and or other projects.

Temporal psychoacoustically quantified data such as pulse and meter are both difficult to remember and essential for objectively engaging analysis with critical thinking. Examples include application to decode scores to inform timing and expression in performance. In other words, charting the mathematics of the Ski-hill graphics also functions both as a mnemonic device to assist students to remember and record the details.

Teaching at all levels is a practical business requiring sequencing, meaning, and creativity. If the music theory and experience align with each other the student is more inclined to be engaged. When teachers are confident in their understanding of the Ski-hill graph and its role for pedagogy, the mathematics and visualisation of student work becomes a powerful learning tool. Teachers are inclined to reach students through plumbing the depths of music with students, especially when there is time and tools for the job. However, conventional meter theory is systemically problematic because time signatures leave out vital psychoacoustical and visualised information and tools for students to adequately represent the meter. Ski-hill Pedagogy and its flexible three-step approach provide pedagogical solutions for teaching the fundamentals for teaching the meter.

WHY SKI-HILL GRAPH PEDAGOGY?

Listening is central to the pedagogy of music and music theory is the listener's means through which to articulate their experience of the music. Music theory in textbooks is not generally understood in this way although teachers are more inclined to seek ways to reach students. Notably, most classroom music texts provide only a small section on music other than Western music. Arguably, the prior absence of contemporary meter theory has contributed to position much of the world's music into the 'too hard' basket. Inertia is disappearing through the availability of Cohn's music theory which enables more meaningful and inclusive studies of all music – this paper is an example of this shift.

Teaching at all levels is a practical business requiring sequencing, meaningful content, and creativity. If the music theory and experience (practical application) align with each other the student is more inclined to be engaged. Students question and probe systems and institutions more than ever before seeking improvements, diversity, and inclusion. Ski-hill Graph Pedagogy provides the answers about the meter students and teachers seek.

When teachers are equipped to articulate meter theory that matches experience, music lessons are scaffolded through a meaningful conceptual framework to enable steering and practice through collaboration and workshop-style lessons. Conventional meter theory, on the other hand, is systemically flawed because the mathematics to represent the acoustics experienced as the meter is wrong and unrealistically presented in pedagogy. Understanding the meter through the mathematics and visualisations of the Ski-hill graph provides a solution to remove the confusion and replace it with realistic answers.

The world's music complexities supersede conventional notation-based music theory and new psychoacoustic- based instruments are required for students learning how to accurately analyse and conceptualise music. Each step of Ski-hill Graph Pedagogy to teach the fundamentals of the meter provides new insights into music listening tailored for each piece of music. The mathematics of the Ski-hill graph, however, is central to accuracy of analysis and representation.

Through applying the mathematics of the Ski-hill graph to analyse the meter, pulses, cycles of the meter, a reliable conceptual context is structured through which to study the details of the rhythm and pitch and other elements of music. A cognitive gap emerges when listeners represent acoustics as the meter using the mathematics of traditional Western notation-based music theory, and teachers seek answers [2].

Ethical issues arise when critical details of the meter ("DNA") is left out through conventional meter, however, applying Cohn's meter theory to analysis addresses this problem so that these details can now be included. For instance, macro structural details of conventional music theory analysis and micro details are possible through the Ski-hill graph's mathematics from listening to decode music including scores. Students become aware of the details of various cycle sizes of the meter, pulses, rhythms, and pitch and their significance in trans-cultural music education can be observed through the same processes.

To protect cultures the collection of accurate datasets is paramount for preservation, transmission, research, and identity. Cohn's theories which inspired Ski-hill Graph Pedagogy enable students from their first lessons to approach music analysis ethically, inclusively and with respect to culture. The flexible three

The flexible three step approach of Ski-hill Graph Pedagogy of the Meter includes:

1. Listen to music and map to a Ski-hill graph all the pulses and meter experienced as ratios 2:1 and 3:1. Pulses mapped as fractions provide the information needed to define through beat-class, the cycle sizes of pulses and, critically, meter cycles. Students learn to acknowledge the whole metric space and apply this knowledge to inform their timing and expression during performance (see Figures 2 and 3).

To do this, during listening, students clap or tap single pulses and tap pairs of pulses to internalise the duple and triple meters of the cyclic hierarchies of the meter. Sometimes the pulses are too fast to tap and requires practice, or the pulses can be sounded and visualised through the Stereo Metronome application. Once students have mapped all the meter, they are positioned to use these fractions to inform the timing and expression of their music performances.

The time signature only provided information about the tempo and one 'main' pulse. The Ski-hill graph enabled the student to jot down a summary of all the pulses and relate each to the music they are studying.

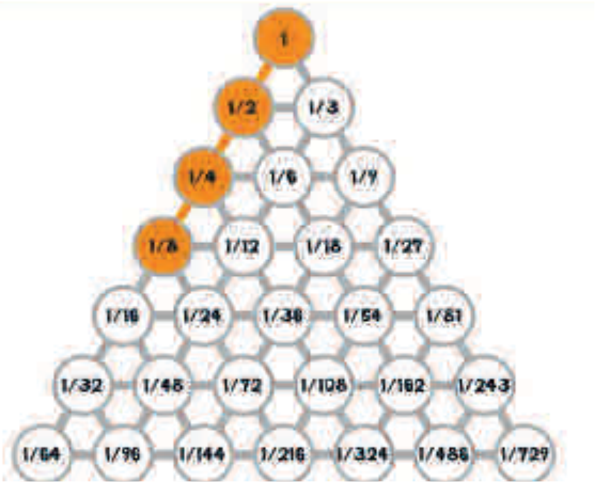

Figure 2. The Ski-hill view: Fractions. *Stereo Metronome*

Figures 3 illustrates the fractions of Figure 2 represented through two different staff notations which sound the same with equivalent pulse to tempo.

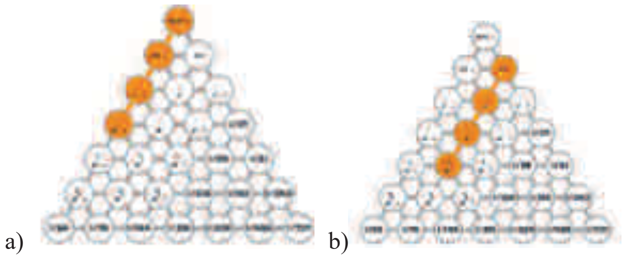

Figure 3. The Ski-hill view Staff notation *Stereo Metronome*

2. Apply the mathematics (fractions, ratios, beat-class) represented through the Ski-hill graph to annotate and decode scores, transcribe music, sight read, compose loops through digital audio workstations (DAWS), and more. Linear scores are transformed into cyclic graphs to observe structural elements of music and to assist students with timing and expression through 0 and 1-based counting. Students observe the depth of each timepoint, learn how the meter is integral for expression, timing, ethical, inclusive, and meaningful analysis (see Figure 4), and how dynamic markings tell us what 'not' to do!

Figure 4 Linear View *Stereo Metronome* Score Annotation

3. Students apply the mathematics represented through the Ski-hill graph to circle cyclic graphs to observe the rhythm and pitch in relation to the meter and to each other. In this way, the meter, rhythms, scales, chords, and motifs can be practiced through polygons and the mathematics of geometry with knowledge of the accurate mathematics to match the experience of music (see Figures 5 and 6).

Figure 5. Circle Graph View -beat-class and polygons
Stereo Metronome

Figure 6 illustrates the rhythm {2, 4, 6, 8, 10} a subset of timepoints selected from the universal set U12 or cycle of 12 elements: C12, d5. Learning to represent mathematics experienced as the meter is a wonderful introduction to the core mathematical principles of set theory for music and mathematics. Isomorphic mappings of sets and subsets of pitch through Cohn's beat-class such as chords, scales, motifs, and melodies as polygons provides critical cultural heritage data sets and visualisations of patterns which can easily be overlooked in the analysis of music through conventional music theory. These micro acoustic details are those which distinguish one piece of music from another. To deliberately conceal these structural details through unsuitable instruments can amount to unethical and inaccurate analysis, contributing to a roadblock for inclusion.

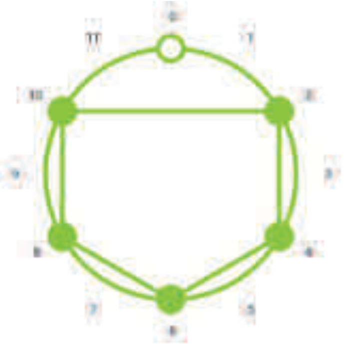

Figure 6. Circle Graph View - Rhythm *Stereo Metronome*

Music education design and benefits to learning

Ideally music education design places a psychoacoustic approach to mathematical music theory as a central tenant of learning. In doing so, this also positions the student as central to the design of education for teaching and learning. Listening in the curricular moves from passive to active when the music theory is also designed with the capacity to represent the student's subjective listening.

I observe my students displaying deeper awareness of their experience of mathematics (set theory) during active listening through their new knowledge of music theory in action. Through applying the mathematics represented in Ski-hill graph networks to decode music, students are taught skills to enable them to become more aware of the details of metrical structure and to apply their new understandings to expression, rhythmic stability, and sight reading, and the ability to discern genres. I have also successfully applied the theories in collaboration with Nigerian scholars to analyse traditional Igbo music from sound not notation (Calilhanna, Onwubiko, and Adeogun, 2019).

From my observations, in addition to the benefits already discussed in this paper, I have reported the following and other benefits and advantages to student learning of the meter fundamentals through Ski-hill Graph Pedagogy:

- Listening and student agency – recognition of subject matter includes subjective experiences.
- Development of aural (listening) skills (spectral awareness).
- Accurate visualisation of the meter, rhythm, and pitch.
- Development of ability to apply (transfer) new knowledge and information from listening and visualising to inform timing and expression: mathematical thinking [84].
- Increases student independence during at-home practice sessions.
- Reduces cognitive load through the integration of information, that is, the visualisation of music theory based on mathematical representation.
- Core structural data common to both music and mathematics and the experience of both.
- Interactive and not passive listening.
- Collaboration workshop-style lessons.
- Multi-media technology and pattern recognition software: Stereo Metronome [83].
- Student and teacher agency and engagement is embedded in the psychoacoustic approach of Ski-hill Graph Pedagogy
- Students and teacher agency and engagement is encoded in the psychoacoustic curricula design of Ski-hill Graph Pedagogy.
- The transdisciplinary teaching concepts such as structures common to music and mathematics including physics and acoustics are central for learning and teaching Ski-hill Graph Pedagogy.

- Students learn the mathematics underpinning the meter and the arbitrary nature of notation through concepts such as equivalence, that is, different notations will sound the same when the maths (ratio of pulse to tempo) stays the same.
- Students learn mathematical properties of the meter through set theory often for the first time including the mathematical music theory of Ski-hill Graph Pedagogy's beat-class, pitch-class, fractions, ratios, angles, integers, exponentials, permutations, maximally even sets and subsets, geometry, polygons, angles, modular arithmetic and more.
- Timing and expression develop from active listening and the Ski-hill graphical mathematics develops skills of prediction, probability [84], and anticipation.
- Students learn the skills of transfer to apply their new knowledge of the meter and its cardinality – permutations – depth of the meter –to all three-steps of Ski-hill Graph Pedagogy for new music.
- Performance and composition are music theory (PTC) in action and all three are music making, creative, and sourced through sound. Theory is central to the three practical parts of Ski-hill Graph Pedagogy.
- Multi-sensory experience: listen, imagine, map, visualise, quantify, kinesthetic, perform.
- The three-step mathematical process of Ski-hill Graph Pedagogy enables students to represent mathematical qualities not represented or easily comprehended through staff notation.
- Fractions, beat-class, and polygons are accurate representations of the meter from listening because of the Ski-hill's accurate mathematics.
- Multi-modal [46] – audio-visual-tactile.
- Engagement of students through active listening and the human auditory system (psychological and physiological), embodied acoustics, music and mathematics cognition and the imagination of the meter (pulses) [71], [85].
- Knowledge and application of metric cycles, and context of the rhythm and pitch to the meter to each other tailored for each piece of music.
- The mathematical music theory of Ski-hill Graph Pedagogy is an intuitive and flexible approach to music theory.
- Intrinsic and subjective knowledge of the meter is accessible and represented extrinsically and objectively through the mathematics of the Ski-hill graphics.
- Students consistently report the mathematics assists in their performance and understanding of music and mathematics at school.
- Macro and microstructures of the meter and tonality are possible for all music analyses.

Pedagogical approaches and systems for teaching the meter are being explored and emerging with different emphasis. Ski-hill Graph Pedagogy aims to provide a toolkit of music theory and instruments of music theory that can be adopted by most teaching styles to expand conventional understandings of the meter.

Ski-hill Graph Pedagogy of the fundamentals of the meter invites a re-evaluation of conventional meter theories and Cohn's theories augment notation-based understandings of conventional meter theory. This new psychoacoustic approach to the meter fundamentals enables students and teachers to articulate their reporting of the many pulses and meters from listening to music.

SIGNIFICANCE OF THE RESEARCH

Research indicating benefits to students from studying music overlooks the fundamental importance of the meter. However, because of Cohn's theories, cognitive sciences, medical science, special needs, education, and more, now have access to music theory which removes the need to deny or distort evidence of listening to music. Students and teachers can now develop spectral skills previously untaught and in applying Ski-hill mathematics solve many problems for analysis. Consequently, Psychoacoustics as a field is also benefitting from the subfield of music education more specially through the inter and transdisciplinary field of mathematical music theory.

Ski-hill Graph Pedagogy provides efficient information coding based on the fundamental principle that system responses (listening) should match their natural stimulus meter theory represented (quantification) for maximizing environmental information (acoustics). The gap between what is taught and what is experienced as the meter is removed and a bridge between science and the arts is formed by representing mathematical music theory of the meter through the Ski-hill graph.

Further research to investigate trans-cultural analysis of music and the use of appropriate instruments is essential. In addition, Ski-hill Graph Pedagogy opens possibilities to benefit learning for children with disability, learning needs, hearing and or sight disability [86], autism, beat perception [87], ADHD, Parkinson's, and motor-based research [88] is yet to be investigated.

CONCLUSION

To conclude, this paper is a musician-music educator-researcher's response to Cohn's [1] contemporary meter theory bringing together a comprehensive psychoacoustic approach to the fundamentals of the meter: Ski-hill Graph Pedagogy. Through a survey of issues surrounding the pedagogy of music theory specifically the fundamentals of the meter, the paper identifies problems encountered with the meter understood as notation rather than as the experience of acoustics as music and mathematics. The paper addresses several problems including the disconnect between pedagogy, experience, and representation, and provides a solution, Ski-hill Graph Pedagogy, inspired by Cohn's (2020) theories.

ACKNOWLEDGEMENTS

With gratitude to Mrs Ronda M. Freeman (Sponsor).

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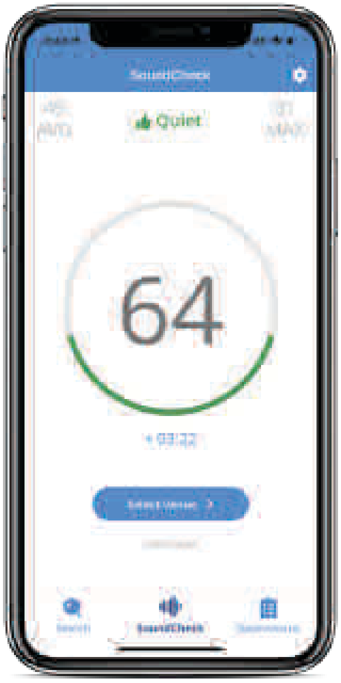

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Is the crying of my newborn damaging my hearing? Acoustic assessment of an infant’s cry and the estimated impact on primary caregivers.

Victoria Rastelli

Norman Disney Young

Abstract

The act of providing care for a newborn is actually not considered a job, however many caregivers spend from 6 – 12 months, or more, conducting this rather beautiful however potentially exhausting task, on a 24hour, 7days per week basis. The primary caregiver attends the newborn needs such as feeding, sleeping, bathing, consoling, burping, changing, and entertaining every day, while he or she is likely to be exposed to a high pitch, high intensity noise which is the newborn’s crying. In addition to this, the caregiver (or receptor) is mostly very close, less than 1 m approximately, to the newborn (the noise source) all the time, but in particular when the noise is at its peak when crying (all the above-described activities).

A crying child can expose caregivers to sound pressures as high as 103 dB(A) in some extreme cases Carney (2014). As the majority of the existing literature and research articles focus on the newborn’s hearing, this article explores the effect and relevance on the caregiver’s auditory impacts, estimates the acoustic dose on a newborn or infant’s (between 0-9 months old) caregiver, the perception of a controlled group of parents of the problem, the possible control measures to minimize their exposure without compromising the newborn’s care, and the importance of further research on this subject.

Review of literature

The exposure of the child's cry could potentially harm caregivers.

Studies of the crying noise exposure for caregivers are not very common, but this has been assessed by several authors. Calderon et al. (2016), stated that elevated noise levels produced from crying children can cause acute discomfort and mild pain. Furthermore, chronic exposure to these intense sound pressures may result in noise-induced hearing loss in a parent, guardian, or caregiver.

Authors like Reijneveld et al. (2004), state that at 6 months 5.6% (95% confidence interval: 4.2-7.0%) of all the parents reported having mistreated in some way their infant at least once because of its crying. Muller et. al. (2023) stated that excessive crying affects around 20% of infants in the first months and this can have a detrimental impact on families, such as anxiety and depression on parents and impacts on the parent - child relationship, among others. These authors recommend to clinicians to be aware of this risk to provide better tools for parents to cope. One of the premises of this investigation is the reverse statement: a more relaxed parent will be able to provide a better care and will be less prone to any mistreat of their infants.

Carney (2014) found evidence that the high-pitched amplitudes projected from crying children lie within a range that is commonly associated with otologic discomfort and even mild pain to those exposed, also recurrence can result in increased stress and irritability and could lead to enhanced risk for hearing loss for the parents of frequently crying children. Some of the decibel levels assessed during the study fall within the unsafe category according to NIOSH (National Institute for Occupational Safety &Health in the United States).

Carney (2014) states that persistent exposure to infant crying at close proximity may cause a parent to experience enhanced ear pressure, headaches, otologic irritation, and even tinnitus. While some of these symptoms are often transitory, they can theoretically become permanent if the frequency and intensity of exposure is extensive enough. For instance, and as a reference, for a working career length, minimizing daily exposure to 15 minutes is recommended for a noise level of 100 dB(A), and only 7.5 minutes is recommended for a noise level of 103 dB(A).

Parents of young children are often exposed to prolonged episodes of crying lasting more than 15 minutes and are typically in proximity when attempting to soothe the child, Carney’s study found that 25 of the 26 children produced a sound intensity of 100 dB(A) or more.

Carney (2014) and Calderon et. al. (2016), recommended the use of earplugs or muffs for caregivers exposed to a high decibel scream, as a prevention for unwanted consequences such as infant abuse. Nonetheless and as stated above, the emphasis in this article would be that preventive measures are a way of reducing the stress for caregivers and therefore enhance the caring experience of their newborn ones.

How much is too much crying? Are all caregivers equally exposed?

The response to this question is subjective. Not all parents are equally affected by the newborn’s cry, not every newborn cries the same intensity or amount per day and no day is the same in the life of a caregiver, at least during the first months of the newborn’s life.

This study presents, as best as possible, a typical day routine and typical causes for the newborn's crying, but sometimes there are no known reasons for the crying, and this is typically referred to as "colic crying". Whānau Āwhina Plunket in NZ defines Colic as a *"crying that can last for several hours without an obvious reason".* This was also described by Chen IL et. al (2006) as a serious problem for parents or caregivers, causing disruptions in families. Muller et. al. (2023) also defines colic crying as *"excessive infant crying of unknown cause"*, that could last for more than 3 hours a day, for more than 3 days per week, for at least a week in a healthy infant up to 4 months of age, this is estimated to affect 17-25% of infants in the first 6 weeks of life, and it is described as a "poorly understood" phenomenon.

There are studies that have quantified infant crying, according to Muller et. al. (2023), normal infant crying is high across the first 6 weeks of life and can peak at 2 h a day before reducing to 1 hour per day between 6 – 12 weeks.

There is a need to clearly hear the newborn cry and identify how to care for him/her?

The hearing health of the caregivers is essential, one aspect LaGasse et. al. (2005) highlighted is the importance of hearing and understanding the reason for crying, so that caregivers can alleviate the conditions that gave rise to the cry. Identifying the type of crying can help identify a disease or simply help parent perception of the infant's needs. Deviations in the signal and/or misunderstanding the message can compromise infant care, parental effectiveness, and undermine the growing relationship. This is especially important as caregivers of children who are deaf are reported to have greater stress in the family group as studied by Meinzen-Derr et al. (2008).

(*The Hearing review,* 2007) states that the child safety depends on the caregiver's ability to hear hence the importance of this type or research.

Current situation in New Zealand

What is happening currently in NZ regarding awareness of potential impacts in caregivers? Is this situation considered sufficiently in depth?

Research on the topic has shown that in NZ, all newborns have their hearing checked at birth by the National Screening Unit [NSU] within the Ministry of Health as part of the Universal Newborn Hearing Screening Programme (www.nsu.govt.nz/pregnancy-newborn-screening/universal-newborn-hearing-screening-programme). The aim is to find out, as early as possible, if the newborn has hearing loss. In Addition, The Paediatric Society of New Zealand -Te Kāhui Mātai Arotamariki o Aotearoa and Starship Foundation, Kids Health (2005), within the NSU provides a useful guide or checklist available for parents and caregivers to be aware of the infants hearing at 3-4 months, 5-7 months and at 9-10 months. Conversely, there is no available similar tool for caregivers to monitor their hearing health, given this is vital for their newborn's care, health and their own overall quality of life.

McLaren (2011), studied the acoustic environment in Early Childhood Centres in NZ, finding that some staff members exceed the 100% maximum daily sound exposure permitted in the workplace. Current legislation is not applied to schools and early education environments as a workplace, much less considers the homes of the caregivers. In McLaren (2011), six participants out of 73 participants (8%) recoded daily sound exposures well in excel of 100% dose, further 13 participants (18%) received daily exposures of 50-100%. Obviously, the crying noise impacts are intensified in Early care centres, however this study aims to raise awareness for parents at home, dedicated full time to the care of the newborn, subjected to lack of sleeping and stress, receiving a substantial exposure to a newborn's crying.

McLaren (2011) proposed a wide range national study to establish excessive noise exposure and hearing loss for teachers and the early education sector, a regular testing programme for occupational hearing loss and noise exposure and a range of options for early childhood centres to manage and mitigate noise (proposed for the Ministry of Education and the old Department of Labour, now part of the Ministry of Business, Innovation and Employment). As McLaren (2011) proposed for the early childhood teachers, this article proposes a similar and voluntary testing programme for caregivers at home.

Methodology

The inspiration for this article stems from the author's recent experience as a new parent. The research questions that motivated this article were:

- Could the crying of the newborn potentially harm the caregiver and its ability to take care of the newborn?
- Is it possible to quantitatively assess the noise exposure?

If this was indeed a problem, the author was interested to propose ways to reduce the auditory stress on parents as a way of helping the overall situation for them and for their newborns.

After reviewing the literature, it was concluded that caregivers at home should be subject of more attention and the focus in this study is to identify what can be done to help them mitigating potential hearing impacts and be in a more relaxed state to improve and enjoy the care of their newborns.

This research methodology is a mix of qualitative and quantitative research. Data collection was made in part using complete active participant observation. A survey with 9 questions was prepared and voluntarily completed by 21 full-time caregivers of 4- to 8-month-old infants in New Zealand to analyse from their point of view, the impacts and relevance of the subject of investigation. The author's own personal experience informed the survey questions, but did not participate in the survey, reducing the risk of losing of objectivity.

The quantitative analysis of this research was hard data collection which included noise measurements of two different crying episodes (same infant, aged 5 months old): feeding and sleeping crying measured at 1 m from the noise source in a typical room (RT approximately 0.7 s.) and data processing: calculation of the noise dose using survey answers, noise measurement results and the regional standard AS / NZS 1269.1:1998 Occupational noise management Part 1: Measurement and assessment of noise immission and exposure.

Results

Data survey results

Participating parents willingly contributed to this investigation.

Results from the survey are shown below:

- Question 1: does your new-born’s cry stress you? The goal of this question was to determine if the crying of the newborn is a factor on the overall stress of the caregiver.

Newborn’s cry is cause of stress, 95.2% of the parents considered stressful (52.4% slightly stressful and 42.9% very stressful).

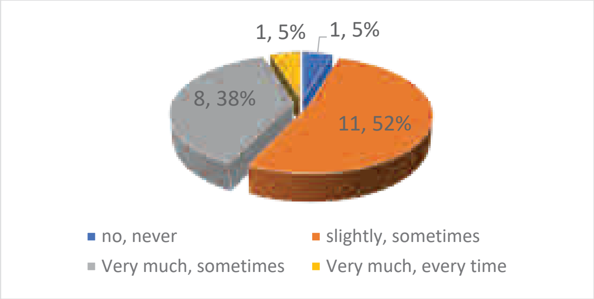


Figure 1 Question 1 "does your new-born's cry stress you?"

- Question 2: how long approximately does your new-born cry on average in a day? The goal of this question was to estimate the noise dose.

In an average day the survey shows that 57.1% of caregivers stated that their newborn cries an average between 15 mins and 45 min in total per day, 33.3% stated that their babies cry less than 15 min a day and a 9.5% stated that the crying can last between 45 minutes and 2 hours.

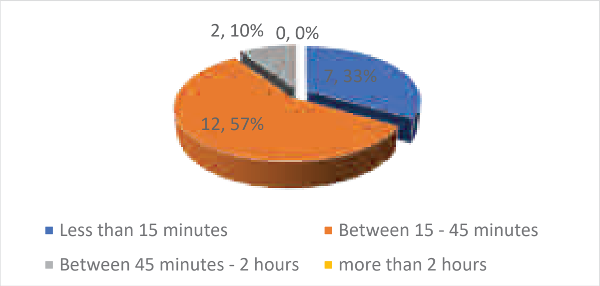


Figure 2 Question 2 "how long approximately your new-born cry in average in a day?"

- Question 3: Which type of activity generates more crying episodes in your newborn? The goal of this question was also to estimate the noise dose.

Newborns cry differently depending on the activity. Most of caregivers in the survey stated that feeding (hunger cry, preparing bottle, latching issues during breastfeeding and related) and sleeping (tiredness cry, rocking to sleep) were the activities that generated more crying episodes (33.3% for feeding and 52.4% for sleeping). Nappy changing also generated crying episodes for some caregivers (9.5%) and one person (4.7%) stated that all the proposed activities in the question generated crying in her / his newborn.

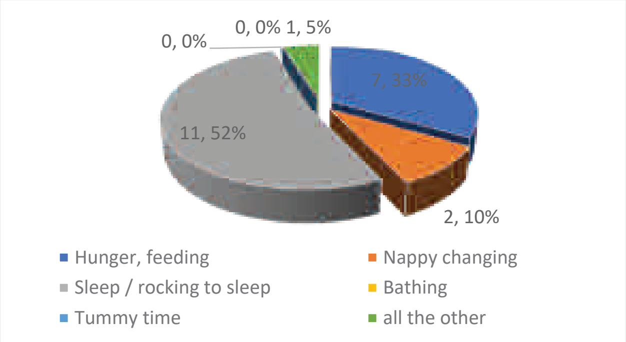


Figure 3 Question 3 "Which type of activity generates more crying episodes in your newborn?"

- Question 4: as a primary caregiver, do you consider your hearing has been affected by your newborn’s crying? The goal of this question was to assess if the affected caregivers considered the impacts on the long term.

Most caregivers do not consider that their hearing has been affected (57.1%), however some of them state that there has been a slight to moderate but non-permanent hearing damage (38.1%). One caregiver stated that their hearing might have been affected permanently (4.8%).

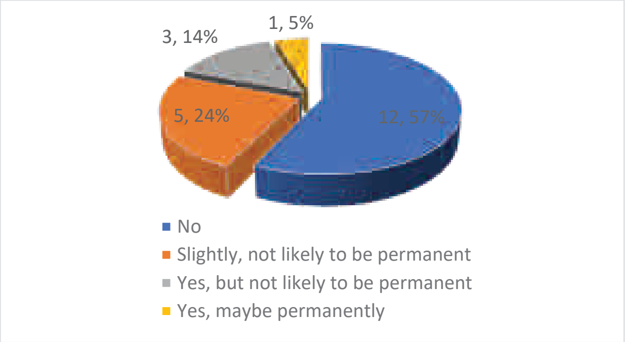


Figure 4 Question 4 "as a primary caregiver, do you consider your hearing has been affected by newborn's crying?"

- Question 5: how many crying episodes would you experience in an average day? The goal of this question was also to estimate the noise dose.

Most caregivers stated that they experience less than 4 in one day (62%), 14% between 4 and 6 episodes per day and 24% more than 6 crying episodes per day.

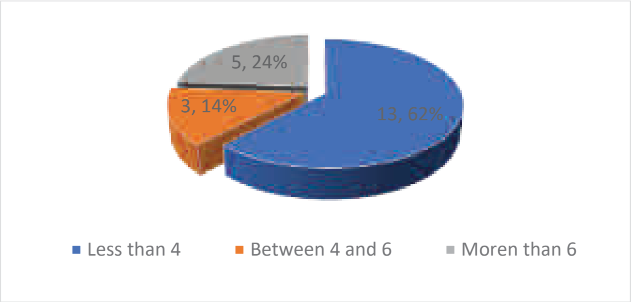


Figure 5 Question 5 "how many crying episodes would you experience in an average day?"

- Question 6: have you felt your “ears ringing” when consoling your newborn? The goal of this question is to assess how parents perceive their newborn crying intensity.

The sensation of buzzing or ringing in the ears (one or both ears) is called Tinnitus, it is a sign of temporary hearing damage and must be considered as a sign to visit a doctor. Among the main causes of Tinnitus are mainly exposure to loud noise and emotional stress. Some of the caregivers stated they felt their ears ringing sometimes (33.3%) or frequently (9.5%).

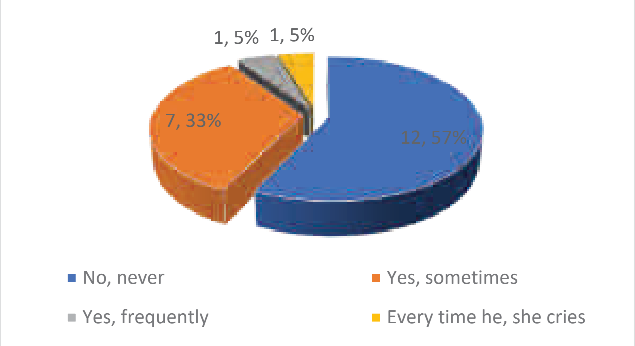
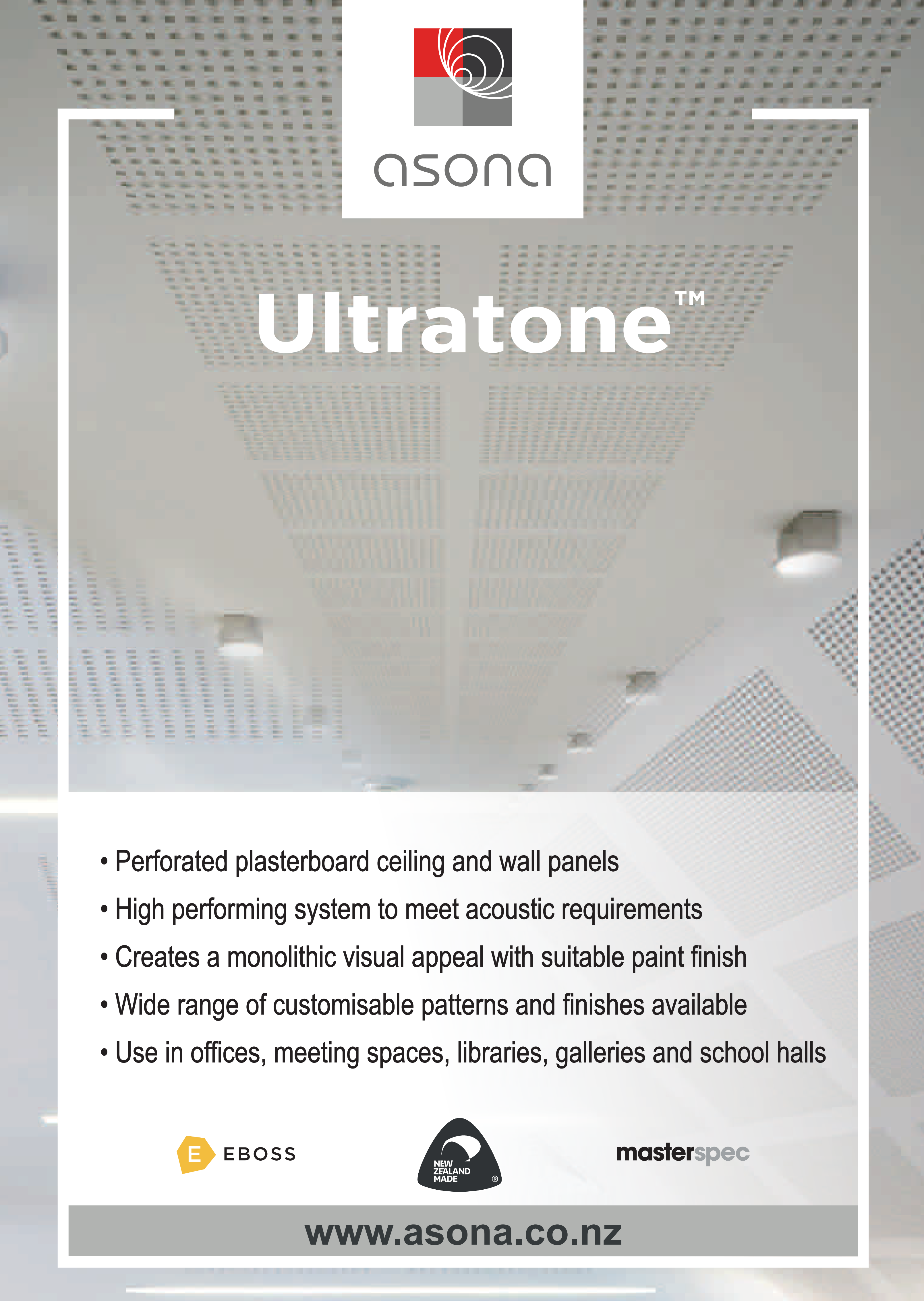


Figure 6 Question 6 "have you felt your "ears ringing" when consoling your newborn?"



- Question 7: would you think is useful to have a hearing assessment before giving birth and follow up ones after 1 and 5 years? The goal of this question is to assess how parents perceive the importance of this subject.

Most of the parents considered this to be somehow to very useful (76.2%). Despite the answers from question 6 about the ears ringing, 23.8% of the caregivers do not think is useful to have a baseline hearing assessment and follow up ones. None of the caregivers that conducted the survey received any information from their health providers regarding any kind of hearing protection or advice during their child's care.

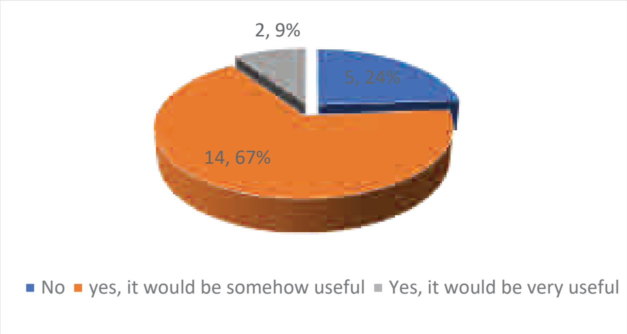


Figure 7 Question 7 "would you think is useful to have a hearing assessment before giving birth and follow up ones after 1 and 5 years?"

- Question 8: Understanding you do need to hear your newborn in distress, would you be keen to use hearing protection during the usual caregiver tasks when your newborn is crying? The goal of this question is to assess the willingness to mitigate the high noise levels while taking care of the situation that triggered the crying, once they know what was happening, for instance: feeding, changing a nappy, rocking to sleep, bathing, etc.

Most caregivers were not keen to use hearing protection (66.7%) versus 33.3% that are interested. This result was not expected, as some caregivers in the survey considered their stress levels and hearing was affected by their newborn's crying, and also other caregivers that stated feeling their ears ringing on some occasions.

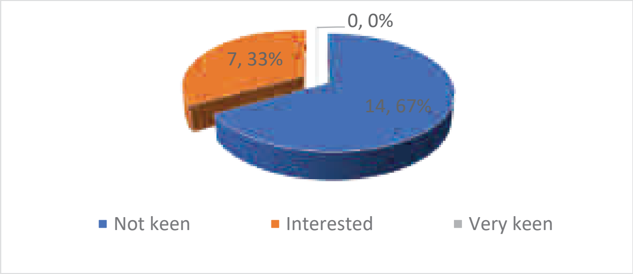


Figure 8 Question 8 "understanding you do need to hear your newborn in distress, would you be keen to use hearing protection during the usual caregiver tasks when your newborn is crying?"

The results of this question might open the path to another subject of investigation:

- Could this answer be influenced by the thought that using hearing protection will prevent caregivers from hearing their newborns at all?
- Is there a lack of information of the available products in the market that can allow caregivers to hear their newborns, while attenuating the effect of the intensity the crying?

- Question 9: do you think is relevant to continue investigating this topic?

Most of the caregivers think that this is somehow to very relevant to continue the investigation (90.5%), however two caregivers do not think is relevant.

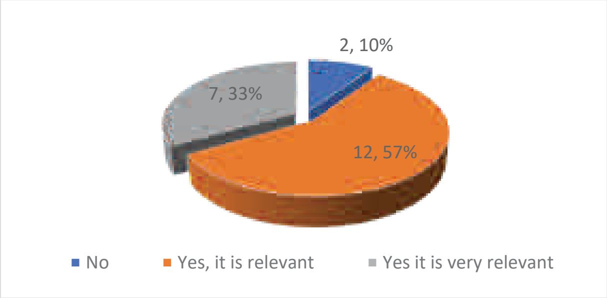


Figure 9 Question 9 "do you think is relevant to continue investigation this topic?"

Noise measurements

Noise measurements were recorded with a Bruel & Kjaer Sound level meter Type 2250 in a semi-reverberant environment (carpet, plasterboard walls and ceiling, soft furniture, drapes on some windows, approximately 0.7 s reverberation time) during three different crying episodes:

- Two different episodes of sleep / tiredness crying
- One episode of hunger crying

All measurements were taken at 1m distance from the newborn in an environment with approximate RT 0.7 s, during a period of average 2- 5 minutes. Results are shown in figure below:

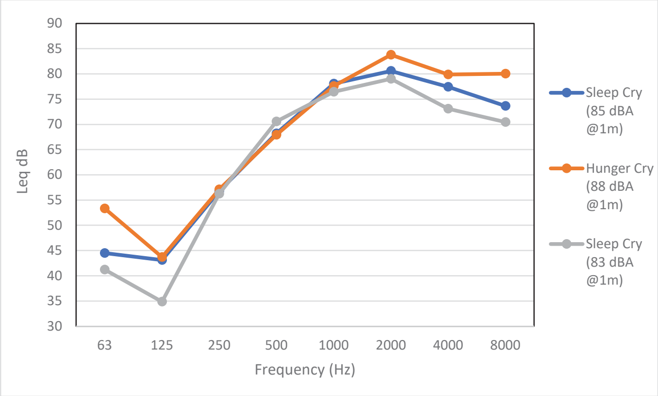


Figure 10 Noise measurements of the newborn's cry

As per the figure above, in all three measurements there is a consistent shape of the spectrum, with the highest intensity noise levels in the mid-high frequencies from 500 Hz to 8KHz, all peaking at 2000 Hz. Noise levels were more intense during a hunger episode, compared with the tiredness crying.

Calculation of the noise exposure

The calculation of noise exposure has been based on the proposed method partial noise exposure ($E_{A,T}$) included in appendix E of AS / NZS 1269.1:1998 Part 1.

Partial Noise exposure calculation was selected in this study because of its applicability to a person that is working at several different tasks, each with a different noise level over the course of a day. A partial noise exposure will be received from each task, depending on the amount of time spent on the task and the associated noise level. Adding the contribution of all partial noise exposures will give the total noise exposure of this person during the day.

The calculation of the exposure has been made as outlined in appendix E of AS/NZ 1269:1998 Part 1:

- Convert each LAeq, Ti to a pascal-squared value using table E2
- Multiply each pascal-squared value by the respective exposure time Ti in hours, to obtain the partial noise exposure E ATi
- Add these partial noise exposures together to obtain the total daily noise exposure E AT
- Read the LAeq, 8h value from Appendix F

Two scenarios were established, based on the reviewed literature and the answers relating to timing and duration of crying episodes provided in the survey.

Scenario 1

The first scenario will consider the following survey responses: the maximum average crying during a day is 45 minutes per day, activities that generate crying are mainly feeding and rocking to sleep and number of crying episodes are between 4 and 6.

We assume that for the 6 feeding episodes that a newborn must have per day, a time of 5.6 minutes per each one gives a total of 0.56 hours per day on crying and 0.56 hours per day rocking to sleep. We assume that for the first weeks, the newborn will need a nappy change and then be rocked to sleep right after the feeding. Total assumed crying time for this scenario was 1.12 hours per day, which would be slightly more than the survey answers but within the range with newborns crying estimations by Muller et. al. (2023). The noise exposure calculation took the measured values of LAeq 88 dB for hunger crying and LAeq 85 dB for sleep crying:

Table 1 AS NZS 1269.1:1998 calculation of the 0-hour Noise exposure - Scenario 1

Process	Measured noise level L_{Aeq} dBA	Duration of exposure, h	Pascal-squared Pa^2 (Table E2)	Partial noise exposure (E$_{ATi}$), Pa^{2}h
feeding	88	0.56	0.25	0.14
sleeping	85	0.56	0.13	0.0728
EAT (Pa^{2}h)				0.2128
Equivalent in decibel (Table E2, Appendix F)				78.3 dB

Scenario 2

This scenario considers the same 6 feeds per day but a little more time for the process per feed (7 minutes per each); this is from bottle heating or breastfeed latching, to the feeding process, burping stage, colic pain period and nappy change both right after the feeding.

This scenario also considers at least 10 minutes after the feeding process is finished, to continue with the process of rocking to sleep. This process can last more time as newborns struggle to fall asleep, even in the case of being tired. Based on experience and in the survey answers, the scenario also considers two more elements: a 2 sessions of minimum 5 minutes of miscellaneous crying (occasional extra nappy change outside of the regular ones), at least 3 sessions of 5 min sessions of "tummy time", that usually upsets the newborn but it is highly recommended by health providers and 5 mins for bathing time. Total assumed crying time for this scenario was 2.2 hours of crying per day, which also is within the range considered by Muller et. al. (2023) and less than the critical case of 3 hours per day of crying in this same study. The particular case of bath crying was not measured and might require further assessment as the receiving room for bathing is usually a more reverberant one.

Table 2 AS NZS 1269.1:1998 calculation of the 0-hour Noise exposure - Scenario 2

Process	Measured noise level L_{Aeq} dBA	Duration of exposure, h	Pascal-squared Pa^2 (Table E2)	Partial noise exposure (E$_{ATi}$), Pa^{2}h
feeding	88	0.700	0.25	0.175
sleeping	85	1.000	0.13	0.13
miscellaneous	85	0.187	0.13	0.024267
Tummy time	85	0.280	0.13	0.0364
Bathing time	85	0.093	0.13	0.012133
EAT (Pa^{2}h)				0.3778
Equivalent in decibel (Table E2, Appendix F)				80.7 dB

Conclusions

- The good management of newborn or infant crying and the auditory impact on caregivers are important topics and can be highly beneficial for both caregivers and newborns, as it will reduce their stress of the daily noise exposure and bring them a more comfortable environment to care and enjoy the caregiver's daily routine.
- Infant crying could become a serious problem in caregivers health, stress, anxiety, ability to take care of their new-borns and in consequence in the quality of the new-borns care. This phenomenon needs more attention and research.
- Survey results show that the activity that generated most crying in the infants was sleeping (52%) and feeding (33%), which sometimes could lead to a crying amount per day between 15 – 45 minutes (57% of survey results) and in some cases between 45 min to 2 hours (10% of survey results).
- 38.1% of caregivers in the survey perceived their hearing affected by their newborn's cry, between a slight to moderate but non-permanent hearing damage, while 4.8% of the caregivers considered their hearing could be permanently damaged.
- 42.9% of caregivers in the survey experimented their ears ringing when their newborn was crying, being this a sign of an exposure to a high pitch cry.
- 76.2% of caregivers in the survey considered useful to have a baseline hearing assessment and a follow up after 1 and 5 years. Despite this, none of them have received information from their health providers about the risks of hearing damage or any noise mitigation information.
- There could be a misconception about the use of hearing protection to attenuate the effect of the intensity and proximity of the crying. Despite many caregivers were affected by the crying and noted that their hearing was impacted, most caregivers in the survey stated not being keen on using hearing protection; only 33.3% were interested in this possibility. Note that the suggestion of hearing protection is not intended for the newborn's crying noise suppression, but to attenuate the effect in proximity.
- 90.5% of caregivers in the survey think that is relevant to continue this investigation. There are no current studies in NZ that address directly assess and care for caregivers hearing health.
- The calculated daily noise dose of the two daily scenarios proves that the equivalent 8-hour noise level is not negligible (78.3 – 80.7 dB). The dose could be different, depending on the case. For both scenarios, the total estimated crying time per day, based on survey results, were within the ranges of the study of Muller et. al. (2023), hence these preliminary noise dose results are representative.

- The newborn crying assessment shows a noticeable spectral shape, with frequencies of 1000 Hz, 2000 Hz and 4000 Hz being the most intense ones. Research indicated that hair cells that pick up high-frequency sounds are damaged first due to their location inside the cochlea.
- It is recommended to include some recommendations for newborn's caregivers with GP, midwives and birth care institutions or similar that help them mitigate the daily noise. This could include taking some "acoustic timeouts" and use for hearing protection devices only once the crying reason is understood and during tasks that require proximity.
- It is recommended to introduce a pilot study conducting a baseline hearing assessment before or right after giving birth and follow up ones after 1 and 5 years (as suggested by AS/NZS 1269.1:1998) for voluntary caregivers, this will provide a better data in time. The National Screening Unit as part of the Ministry of Health in conjunction with the Ministry of Business, Innovation and Employment, with the branch dedicated to Worksafe could be interested in this study.
- A more relaxed caregiver means a better quality of environment for everyone. Noise impacts can be detrimental to not only audition but be stressful in a time where overwhelming tasks must be conducted daily. Hence more attention should be paid to caregivers particularly in the initial months after birth to be able to enjoy this precious time.

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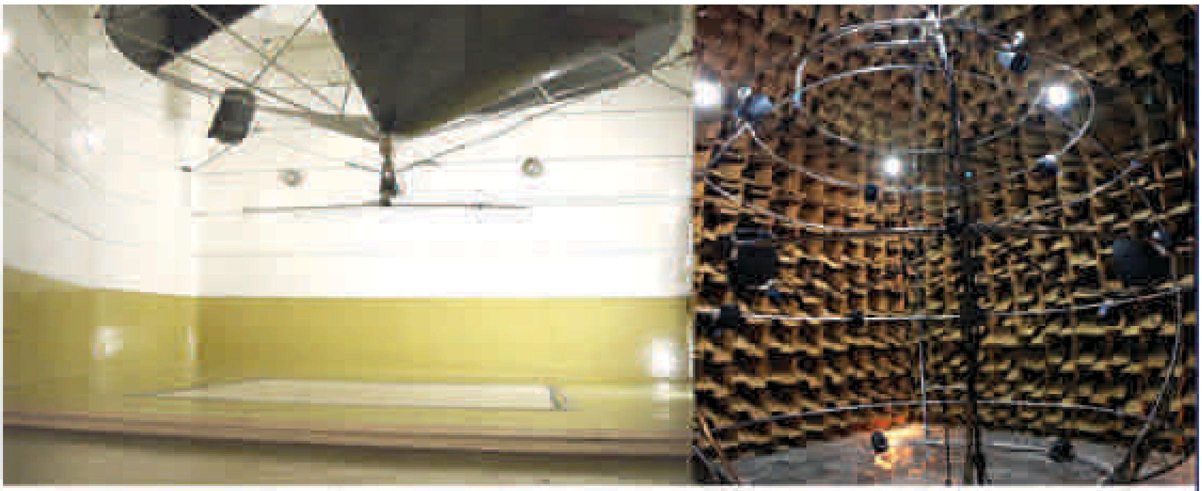

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Remarkables Primary School

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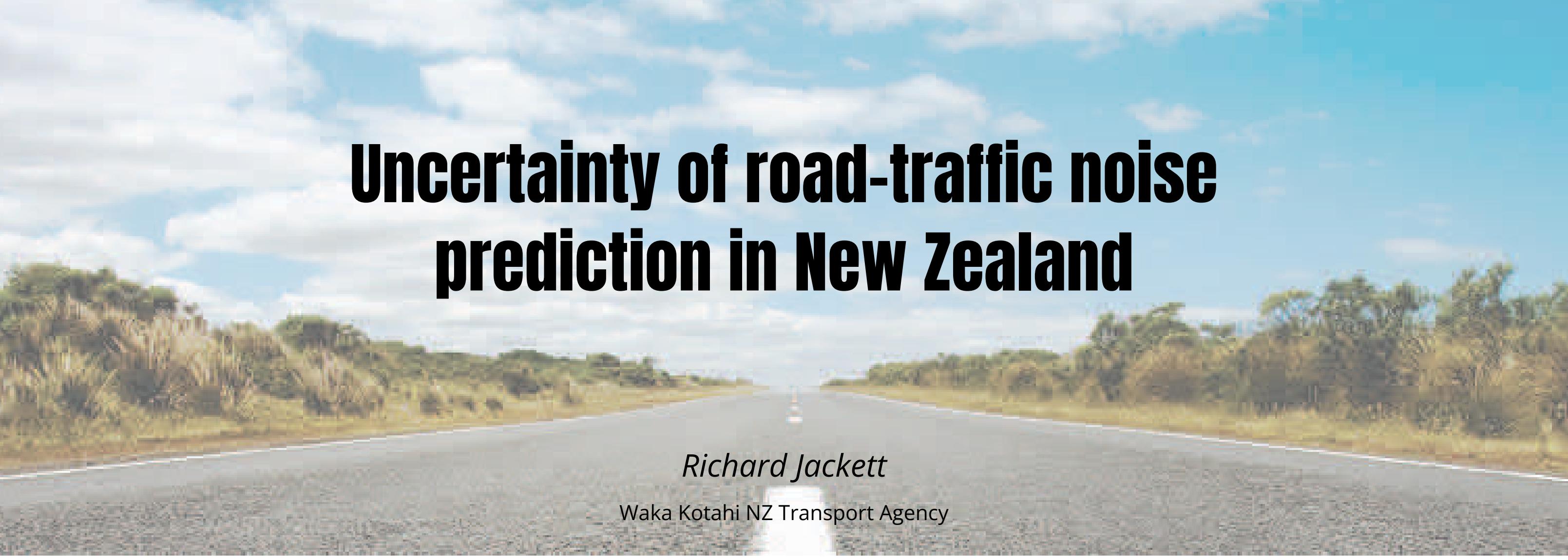

Uncertainty of road-traffic noise prediction in New Zealand

Richard Jackett

Waka Kotahi NZ Transport Agency

Abstract

Road-traffic noise assessment in New Zealand (NZ) relies primarily on modelling rather than measurement. The 1988 Calculation of Road Traffic Noise (CRTN) algorithms were adapted for NZ in the 1990s and remain in common use. However, the prediction uncertainty was incorrectly estimated as ± 2 dB at 95% confidence. This value has since propagated into NZ standards and guidance, setting an expectation for the accuracy of road-traffic noise predictions that is unattainable. A re-examination of CRTN, other literature, and new measurement data, indicates that prediction uncertainty under the best-case scenario is, and has always been, approximately ± 5 dB at 95% confidence. For some road surface types, site geometries, and/or predictions far from the road, the uncertainty increases further. A table of indicative prediction uncertainties for the application of CRTN in NZ is provided.

Keywords: Road-traffic noise, noise modelling, noise prediction, error, uncertainty, CRTN, CoRTN

1. Introduction

1.1 BACKGROUND

Road-traffic noise assessment in New Zealand (NZ) relies upon modelled predictions of future road-traffic noise levels. The Calculation of Road Traffic Noise (CRTN) is a set of noise prediction algorithms developed for the UK in the 1970s and refined in the 1980s [1]. In the 1990s, New Zealand adapted the algorithms for use with its roads and vehicle fleet [2] [3] [4]. CRTN has since become the de facto prediction method for road-traffic noise assessments and mapping in NZ [5].

In the 1990s, Barnes & Ensor [2] used many traffic noise measurements to adapt CRTN to NZ, and reported achieving a prediction uncertainty of ± 2 dB at the 95% level of confidence. This value was written into the previous 1999 NZ road-traffic noise guidelines [6] in an informational sense, and appears in the current NZ standard for road-traffic noise NZS 6806:2010 [7] as an accuracy requirement. However, for reasons discussed in this paper, ± 2 dB is not representative of the overall uncertainty of prediction – in practice, it is over twice that value – and represents an unattainable target for 95% confidence.

1.2 SCOPE

The realised acoustic quantity in CRTN-based prediction of road-traffic noise is not an average of $L_{\text{Aeq(24h)}}$ (via $L_{\text{A10(18h)}}$) over one year, as might be implied by its use of Annual-Averaged Daily Traffic Volumes (AADT) as an input parameter. CRTN predicts traffic noise only from dry roads and assumes downwind propagation to all receiver locations. This is a different acoustic quantity than might be measured by long-term $L_{\text{Aeq(24h)}}$ noise monitoring, despite sharing the same suffix. This study was concerned with the uncertainty associated with *CRTN-based* prediction of long-term road-traffic noise from NZ roads.

Of most concern to noise assessments is the risk of under-prediction, thus defining the upper limit of the confidence interval was the focus of this study. Henceforth all uncertainties and errors are given as standard errors (coverage factor k=1) unless explicitly stated as being 95% confidence limits (k=2).

A recent analysis of the road surface's contribution to road-traffic noise [8], including substantial new data on surface variability, has provided an opportunity to review CRTN prediction uncertainty in NZ. Indicative values for prediction uncertainty under various common scenarios have been suggested that should represent an improvement over the current assumption.

2. Historical context to prediction uncertainty

2.1 UNCERTAINTY OF CRTN IN ITS NATIVE STATE

To evaluate the accuracy of their empirical CRTN prediction methodology (the 1975 version), authors Delany et al [9] compared their predictions against measurements (2064 pairs) and reported a mean error of -0.6 dB (a bias towards underprediction) and an RMS error of 2.5 dB. While not strictly an RMS error [1], because it incorporated some of the measurement data used to build the model, it is the best estimate available [2]. This result implies a prediction uncertainty in the region of ± 5 dB at the 95% level of confidence. Much of the observed residual variance was ascribed by Delany et al to the different absorptive properties of notionally similar ground surfaces. Co-author Hood considered that failing to account for differences between road surfaces was "the major source" of the prediction error [10].

Ahead of the 1988 revision to CRTN, Hood [10] revisited prediction uncertainty, and performed independent measurements close to the road [3], finding a mean error of +0.7 dB (overprediction) and an RMS error of 2.1 dB (n=263 pairs). Further from the road (> 50 m) Hood found that propagation effects also became significant.

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[1] An RMS error describes the root-mean-square (RMS) deviation from the 'true value' (computed out-of-sample), whereas an RMS residual describes the RMS deviation from the predictor (computed in-sample). The former encompasses additional sources of systematic error. Measurement error makes a contribution to both.

[2] Delany et al also made an alternative evaluation using only their "best quality" measurements [RMS "error" 2.0 dB, mean error +0.1 dB, n=328 pairs], which is sometimes quoted as the uncertainty of CRTN, but this evaluation appears to be much closer to that of an RMS residual and therefore not a full accounting of prediction error.

[3] It is implied, but not stated, that only bituminous surfaces were included in the survey but were not corrected for surface texture.

The 1988 CRTN publication [1] introduced a form of road surface correction and modified the ground absorption calculations but didn't address the uncertainty of prediction in a quantitative sense.

2.2 ADAPTION TO NZ

2.2.1 INITIAL ADAPTATION

The adaptation of CRTN to NZ conditions in the 1990s ambitiously aimed for an uncertainty of ± 2 dB at the 95% confidence level, and Barnes & Ensor's report [2] plots prediction vs measurement residuals that are generally within a ± 2 dB range. However, in practice this result does not represent a 95% confidence interval on road-traffic noise prediction:

1. The RMS residual is not a full accounting of prediction error [1] (the residual was calculated on the same dataset used to tune the adaptations, and doesn't consider measurement error for example). No estimate of systematic error for either the adaptations or the prediction was given.
2. The modelling relied on measured input parameters, not predictions. Parameters like sand circle measurements of surface texture, exact traffic counts, and detailed vehicle mix can't be known years in advance of the road being constructed, and they vary over time.
3. Perhaps because of the difficulty predicting some of those inputs, the proposed adaptations (a new variable for measured surface texture and a new variable for the ratio of medium to heavy trucks) were not adopted into NZ standard practice, despite being necessary to achieve the declared residuals.

Prior to the adaptations being applied, Barnes & Ensor's data [4] showed CRTN (1988) achieving an RMS error of 2.7 dB (mean error +0.6 dB, *n*=80) close to the road, quite similar to that found by Delany et al 20 years earlier. With the adaptations applied, an RMS residual of 1.2 dB (mean error -0.02 dB, *n*=80) was achieved.

A subsequent independent evaluation at sites close to the road with the adaptations applied [3] suggested [4] an RMS error of 1.6 dB (mean error +0.2 dB, *n*=20).

Expanding these errors to *k*=2, it follows that ± 2 dB at the 95% confidence level underestimated the uncertainty of CRTN prediction uncertainty in NZ, especially given the adaptations were not fully adopted.

2.2.2 PRESENT IMPLEMENTATION

Road surface corrections were ultimately incorporated into NZ practice [4] [11] but eschewed sand circle texture measurements in favour of a system based only on the surface specification (which could be known in advance). The per-site correction for medium-to-heavy truck ratio was never adopted. An offset of -2 dB was applied to all predictions to minimise the mean error.

However, 30 years have passed since the NZ adaptation measurements were conducted, and further changes to the NZ vehicle fleet and road surface specifications are likely to have introduced additional systematic error to the predictions. At the time of writing, a re-calibration of CRTN for NZ is underway [12] [13], and aims to accurately characterise NZ surface types and minimise the overall mean error of prediction.

3. Components of prediction uncertainty

The main sources of error close to the road (say within 50 metres) are assumed to be:

- The absolute calibration of CRTN to NZ's surfaces and vehicle fleet (Type B [5]).
- CRTN's inherent predictive ability across a variety of sites and input parameters (Type A).
- Variation in tyre/road noise emission within a surface classification (Type B).
- The representation of terrain and structural screening effects (Type B).
- Error associated with forecasting modelling parameters (Type B).

Further from the road, propagation effects become significant, introducing additional sources of error:

- Ground absorption (Type B).
- Wind direction and speed, temperature inversions (Type B).

The following generic uncertainty analysis attempts to account for these dominant sources of error, with the assumption that more minor omitted effects would not significantly alter the uncertainty estimate. Where the error distribution was non-symmetrical, only the upper half-width was considered.

3.1 CALIBRATION OF CRTN TO NZ

The original method of calibration for NZ [2] derived a correction based on a single asphalt specification, the 'reference surface', and then specified additional 'surface corrections' for each surface relative to the reference surface [11], each step contributing some uncertainty. The new methodology [12] calibrates each surface type in absolute terms, with a single uncertainty component. In either case, the calibration attempts to correct the systematic error of applying CRTN to a country and time different to what it was developed for (different surfaces and vehicle fleet), aiming to minimise the overall mean error.

The uncertainty of the 2023 calibration was derived as 1.2 dB at the *k*=1 level [13].

3.2 RANDOM ERROR OF PREDICTION

This component represents the limit of CRTN's ability to use finite input data to predict long-term noise levels for sites close to the road. It is intended to capture the residual variation about the mean, after having accounted for the various known sources of systematic error. In that sense it is similar to the 'repeatability'

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[4] We have digitised data from the original reports and recomputed metrics to facilitate like-with-like comparisons.

[5] Type A uncertainty evaluations require repeated measurements, whereas Type B evaluations require external information.

component for random error within a measurement uncertainty budget. It is assumed to contain many contributing factors, including some that are not truly random but which cannot be isolated and corrected separately (including some known influences on noise that CRTN does not model, such as variation in ambient temperature).

The estimate of this component's magnitude has been informed by results from the 1990s surveys [2] [3]. It unavoidably also contains some contribution from measurement error. The risk of double-counting propagation, road surface variation, and forecasting errors within this uncertainty budget is minimised because those surveys were conducted close to the road, corrected for their specific surface influence, and used actual traffic counts, respectively.

The residual [4] from Barnes & Ensor's data [2] was 1.2 dB, and this value has been adopted as the best estimate for the random uncertainty component (*k*=1).

3.3 ROAD SURFACE VARIABILITY

Road surface corrections account for the tyre/road noise emission of different surface specifications. Individual surface specifications are well-defined but still result in a broad range of acoustic performance in practice. Recent analysis of 1000 km of close-proximity (CPX) noise measurements has provided noise level probability distributions for each of the most common state highway surface specifications [8] (Figure 1). Porous asphalt was found to be particularly variable.

CPX measures tyre/road noise emission, but an indicative variance has been derived for the corresponding wayside traffic noise level [14], representing the variation between surfaces built to the same surface specification. The standard deviations were found to be common within their three broad surface classifications:

Chipseal sd = 1.0 dB

Non-porous Asphalts sd = 1.0 dB

Porous Asphalts[6] sd = 2.0 dB

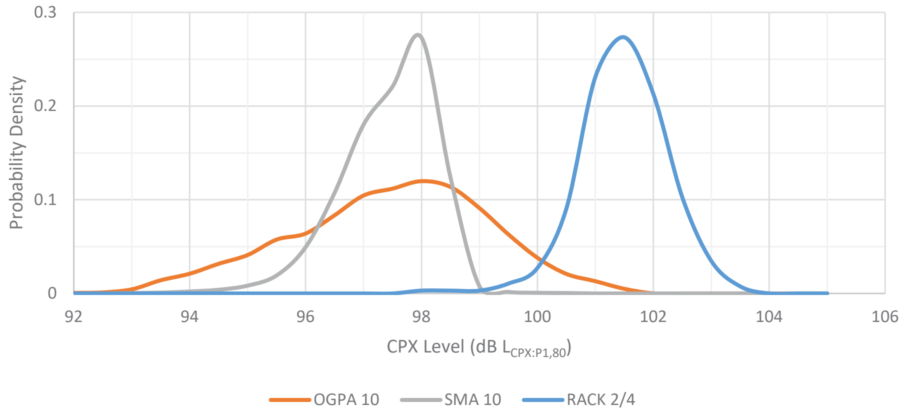

Figure 1: CPPX level probability distribution for three arbitrarily-chosen surface specifications: porous asphalt (OGPA), non-porous asphalt (SMA), and chipseal (RACK).

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[6] Current (unpublished) research suggests that the variability of some porous asphalts could be reduced in future.

3.4 PROPAGATION EFFECTS

Much of the propagation uncertainty close to the road has already been captured implicitly by the random error component (section 3.2). Further from the road the influence of propagation effects increases, along with error in correcting for them. In Table 1 indicative uncertainty estimates have been described over discrete distance ranges, with those for the first 50 metres from the road reduced in influence by 50% to mitigate potential double-counting.

The standard error of the mean due to variation in propagation has been informed by the day-to-day variability [15], but adjusted for its potential for long-term influence (climate rather than weather). Only the upper half-width has been considered, corresponding to levels higher than predicted, because the probability distribution for wind influence is bimodal and asymmetrical [15]. The estimates in Table 1 are intended to capture (i) prevailing conditions that exceed the "light downwind" default [7], and (ii) an allowance for systematic error in CRTN's propagation corrections. Prediction beyond 300 m has not been evaluated but would have larger uncertainty.

Table 1: Indicative uncertainty estimates for factors affecting propagation, with distance from the road edgeline

Component	**Uncertainty upper half-width in dB** (assuming uniform distribution)			**Notes**
	Distance from edgeline to receiver			
	Less than 50 metres	50 to 150 metres	150 to 300 metres	
Atmospheric absorption	--	0.1	0.2	Over the typical range of NZ weather conditions [15]
Ground absorption correction	0.36 *	1.6	2.0	Estimated based on comments from Delany and Hood, evaluated at I = 1
Ground absorption estimation of I	0.57 *	1.8	2.2	From CRTN's chart 8 and table 20.4, the variation within an I classification: ± 0.25
Wind velocity, turbulence, and atmospheric stability.	0.50 *	1.2	3.0	The realised quantity already assumes downwind propagation, but this considers stronger downwind propagation.
Combined Standard Uncertainty (k=1)	0.48 *	1.6	2.4	

* assumed to be partially accounted for within the random error component, these components are shown at half their derived value.

3.4.1 ATMOSPHERIC ABSORPTION

Error due to differences in atmospheric absorption within 300 metres of the road over the range of climatic conditions in NZ is negligible [15].

3.4.2 GROUND ABSORPTION

Two uncertainty components for ground absorption have been considered: the systematic error associated with the correction itself, and error associated with selection of parameters for a given scenario.

The CRTN chart 8 correction is subtractive only, with an unknown systematic error associated with its ability to correct for ground absorption across the variety of terrain forms and ground cover encountered. Within acoustically soft surfaces (I=1) Hood [10] reported that measured 'fully soft ground' coefficients could range from -5 for mown grass to -12 for corn. CRTN's soft ground correction is equivalent to a coefficient of about -6.5. The under-prediction error of CRTN's ground absorption has been estimated as the difference between the chart 8 correction and the mown grass estimate, $\varepsilon+ = 1.5 \log_{10}(d/10)$, where d is the separation distance in metres.

For any given modelling scenario, the practitioner must select the appropriate proportion of ground absorption (either following CRTN's table 20.4 or by assigning ground cover within a GIS interface). There is unavoidable subjectivity in this process, which combined with the breadth of the five discrete absorption classifications, gives rise to significant uncertainty in the application of the ground absorption correction. An indicative half-width has been derived from chart 8 based on the classification width, $\Delta I = 0.25$.

3.4.3 WIND AND TEMPERATURE INVERSION EFFECTS

CRTN predicts for permanently "moderate adverse" wind conditions, which in the parlance of NZS 6801 [16] is slightly enhanced propagation conditions. Wind and temperature inversion characteristics are highly location dependent, but generic uncertainty bounds have been estimated for broadly "NZ conditions".

Temperature inversions are typically a night-time phenomenon, when human sensitivity to noise may be quite high, but when the $L_{Aeq(24h)}$ metric is least sensitive due to the low source level. Enhanced propagation from temperature inversions has been captured by the "downwind" calculation below.

Delany et al [9] put the coefficient for downwind propagation over hard ground within the interval (10, 12) based on measurement and simulation, and settled on the most conservative and convenient 10. This is the theoretical value for cylindrical propagation of sound over a fully-reflective surface.

The CONCAWE report [17] provides corrections for the effects of wind and atmospheric stability in octave bands from an industrial (point) source, under six different meteorological categories and at various distances. Category 4 represents spherical sound propagation with zero meteorological influence (equivalent to CRTN's chart 7 equation) while category 5 represents enhanced propagation (equivalent to CRTN's description of "moderate adverse"). Category 6 represents strongly enhanced propagation. Dravitzki et al [15] calculated the equivalent CONCAWE corrections using a typical road traffic noise spectrum. We have estimated the magnitude of the effect as the category 6 correction minus

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[7] CRTN's section 4 actually states "moderately adverse wind velocities" but its definition in 39.2(ii) of downwind at "not more than 2 m/s" aligns with the lower end of the NZS 6801:2008 meteorological window.

the category 4 correction, as a function of distance (1.6 dB @ 100 m, 4.7 dB @ 200 m, 6.2 dB @ 300 m).

This magnitude of enhancement could occur for some subset of days within a year for any given receiver, defined by relative positions of road and receiver and the local climate. From regional climate data [18] it has been inferred that few locations in NZ have a prevailing wind direction that occurs for more than 75% of the year. The frequency of occurrence of wind speeds exceeding "slightly enhanced" cannot be quantified from the available climate record (in large part because those speeds are measured at 10 m high in exposed locations) but was assumed to generally be lower than 50% of the year. Consequently, strongly enhanced propagation conditions will typically exist for less than 37.5% of the year at most receivers.

This upper bound on likelihood was combined with the magnitude of the error to estimate uncertainty half-widths, as shown in Table 1.

3.5 SCREENING

The influence of screening is substantial and highly site-specific, and therefore this generic accounting of its uncertainty is only indicative. However, most receiver locations experience some degree of screening from at least some segments of the road, due to terrain, buildings, noise barriers, fences, and so on, so a fixed general uncertainty component applying to all predictions is appropriate [8].

The general component should capture the accuracy of CRTN's screening equation and procedures, including how the 2-dimensional procedures have been adapted for 3-dimensional computer modelling by software vendors. It was assumed to be dominated by the accuracy of CRTN's screening equation, which has been compared to measurement [19], finding agreement within ± 1 dB for walls, and in general an underestimation of the screening effect for buildings [19] [20].

An additional optional component has been introduced to account for deviations between the modelled geometry (including topography) and the final real-world geometry. This component applies only where screening error could be significant for a given receiver, particularly where there is an increased level of geometrical sensitivity with respect to the effect of screening, either vertical or horizontal. For instance, it would apply where the line of sight between a receiver location and acoustically significant segments of road is only just broken, or nearly broken, after taking into account uncertainty in the modelled location of the receiver, roads, terrain, and any screening structures. It may also be appropriate to apply in situations where the transmission loss of screening is uncertain (e.g. behind boundary fences).

To estimate the optional component, an indicative geometric error of ± 1 metre has been assumed, cumulative over receiver, screen, and source locations. From a set of near-road CRTN predictions (via SoundPLAN) involving various noise wall configurations (located adjacent either the road or the receiver, heights 0 m to 5 m, *n*=558) the largest marginal change in noise level at each receiver for a 1-metre change in screening was 2.1 dB on average. The 95th percentile change of ± 3.4 dB has been taken as an indicative uncertainty limit for a 1-metre geometry error.

As both the effectiveness and geometrical sensitivity of screening decreases with increased distance from the road [1] [21], so do the magnitudes of the uncertainty components in Table 3.

3.6 FORECASTING ERROR

Noise level predictions for roading projects are typically evaluated for a date at least 10 years into the future, and there is error in the projections of input parameters (Table 2).

It is good practice to conservatively model input parameters and road alignments. Nonetheless, actual traffic volume and mix can exceed 'worst case' projections. The mean traffic speed is unlikely to exceed the planned posted speed limit. Lane positions should be accurate to within 1 metre. Wholesale changes made to the road design, including the posted speed limit, are not noise modelling errors, and are excluded.

3.7 OTHER COMPONENTS

The components identified above are assumed to capture the majority of the dominant effects across most modelled scenarios and contribute indicative values to form a 95% confidence interval. However, some scenarios may have additional characteristics

Table 2: Forecasting error in road input parameters

Component	Value (dB)	Divisor	Description
Traffic volume	1.14	1.73	Exceedance of highest AADT projection by up to 30%
Mix	0.61	1.73	Exceedance of highest %HCV projection by up to 30%
Speed	0.45	1.73	Unlikely to exceed the planned posted speed limit (5%)
Road surface	--	--	Included elsewhere (section 3.3)
Lane position	0.31	1.73	Function of distance. Value assumes 10 m ± 1 m.
Combined Standard Uncertainty (k=1)	0.81		

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[8] The presence of screening removes CRTN's ground absorption correction for that road segment, but any given prediction may incorporate several segments, so both components have been retained in the uncertainty budget.

that could increase error beyond the generic estimates given in this paper, for example:

- Complex terrain, including high elevation differences/angles between road and receiver.
- Accelerating/decelerating vehicles and intersections (though current practice to model intersection approaches using the speed limit reduces the likelihood of underprediction [22]).
- Areas of high road gradient.
- Site-specific traffic characteristics (e.g. a high prevalence of logging trucks).
- Local climate (prevailing strongly enhanced conditions).
- Geometry or other factors leading to high sensitivity in screening or ground absorption effect.

3.8 EXCLUDED

Noise sources not considered by CRTN were excluded from this uncertainty analysis: audio-tactile pavement markings, noisy engine brakes, excessively loud exhausts, significantly degraded or damaged road surfaces, bridge joints & railway crossings (and other very localised noise sources), horns & sirens, vehicle sound systems, and others.

4 Evaluation of overall uncertainty

4.1 COMBINED UNCERTAINTY

The CRTN prediction uncertainty of the long-term $L_{Aeq(24h)}$ noise level at an arbitrary receiver has been estimated by combining the components in quadrature (Table 3).

4.1.1 VALIDATION

Independent from this uncertainty analysis, 111 days of noise monitoring was conducted across 18 unscreened sites within 30 metres of the road (11 non-porous and 7 porous surface types) [23]. The measured 'good weather' LAeq(24h) were paired with CRTN-predictions based on nominal surface type (2023 surface corrections) and measured traffic volume and traffic mix for each site during the survey [13].

Table 3: Indicative uncertainty budget for CRTN prediction in NZ

Component	**Uncertainty upper half-width in dB**						**Div.**	**Ref.**
	Receiver distance from edgeline in metres							
	< 50		50 - 150		150 - 300			
	General	Porous	General	Porous	General	Porous		
NZ calibration 2023	1.2	1.2	1.2	1.2	1.2	1.2	1	§3.1
Random error	1.2	1.2	1.2	1.2	1.2	1.2	1	§3.2
Road surface var.	1.0	2.0	1.0	2.0	1.0	2.0	1	§3.3
Propagation	0.5	0.5	1.6	1.6	2.4	2.4	1	§3.4
Screening (general)	1.0	1.0	0.5	0.5	0.5	0.5	√3	§3.5
Screening (optional)*	3.4*	3.4*	2.0*	2.0*	1.0*	1.0*	√3	§3.5
Forecasting inputs	0.8	0.8	0.8	0.8	0.8	0.8	1	§3.6
Rounding to 1 dB	0.5	0.5	0.5	0.5	0.5	0.5	√3	
Combined standard uncertainty	2.3	2.9	2.7	3.2	3.2	3.7	k = 1	
Expanded uncertainty	4.6	5.7	5.4	6.4	6.5	7.3	k = 2	

* The optional screening component is included when prediction error for the screening effect could be significant, following the description in section 3.5. This component was not included in the combined or expanded uncertainty calculation shown in the table.

The mean error for the 18 predictions had a 95% confidence interval of [-0.8, +1.8] dB, which is within the uncertainty interval previously derived for calibration, [-2.4, +2.4] dB.

The RMS residual across the 18 predictions was 2.2 dB. By comparison, Table 3, after excluding the calibration, forecasting, rounding and optional screening components, suggests indicative combined standard uncertainties of 1.7 dB for non-porous surfaces and 2.5 dB for porous surfaces, within 50 metres of the road.

Overall, the RMS error of the validation predictions was 2.4 dB. This compares well with the indicative standard uncertainties of 2.3 dB for non-porous surfaces and 2.9 dB for porous surfaces from Table 3.

4.2 UNCERTAINTY MATRIX

The matrix in Table 4 suggests indicative CRTN road-traffic noise prediction uncertainties in decibels at the 95% level of confidence for combinations of distance, surface type, and sensitivity to screening.

Depending on additional receiver- or project-specific factors, the actual error could exceed than indicated (see section 3.7).

The uncertainty estimates were evaluated based on the risk of underprediction, and while the overprediction uncertainty is also implied by the presentation in Table 4, it may not be reliable under some circumstances.

Table 4: Indicative 95% uncertainty limits in dB CRTN prediction of long-term road-traffic noise level $L_{Aeq(24h)}$

Scenario	**Indicative 95% uncertainty limits (dB)**		
	Receiver distance from road edgeline in metres		
	< 50	50 - 150	150 - 300
General	± 5	± 6	± 7
Sensitive to Screening	± 6	± 6	± 7
Porous Asphalt	± 6	± 7	± 7
Porous Asphalt and Sensitive to Screening	± 7	± 7	± 8

It is noted that conservative modelling practices can reduce the likelihood of underprediction. Typical modelling conventions in NZ are to populate CRTN's 18-hour traffic flow with the AADT, and to treat the posted speed limit as the mean traffic speed, which collectively increase predictions by about +1 dB on average. New surface corrections will represent the 75th percentile noise emission of each surface type, which on average is +1 dB higher than the mean [13].

4.3 RELATIVE ERROR BETWEEN SCENARIOS

Noise modelling is frequently used to compare between different scenarios or options, where the primary goal is to understand the effect of one road project design over another [7]. The uncertainty of the difference between two predicted levels can be lower or higher than the absolute uncertainty of either prediction, depending on whether there are systematic components that cancel out. Table 3 could be used to estimate the uncertainty of the difference.

5. Conclusions

The long-held assumption of ± 2 dB uncertainty at the 95% level for road-traffic noise prediction in NZ is incorrect. Analysis of available NZ measurement data suggests indicative uncertainties between ± 5 dB and ± 8 dB for the range of conditions typically described by NZ road-traffic noise assessments (Table 4). This finding does not suggest that the quality of road-traffic noise prediction in NZ has degraded over time, or that CRTN performs worse than alternative prediction methods.

NZS 6806:2010 requires that prediction not differ from the measured level by more than ± 2 dB [7], which is unrealistic for any prediction method given the magnitude of uncertainty demonstrated here for CRTN prediction. The additional uncertainty of measurement can be of a similar or greater magnitude [15]. The next revision of the standard should replace this requirement with achievable noise model validation criteria.

Propagation effects dominate the uncertainty far from the road (150 m to 300 m). The likelihood of underprediction is most significant when strongly enhanced propagation corresponds to the prevailing climate at a receiver. Analysis of climate data could identify locations within a project area where the CRTN assumption of slightly enhanced propagation may understate the long-term road-traffic noise level.

The contribution of porous asphalt variability to overall uncertainty is significant. If better consistency in porous asphalt's acoustic performance could be achieved, it may lower the overall prediction uncertainty.

The evaluation of the screening uncertainty component was only indicative, and in practice the prediction error of the screening effect is highly situation dependent. In some scenarios the screening effect can be sensitive to fairly small changes in relative geometry, which suggests that conservative placement of receiver locations (e.g. high, multiple) would reduce the risk of underprediction due to geometry errors.

Each prediction of road-traffic noise has its own associated uncertainty that depends on local factors and is therefore best determined by the practitioner. The generic uncertainty estimates in this paper should aid in that process, and for many scenarios and applications the indicative uncertainty matrix in Table 4 will provide sufficient indication of prediction error.

6 Acknowledgements

The author acknowledges the support and advice of the Waka Kotahi road surface research group.

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