

Institution: University of Derby		
Unit of Assessment: 12		
Title of case study: Democracy of Sound – Impact in immersive and live audio applications		
Period when the underpinning research was undertaken: 2001-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Dr Bruce Wiggins Dr Adam Hill	Senior Lecturer Associate Professor	1999–present 2012–present
Period when the claimed impact occurred: 1 August 2013–31 July 2020		
Is this case study continued from a case study submitted in 2014? No		
1. Summary of the impact (indicative maximum 100 words)		
<p>This impact case study focuses on the “democracy of sound” – delivering a consistently high-quality and safe listening experience to all. The underpinning research centres on analysis and optimisation of sound reproduction and reinforcement, where the resulting impact is international in reach. Three impact themes have emerged from this research: (1) expanded and enhanced creative immersive audio technology (VLC Media Player, YouTube, Reaper); (2) enhanced live event listening experiences (Glastonbury Festival, The Prodigy, Alto Aviation, Gand Concert Sound, National Library of New Zealand); and (3) improved understanding of health-related aspects of sound (World Health Organization, BBC <i>Blue Planet II</i>, British Standards Institute, International Electrotechnical Commission).</p>		
2. Underpinning research		
<p>The impact detailed in this case study enabled improvements in the “democracy of sound.” Each of the three impact themes was a result of underpinning research as follows:</p>		
(1) Expanded and enhanced creative immersive audio technology		
<p>Ambisonics has become the standard surround sound approach for use within augmented/virtual reality systems as well as for immersive headphone and loudspeaker playback. The advantage of Ambisonics is that it separates encoding (recording) from decoding (playback), permitting immersive audio over any suitable system. Research by Wiggins since the early 2000s has resulted in a suite of software tools called WigWare, allowing users to implement Ambisonics within their audio workflows [3.1]. The software was augmented in 2008 with a ‘true’ 3D reverb effect (the first of its kind), with an enhanced version released in 2015, allowing for realistic reverberation to be applied to 3D audio.</p> <p>The research improved decoding algorithms (particularly over ‘irregular’ loudspeaker arrays) using head-related transfer functions as well as more traditional energy and velocity vector models, optimised using a modified heuristic Tabu search algorithm with multiple defined fitness functions [3.1]. This was necessary as there was no published method of generating Ambisonic decoder coefficients for irregular speaker layouts, where prior work carried out by other researchers had led to sub-optimal results. Later work concentrated on optimising headphone-based reproduction [3.2]. This research has advanced the understanding of Ambisonics in terms of practical implementation and optimisation.</p>		
(2) Enhanced live event listening experiences		
<p>Research by Hill focuses on delivering the same high-quality listening experience to all audience members. The primary challenge is coherent acoustic interference due to time difference of arrival from multiple sound sources, resulting in position-dependent listening experiences. To overcome coherent interference, electroacoustic decorrelation is required. A novel algorithm, dynamic diffuse signal processing (DiSP), was developed between 2015 and 2019 [3.3]. This provided decorrelation between discrete loudspeakers, as well as between each individual loudspeaker’s direct and reflected sounds, through a time-varying decorrelation process (the first of its kind). Sharp transient content (necessary for high-quality sound) is preserved by bypassing DiSP when</p>		

necessary using a transient detection algorithm, originally developed by Hill in 2010 [3.4]. Experimentation demonstrated up to 50% reduction in seat-to-seat magnitude response variance, with no perceptible audio quality degradation [3.3]. DiSP can be applied to any system, without calibration, making the solution universal.

In parallel with this research, it was necessary to develop a method to quantify sound system performance in terms of spatial consistency (no such method existed for live sound). Array Performance Rating (APR) was created and led to the development of an optimization routine specifically for subwoofer systems (the first of its kind) in 2018 for use within sound system design software [3.5]. This permitted automatic calibration and optimization (with or without DiSP) from small home-theatre systems to large arena systems.

(3) Improved understanding of health-related aspects of sound

In addition to *high-quality sound*, a “democracy of sound” should provide *equal rights* to all listeners, including the right to a safe listening experience. Research into the standard method for quantifying speech intelligibility (STI) was carried out between 2015 and 2018, where it was found that in certain scenarios STI doesn’t reflect true speech intelligibility [3.6]. The problem is rooted in high-level late-arriving reflections, which cause STI to significantly underestimate intelligibility. This could prevent a sound system in a public place from being signed off, even when the system delivers perfectly acceptable speech intelligibility.

Additionally, important work in audience safety and community wellbeing at live events was investigated as part of a research project within the Audio Engineering Society (led by Hill) between 2017 and 2020. A comprehensive critical review of published research was carried out, where significant knowledge gaps were identified and good/bad practice was highlighted. It was found that audience members closest to a performance stage are regularly exposed to unsafe sound pressure levels (often exceeding 140 dBC). In such cases, foam earplugs are ineffective due to excessive low-frequency content travelling to the inner ear through bone and tissue conduction (a little-known fact, outside of NASA and the military). Good practice was also highlighted for music-based annoyance minimization within local communities, including a critical analysis of relevant noise pollution regulations across the globe. The work identified 25 shortcomings in the present knowledge base, which must be addressed to ensure maximisation of audience safety and minimisation of community annoyance in relation to outdoor live events.

3. References to the research (indicative maximum of six references)

University of Derby researchers are indicated by black, underlined text:

[3.1] Wiggins, B. (2007). The generation of panning laws for irregular speaker arrays using heuristic methods. Proceedings of the Audio Engineering Society (AES) 31st International Conference: New Directions in High Resolution Audio, London, 25-27 June

Access: <https://www.aes.org/e-lib/browse.cfm?elib=13946>

Evidence of quality: Final paper from the project detailing the deriving of Ambisonic decoders for irregular loudspeaker arrays pioneered by Wiggins. This project’s work has been cited internationally over 100 times including by the BBC, in IEEE and in 5 patents.

[3.2] Wiggins, B. (2017) “Analysis of Binaural Cue Matching using Ambisonics to Binaural Decoding Techniques.” 4th Intl. Conf. on Spatial Audio, 7-10 September, Graz, Austria.

Access: <https://derby.openrepository.com/handle/10545/621858>

Evidence of quality: Research on correcting the diffuse field response of the newly released YouTube spatial audio algorithm which was utilised internationally by practitioners to improve the quality of 360/VR videos on the platform.

[3.3] J. B. Moore and A. J. Hill (2018) “Dynamic Diffuse Signal Processing for Sound Reinforcement and Reproduction,” *JAES*, Vol. 66, No. 11, pp. 953–965.

Access: <http://www.aes.org/e-lib/browse.cfm?elib=19871>

Evidence of quality: Accepted after peer review. The research details the development of this novel audio decorrelation algorithm including a rigorous objective and subjective evaluation, proving the algorithm’s effectiveness in homogenizing live event and at home listening experiences with no perceptual degradation to the audio signal.

[3.4] Hill, A.J.; M.O.J. Hawksford (2011) "Wide-area psychoacoustic correction for problematic room modes using non-linear bass synthesis." *JAES*, Vol. 59, No. 11, pp. 825-834.

Access: <http://www.aes.org/e-lib/browse.cfm?elib=16150>

Evidence of quality: Accepted for publication after peer review. The research covers a novel approach to room acoustic correction using virtual bass, where subjective testing is carried out to demonstrate the approach's effectiveness (differences in listening experiences between seats originally judged to be significant were reduced to being imperceptible, all while maintaining good sound quality across the listening area).

[3.5] Hill, A.J. (2018) "Live sound subwoofer system performance quantification." 144th Convention of the AES, Milan, Italy.

Access: <http://www.aes.org/e-lib/browse.cfm?elib=19442>

Evidence of quality: Accepted for presentation and publication after peer review. This was the first comprehensive live sound subwoofer system performance metric ever developed and demonstrated how system efficiency can be improved using such an analysis technique. The metric was verified and expanded upon by researchers at L-Acoustics (France) in <http://www.aes.org/e-lib/browse.cfm?elib=19777>.

[3.6] Hammond, R.; P. Mapp; A.J. Hill (2016) "The Influence of Discrete Arriving Reflections on Perceived Intelligibility and Speech Transmission Index Measurements." 141st Convention of the AES, Los Angeles, USA.

Access: <http://www.aes.org/e-lib/browse.cfm?elib=18433>

Evidence of quality: Accepted for presentation and publication after peer review. First published findings proving the flaw in quantifying speech intelligibility using STI in the presence of strong late-arriving reflections. This paper is referenced in BS 7827:2019.

4. Details of the impact

(1) Expanded and enhanced creative immersive audio technology

In the early 2000s, it was difficult to utilise published work on Ambisonics for audio production due to a lack of available tools. To this end, 1st and Higher Order Ambisonic software developed by Wiggins [3.1] could be loaded into Digital Audio Workstations, allowing existing workflows to be leveraged with minimal changes. Both the software and a set of instructional videos were made available online to facilitate uptake [5.1]. The impact was in niche areas until May 2016, when YouTube released a spatial audio implementation which permitted head-tracked audio within 360° videos. Ambisonics was used here, and the format is now mainstream. Early adopters required tools and learning materials, which were provided by Wiggins [5.1]. For example, what's thought to be the world's 1st 360° YouTube music video with spatial audio used AmbiFreeverb2 as the 3D reverb effect (109k+ views) and was featured on YouTube's playlist showcasing immersive audio (>3 million subscribers before it was unlisted) [5.1]. The creator of these early videos stated: "*Bruce Wiggins' website was essential in obtaining tools and knowledge that were not available anywhere else to me at that point in time. He provided AmbiFreeVerb2, which became essential in my early endeavours to produce a professional sounding 3D music mix.*" An early criticism of YouTube's implementation was that it had an unnatural frequency response. Wiggins' research provided publicly available correction filters [3.2] – the owner of Tumble and Yaw continues: "*...it became clear that YouTube's binaural rendering filter applied some severe equalization curves, which especially in music mixes made for a very unnatural thin sound. Again, Bruce came to the rescue, providing the community with an inverse filter curve, which could be applied to the mix, before uploading it to YouTube, thereby ensuring that the mix sounded exactly again as intended.*"

One of the world's most popular cross-platform media players, VLC v3.0, added Ambisonics support in 2018 [5.2]. VLC allows audio to be rendered over standard irregular speaker arrangements such as 5.1 and 7.1. A VLC developer contacted Wiggins in 2017 as an expert in irregular decoder design [3.1]. This resulted in the decoding coefficients used to reproduce audio from 360 videos being provided by Wiggins for 1st to 3rd order Ambisonics for 5.1 loudspeaker arrays, and the software library author using a derivation method based on Wiggins' work to generate decoders for 7.1 [5.2]. VLC is the only media player available that can render 360/VR videos over surround loudspeaker arrays, which has been made possible using Wiggins' research. VLC has been downloaded over 672 million times since v3.0 [5.2].

(2) Enhanced live event listening experiences

On a larger scale, Wiggins' reputation in spatial audio led Funktion One to approach the University in 2006. WigWare was augmented with bespoke tools for use at large-scale outdoor events. Initial outdoor tests showed lower noise levels off-site and more acoustic envelopment on-site compared to other stages controlled in a standard stereo-based manner. Since August 2013, WigWare has continued to be used annually by Funktion One on the Glade Stage at Glastonbury Festival (~200,000 attendees per year), and at other events, internationally. The founder of Funktion One, while receiving a lifetime achievement award in 2017, stated: *"The Ambisonics [at Glastonbury in 2017] was working the best I've ever heard it, the bass was incredible and Goldie's set has to be in my top five audio experiences of a lifetime."* [5.3]

Hill's ongoing research on live sound subwoofer system optimization [3.5] was adopted by Gand Concert Sound (USA) at Pitchfork Music Festival (from 2012 to 2019, with ~60,000 attendees, held over three days each year) and more recently at Ashley Arts Festival in July 2019 (50,000 attendees). This stemmed from collaborative research between Hill and Gand Concert Sound engineers since 2009 [5.4]. Gand Concert Sound's Chief Engineer commented that originally the sound system design gave a, *"...disproportionate build-up of [subwoofer] content right down the middle – usually referred to as "power alley". When Dr. Hill told us that he had developed a method to counteract this, we were all intrigued and eager to try. The client [from Ashley Arts Festival] was extremely happy and impressed. I am looking forward to implementing this method more this coming summer."* [5.4]

Also in 2019, Hill's subwoofer system optimization [3.5] was implemented on The Prodigy's "No Tourists" tour, spanning 26 sports arenas around the world. The Prodigy's sound engineer (who came across the optimization approach through word of mouth) said the subwoofer system design, *"based on [Hill's] research, and produced using data from [Hill's] proprietary software, gave us a new and more detailed insight into the system we were intending to utilise for this tour. We had previously used the manufacturers' predictive software which had proved, at times, unsatisfactory for the purpose. [Hill's] software, and the results obtained from it, produced a very robust solution for our problem."* [5.5]

This optimization was applied to corporate aircraft through a consultancy with Alto Aviation (USA) in 2018, which came about from an Alto engineer discovering and using Hill's acoustic modelling software [5.6]. Hill's optimization routine was built into Alto's existing software, saving time required for system tuning. Alto Aviation's VP of Engineering commented that: *"[we] now regularly use the bass optimization algorithms as part of our product installation. This is typically over 100 installation per year. The tool saves us up to one hour on each installation and the resulting sound quality and bass balance is noticeably improved."* [5.6]

The impact from Hill's diffuse signal processing (DiSP) research [3.3] occurred in 2018. Acoustic Directions' (Australia) Principal Acoustician said: *"the decorrelation algorithm was able to substantially improve the amplified sound in the new auditorium at the National Library of New Zealand in Wellington. We were the acoustic engineers for that project, which recently won one an architectural award and is now being praised for its acoustic qualities. That outcome is due in part to Adam's work for which we are grateful. We have also used that algorithm in sound systems in courts in South Australia and found it to be very helpful in creating highly natural amplified speech."* [5.7]

The transient content detector used within DiSP came from Hill's research on virtual bass synthesis [3.4]. This algorithm was adapted for use within an underwater acoustics project (Hill was invited to contribute to the project upon recommendation from a mutual acquaintance of the lead researcher, who was aware of Hill's work in audio and acoustics), focusing on coral reefs with the aim of estimating reef health at any measurement distance underwater. The research was featured on BBC *Blue Planet II* (the most-watched show in the UK in 2017, so popular in China that it caused the entire internet to slow down, and awarded the 'impact award' from the National Television Awards 2018) [5.8], where Hill's co-author spoke about the importance of improving and maintaining the health of coral reefs.

(3) Improved understanding of health-related aspects of sound

Hill's research highlighted flaws in the standard measurement procedure for speech intelligibility [3.6]. These findings are referenced in the latest version of BS 7827:2019 *Designing, specifying,*

maintaining and operating emergency sound systems for sports grounds, large public buildings, and venues - Code of Practice as well as IEC 60268-16:2020 Objective rating of speech intelligibility by speech transmission index. A BSI and IEC Standards Committee Member (who chaired the latest revisions on both standards and prompted/supported Hill's research into this area) stated that: "[t]he work has already had an impact on the PA and emergency sound system industry in that it has been cited in and influenced associated International and British standards that are regularly specified and mandated. It is also likely to further influence industry guidance and practice as the findings become more widely known and as other related standards become due for revision." [5.9]

Hill's comprehensive work on sound exposure and noise pollution highlighting significant knowledge gaps and variable international practice [5.10] has impacted work towards an international regulatory framework for audience safety, the World Health Organization's (WHO) Make Listening Safe initiative, which Hill was invited to contribute to through recommendations from two independent researchers. One of the WHO researchers leading this initiative stated: *"The research of Dr Hill has so far had substantial impact on the WHO regulatory framework for loud sounds that is expected to be published in 2021. During the next year WHO is planning to develop a draft of the regulatory framework, parts of which will be based on the research undertaken by Dr Hill. In addition, the draft will be sent to Dr Hill to provide comments and suggestions in his expert role."* This regulatory framework will lead to worldwide changes in practice at live events to ensure the safety of all audience members [5.10].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[5.1] Evidence group of software, instructional content and use with YouTube 360 Videos:

- a. www.BruceWiggins.co.uk - The Blog of Bruce Software and Blog Posts.
- b. Immersive Videos With Spatial Audio YouTube Playlist <https://tinyurl.com/vdf3shj>
- c. 360 videos w/spatial audio <https://tinyurl.com/tj7ouls>
- d. Statement from Recording and Mixing Engineer, Tumble and Yaw (March 2020).

[5.2] Group of VLC Media Player impact evidence:

- a. VLC Media Player <https://www.videolan.org/vlc/index.en-GB.html>
- b. VLC Code listing using coefficients from Wiggins <https://tinyurl.com/y5guqty5>
- c. VLC Download Stats <https://www.videolan.org/vlc/stats/downloads.html>

[5.3] Group of Funktion One impact evidence:

- a. Pro Sound Awards: Funktion-One's Tony Andrews to receive Lifetime Achievement award <https://tinyurl.com/umm5v2e>
- b. Statement from founder/designer at Funktion One (April 2020).

[5.4] Group of Gand Concert Sound impact evidence:

- a. Pitchfork Music Festival statistics: <https://tinyurl.com/y3j68ttq>
- b. Ashley for the Arts Festival statistics: <https://tinyurl.com/w8sjxof>
- c. Collaborative research: <https://tinyurl.com/tzbuww6>, <https://tinyurl.com/r5t54ae>
- d. Statement from Chief Engineer, Gand Concert Sound (March 2020).

[5.5] Statement from The Prodigy's sound engineer (March, 2020).

[5.6] Statement from Alto Aviation's Vice President of Engineering (March 2020).

[5.7] Statement from Principle at Acoustic Directions (March 2020).

[5.8] *Blue Planet II* impact articles: <https://tinyurl.com/u9hqyj2>, <https://tinyurl.com/sebx3as>

[5.9] Group of speech intelligibility impact evidence:

- a. BS 7827 <https://tinyurl.com/smhzhk4>, IEC 60268-16 <https://tinyurl.com/yy3rwgho>
- b. Statement from BSI & IEC Standards Committee member (March 2020).

[5.10] Group of World Health Organization impact evidence:

- a. Understanding and managing sound exposure and noise pollution at outdoor events. AES Technical Document AESTD1007.1.20-05. Hill, A.J. (chairman and editor) (2020) https://www.aes.org/technical/documents/AESTD1007_1_20_05.pdf
- b. Make Listening Safe <https://www.who.int/pbd/deafness/activities/MLS/en/>
- c. Statement from WHO Listening Safe Initiative leader (March 2020).

Note: all URLs accessed and correct as of 20 November 2020.