Institution: University of York		
Unit of Assessment: 12 - Engineering		
Title of case study: Virtual Acoustics: Influencing Environmental Public Health Policy, Creative Practice and the Cultural Sector		
Period when the underpinning research was undertaken: 2000-2020		
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:**
Damian Murphy	Professor of Sound and Music Computing	Sep 2000 – present
Helena Daffern	Senior Lecturer	Feb 2010-present
Period when the claimed impact occurred: Aug 2013 – Dec 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Research in virtual acoustics, immersive audio, and auralisation at the University of York AudioLab is founded on the OpenAIR project, an international database of open access acoustic spatial room impulse response data. OpenAIR has delivered impact in three different sectors. Sound demonstrations that use auralisation research to present alternative noise mitigation strategies to key stakeholders for major infrastructure engineering projects, including the A303 Stonehenge Bypass, have been recommended by Public Health England as best practice in environmental public health policy. OpenAIR research has changed creative practice in music production and sound design, having been used in both leading computer games (Grid Autosport and the DiRT Rally series), and the Live, Reason and Studio One digital audio workstation music production software platforms. Virtual acoustics research is transforming how the cultural sector engages both new and existing audiences with more traditional forms of exhibition content and music performance through the use of authentic, interactive and immersive audio experiences.

2. Underpinning research (indicative maximum 500 words)

2.1 Virtual Acoustics: Virtual acoustics is the recreation, simulation – or auralisation – of the sound of a physical environment, based on a measurement or model of the underlying wave propagation behaviour through, or within, it. Auralisation is particularly important in architectural or environmental acoustic engineering design processes to audition the sound qualities of a space before its construction. Auralisation may also be extended from the physical to virtual and creative domains where the simulation of sound wave propagation can be deployed in immersive and interactive virtual reality (VR) applications, to augment music production, audio content and sound design for various media, or in the reconstruction of historic buildings that no longer exist. **Spatial Room Impulse Response (SRIR)** data, such as that hosted by the **OpenAIR Library** underpins research in virtual acoustics, sourced from physical measurements of real spaces, or from calibrated and verified simulations; research on which York has been leading since 2004.

2.2 Structure of Underpinning Research: Between 2004-2005 Murphy developed the first set of SRIRs for heritage sites of historic acoustic interest around the UK. This work was novel as: (i) it exploited a method of acoustic SRIR capture using exponential sine wave sweeps to give non-time averaged, low-noise measurements that minimise signal chain distortion, resulting in acoustic data optimised for auralisation and audio production purposes, rather than more traditional acoustic analysis; (ii) it used a flexible, loudspeaker-agnostic, multi-microphone capture method, including the then little used Soundfield Ambisonic B-format microphone; (iii) it measured and documented SRIRs for historic sites, rather than concert halls or opera houses where prior work was concentrated due to the critical requirement for optimal acoustics in such venues, opening up new areas of research in heritage acoustics (3.1). The resulting Ambisonic B-format SRIRs have been exploited widely as this audio format is now a core element of current VR/immersive audio systems.

This SRIR dataset was formalised, extended and made available online under a Creative Commons license in 2010 as the **OpenAIR Library** (Open Acoustic Impulse Response Library - https://openairlib.net/) (3.1, 3.2). The first open access resource of its kind, OpenAIR additionally allowed third-parties to add their own contributions to the repository, bringing a wider, international scope to the uploaded and archived SRIRs. OpenAIR measurement methodology was later extended to incorporate outdoor environments for sound design and environmental acoustic applications (3.3), as well as to car interiors for specific computer gaming scenarios (3.4).

OpenAIR started with SRIR measurements from four UK historic sites and now currently holds 47 datasets of multiple high quality Ambisonic B-format SRIRs from a range of locations (e.g. Newgrange Passage Tomb Ireland; St Albans Cathedral, UK), including heritage sites, performance spaces, landscapes and computer models. This live resource is subject to regular updates, most recently including research into the use of WebAudio to facilitate browser interaction with SRIR data, and has been part of a series of UKRI (AHRC, EPSRC, InnovateUK) projects over more than ten years, including the University of York's Digital Creativity Labs (on which Murphy is Co-I) and collaborations with, for example, UK games company Codemasters, engineering firm AECOM, BBC R&D, AgeUK, the National Trust and Opera North. All have of whom have directly benefitted from the impact of this research resulting in changes to their practice and an enhanced offering to their respective clients, customers or audiences.

This underpinning research in audio signal processing, acoustics and engineering has been deployed in three complementary application areas of interdisciplinary research activity:

2.3 Auralisation for Architectural and Environmental Acoustic Design: Murphy hosted a two-year Royal Society Industry Fellowship from AECOM, a world leading infrastructure consulting firm, researching immersive audio for the auralisation of urban, architectural and environmental design scenarios. This focused on using Ambisonic B-format assets, including environmental recordings, SRIRs and acoustic models, within 360-degree visual content for the emerging next generation VR head mounted displays (e.g. Oculus Rift).

2.4 VR Choir Technology: Daffern's research on singing science investigated performer-centric virtual acoustic scenarios, where, essentially, sound source and receiver/listener are co-located, as compared to the audience-centric listening experiences of OpenAIR. Utilising OpenAIR data and the VR research of (2.3) Daffern led the development of VR Choir technology that enables an individual to sing in a realistic virtual environment that is both real-time and interactive with 3-Degrees-of-Freedom movement. The results of this work have been deployed in various scenarios, with a particular focus on enabling people with social anxiety or health issues to participate remotely in community singing via VR, researching the associated health and wellbeing benefits of the participants involved (3.5).

2.5 Virtual Acoustic Modelling and Simulation: Murphy has researched how SRIRs might be obtained through simulation for sites or spaces that do not (or no longer) exist, that exist in part, or where SRIR data is incomplete or compromised in some manner (3.2, 3.6). Most recently this involved research into the architecture and acoustics of the historic (c. 1800) House of Commons chamber in the Palace of Westminster using acoustic modelling and SRIR measurements obtained from the existing Chamber. This research in particular considered the auditory experience of women actively listening to Parliamentary speeches of the time as they gathered in the roof space void above the House of Commons chamber, when they were otherwise excluded from these spaces and the formal political process.

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

3.1. **D.T. Murphy**, S. Shelley, A. Foteinou, J.S. Brereton, and **H. Daffern**, *Acoustic Heritage and Audio Creativity: the Creative Application of Sound in the Representation, Understanding and Experience of Past Environments*, Internet Archaeology, 44, 2017. DOI: 10.11141/ia.44.12 *** +**

3.2. A. Southern, **D.T. Murphy,** and L. Savioja, *Boundary absorption approximation in the spatial high-frequency extrapolation method for parametric room impulse response synthesis*, J. of the Acoustical Society of America, 145(4), pp. 2770-2782, 2019. DOI: 10.1121/1.5096162 **# * +**

3.3. S. Harriet, and D.T. **Murphy,** *Auralisation of an Urban Soundscape*, Acta Acustica United With Acustica, 101(4), pp. 798-810, 2015, DOI: 10.3813/AAA.918874 **# ***
3.4. S. Shelley, **D.T. Murphy**, and S. Goodwin, *Impulse response estimation for the auralisation of vehicle engine sounds using dual channel FFT analysis*, Proc. of the Sound and Music Computing Conf. (SMC), pp. 506-511, Stockholm, Sweden, Jul. 30 - Aug. 3, 2013, DOI: 10.5281/zenodo.850291 * +
3.5. **H. Daffern**, D. A. Camlin, H. Egermann, A. J. Gully, G. Kearney, C. Neale, and J. Rees-Jones, *Exploring the potential of virtual reality technology to investigate the health and well-being benefits of group singing,* Int. J. of Performance Arts and Digital Media, pp. 1–22, 2018, DOI: 10.1080/14794713.2018.1558807 * +
3.6. A. Southern, S. Siltanen, **D.T. Murphy,** L. Savioja, *Room Impulse Response Synthesis and Validation Using A Hybrid Acoustic Model*, IEEE Trans. Audio, Speech, and Language Processing, 21(9), pp. 1940-1952, 2013, DOI: 10.1109/TASL.2013.2263139 ^ * +

Key:
= returned to REF 2021; **^** = returned to REF 2014; ***** = peer reviewed;
+ = resulting from peer reviewed funding: *The Virtual Acoustics and Auralization Database,* AHRC, AH/H036938/1; *From OpenAIR to the Open Air*, AHRC, AH/J013838/1; *WEb Audio Virtual Environment Rendering (WEAVER)*, AHRC, AH/N00356X/1; *Digital Creativity Labs*, EPSRC, EP/M023265/1; *The Hills Are Alive*, AHRC, AH/R009139/1; *Next Generation Auralisation for Architectural and Environmental Acoustic Design*, Royal Society, IF130114.

4. Details of the impact (indicative maximum 750 words)

Impact is evidenced in three areas: in **environmental public health policy** as auralisation becomes an example of best practice in national infrastructure engineering design as part of public consultation and stakeholder engagement processes; in **creative practice** as OpenAIR data becomes embedded in music production tools and sound design methods; in the **cultural sector** as virtual acoustics research is used by organisations to engage both new and existing audiences with traditional forms of exhibition content and music performance.

Environmental Public Health Policy: Auralisation in Engineering

Following the Royal Society Industry Fellowship collaboration at the University of York (2014-2016), AECOM have used York research (e.g. 3.3) as a platform for the deployment of auralisation and VR in their acoustic consultancy work. This has resulted in **AECOM securing six new contracts internationally** [text removed for publication], with the role of York's research emphasised by Murphy's engagement as a consultant.

This role was most notable in the **Sound Demonstrations for the A303 Stonehenge Bypass (Highways England)**, one part of a much larger GBP1.7 billion multi-partner project (5.1). These were used in the public consultation phase for this major road redevelopment, enabling key stakeholders and members of the public to, *"better understand the impact of the proposed changes in terms of soundscape and environmental noise levels and make more informed decisions accordingly*", using immersive audio/VR auralisations (5.1). In 2018, **AECOM were awarded the John Connell Innovation Award by the Noise Abatement Society for this work** (5.1, 5.2), with the Honorary Secretary to the Institute of Acoustics commenting, *"The simulation allows one to instantly experience and understand not just the addition of unwanted noise, but also the reduction and removal of such unwanted sounds. This provides various stakeholders an opportunity to appreciate the value in planned investments."* (5.1)

This A303 project work was cited as an **example of best practice by Public Health England (PHE) to the Planning Inspectorate** as part of the scoping consultation phase for the M54-M6 link road planning process. Highways England again contracted AECOM with Murphy acting as consultant to prepare auralisations for this road infrastructure development (5.1). It is estimated by AECOM that the sound demonstrations prepared for these two projects have directly engaged with 500 members of the public since 2018.

Creative Practice: OpenAIR data in music and game audio development

In the fields of sound design and music production, **OpenAIR data has been incorporated into three of the leading international commercial digital audio workstation software platforms - *Presonus Studio One, Reason Studios Reason*** ([text removed for publication]), and

Ableton Live, ([text removed for publication]) (5.3). Since 2012 OpenAIR measured or modelled acoustic data has significantly contributed to a core component of this software: the ability to apply reverberation modelling to recorded or synthesized sound using audio convolution with SRIRs. This is due to the high-quality OpenAIR SRIR data capture methods, the flexible audio file format used, and their distribution via a flexible use Creative Commons License where many other libraries are proprietary or developed only for commercial applications. Examples of user feedback from published industry reviews with reference to specific measured OpenAIR data include:

"I can't speak for the authenticity of Terry's Typing Room but I did rather like the effect of Swedish Nuclear Reactor 2 … I was certainly using it in place of [Ableton] Live's standard reverb, with good - and often fascinating - results." (5.4)

"A convolution reverb is only as good as its impulse responses (captured reverb settings), and OpenAIR comes with some fantastic examples… This is a strong addition to [Studio One's] effect stable" (5.4)

Codemasters have pioneered the use of Ambisonic technology in game audio (5.5) resulting in **OpenAIR research (3.4) and data being incorporated into the *Grid AutoSport* racing video game**, originally released in 2014 for Microsoft Windows, Sony Playstation 3 and Xbox 360 platforms, and since ported to Linux, Mac OS X (2015), iOS (2017), Nintendo Switch and Android (2019). Steamspy suggests that there are 500,000-1,000,000 users across the main gaming platforms, with the iOS platform reporting more than 100,000 paid users within 12 months of release (5.6). Murphy is acknowledged in the game's credits under Sponsors and Outsource Companies for the research contribution made to this game (5.7). Ambisonic SRIR convolution for the development of immersive and interactive in-cabin environments (3.4) has become key to Codemasters' ongoing sound design practice. This has been used in *DiRT Rally* (2016), with more than 800,000 sales (5.4), *DiRT Rally* 2 (2019), with more than 1,000,000 users (5.6), and the forthcoming *Dirt 5* (5.4) in which, *"the future for interactive audio has never sounded so exciting,"* according to Codemasters' Audio Director (5.5). OpenAIR research will continue to influence creative practice in gaming through its future use on, *"directly related technology for NaturalMotion Ltd, a world-class British game maker, … OpenAIR [will benefit the] … company and industry such as this for years to come."* (5.5).

Cultural Sector: Engaging New Audiences

Authentic, interactive and immersive audio can be transformative and engaging in the design and delivery of cultural experiences. York's virtual acoustics research has been a key component in the production of exhibition/performance content for three cultural sector organisations as they seek to engage more widely with both existing and newer audiences:

The **UK Parliament Voice & Vote Exhibition** welcomed 107,328 visitors into Westminster Hall between June and October 2017 to celebrate the centenary of women's enfranchisement in the UK (5.8). Curators drew on virtual acoustics research to design and deliver an immersive auralisation experience that used architectural and documentary evidence to model an acoustic reconstruction of the ventilator space where early 19th century women gathered to listen to speeches in the House of Commons. Visitors entered the exhibition via a recreation of this ventilator space and the curators describe the change that this represented for Parliament:

"The recording, built on the project's research, was the first time that such authentic sound (rather than a studio recording) had been used by a parliamentary exhibition to create an immersive experience. It propelled the authenticity of the exhibition story by giving audiences listening at the replica ventilator an opportunity to hear a plausible reconstruction of modelled history in action. Indeed, the ventilator was the only immersive part of the exhibition with an authentic soundscape, and it succeeded in starting the exhibition with a distinct physical, visual and aural impact." (5.8)

The exhibition has had a permanent legacy, with 'Women in Parliament' specialist tours now featuring the material (5.8).

In partnership with the **National Trust**, Daffern's research underpinned **The Hills Are Alive**, a VR Choir experience that enabled remote audiences to participate in community choir performances that took place at the top of four Lake District mountains commemorating the gifting of 14 such summits to the nation at the end of the Great War. The National Trust's Visitor Experience and Engagement Manager for the North Lakes portfolio writes:

"Through Dr Daffern's research, we were able to make the immersive experience of group singing on a mountain summit accessible to people who could not be there on the mountain top with us – whether through health issues or disability. We were able to host the research at Keswick Museum, embedding the project in the heart of the local community and making it accessible to a much wider audience than would have otherwise been possible." (5.9)

The project reached an estimated audience in excess of 138,000,000 through print, TV and radio press coverage (5.9), which encouraged visitors to view the exhibit at Keswick Museum in the summer of 2018 and 140 participants to take part in the VR Choir experience at the Lakes Alive Festival, 7-9 September 2018. The project received an Outstanding Achievement award at the National Trust Curation and Experiences conference in 2019 (5.9). 100% of participants surveyed reported positive experiences - feeling happy, delighted, aroused and excited after their participation (3.5). This project has also prompted a wider discussion within the National Trust about using similar technologies to better facilitate accessibility and inclusivity; *"It has prompted us to explore the possibilities of using immersive technology to make future projects more inclusive to those who cannot visit the places in our care themselves"* (5.9).

The **Ghosts in the Machine** project with **Opera North** aimed to convey the power of opera as a storytelling artform using VR Choir auralisation and OpenAIR data to create an interactive trailer for a production of The Turn of The Screw: https://www.operanorth.co.uk/turn-of-the-screw-immersive-trailer/. The viewer can mix a personalised immersive audio experience for a new composition based on the original score, exploring different architectural soundscapes and how this interaction affects the viewer's emotional response to the music. The trailer was the most visited page on the Opera North website since January 2020 with 99,853 views and more than 2,143 tickets booked directly post-viewing through tracked visitor engagement (5.10). From a focus group of school pupils 60% agreed that the trailer made them more interested in seeing live opera, with 96% stating that the trailer had changed their view of the artform. As well as creating a "*completely new way to think about reaching new audiences*", the trailer led to a shift in Opera North's marketing to include active participatory techniques, and a doubling of their investment in digital engagement with the Covid-19 outbreak. Opera North are promoting this new approach toward digital technology across the sector and leading a session on digital innovation in the arts for the Leeds Digital Festival (5.10).

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

5.1. Testimonial: Global Auralisation Lead, AECOM, with attachment from PHE.
5.2. John Connell Award Announcement: https://www.ioa.org.uk/news/innovation-award-winners-john-connell-awards-announced
5.3. Evidence of OpenAIR User Numbers in Live and Reason.
5.4. Evidence of OpenAIR inclusion in published industry reviews of Live and Studio One: https://www.soundonsound.com/reviews/ableton-live-9-push; http://www.musicradar.com/reviews/tech/presonus-studio-one-2-professional-526907;
5.5. Testimonial: Codemasters Principal Programmer (2003-2015), Interactive Audio Tech Consultant.
5.6. Codemasters games public sales data:
a) Grid AutoSport: https://steamspy.com/app/255220; **b)** Grid AutoSport (iOS): https://toucharcade.com/2018/07/26/grid-autosport-100k-sales/; **c)** DiRT Rally 2: https://steamspy.com/app/690790
5.7. Grid AutoSport Credits: https://www.mobygames.com/game/windows/grid-autosport/credits
5.8. Testimonial: Deputy Curator and Head of Interpretation, Parliamentary Heritage Collections Team, and Senior Archivist, Parliamentary Archives
5.9. Testimonial: Visitor Experience and Engagement Manager for the National Trust North Lakes Portfolio
5.10. Testimonial: Opera North Projects Director