Institution: University of York		
Unit of Assessment: 12 - Engineering		
Title of case study: Binaural Surround Sound for Virtual Reality Systems		
Period when the underpinning research was undertaken: Nov 2014 to Dec 2019		
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. Gavin Kearney	Associate Professor in Audio and Music Technology	Jan 2011 - present
Period when the claimed impact occurred: Nov 2017 to Dec 2020		
Is this case study continued from a case study submitted in 2014? N		

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

Google have adopted York research on binaural surround sound for Virtual and Augmented Reality (VR/AR) stemming from the EPSRC funded Spatial Audio for Domestic Interactive Entertainment (SADIE) project (EP/M001210/1). The work developed spatial audio filters and decoders that have been integrated into Google's *Resonance* VR pipeline. This includes YouTube VR, which currently has 3.25 million subscribers and delivers spatial audio exclusively using the SADIE filters making them the benchmark for spatial audio quality in VR/AR apps. Consequently, the work has had a significant impact on player experience in VR gaming worldwide, including the world's biggest game, Fortnite, which has 350 million accounts and utilises the York filters.

Figure 1. The Google Daydream VR headset (Left) and Google Cardboard (Right) use mobile apps that utilise the SADIE binaural filters

2. Underpinning research (indicative maximum 500 words)

The creation of immersive 3D sound over headphones is an essential component of interactive VR/AR content generation and consumption. York has a strong history in working in immersive sound since the 1980's; however, recent work by Dr Kearney and his research team has represented a paradigm shift in its application and impact. Since the SADIE project began at York in 2016, the team has developed underlying binaural (two-ear listening) technologies that can be deployed over headphones for VR/AR applications and that can form realistic soundfields akin to those experienced in the real world.

At the heart of this work is the SADIE binaural database [3.1, 3.2], a collection of measured binaural filters also known as HRTFs (Head-Related Transfer Functions), measured by Dr Kearney and his team. HRTFs are typically measured from probe microphones in a subject's ears or from binaural dummy head microphones with test signals played back from loudspeakers positioned at specific angles to the head (see Figure 2). Rendering audio through the measured filters over headphones, the listener has the impression the sound is external to their head at a specified point in 3D space. The subsequent post-processing of the captured audio requires careful signal processing to ensure optimal sound quality.

The SADIE database is the first ever binaural measurement database optimised for VR and AR applications. This is because the measurement positions around the head were chosen so as to replicate the positions of a real spherical loudspeaker system around the head i.e., when listening on headphones via the filters, the subject has the impression they are listening to a real loudspeaker system. This enables the use of another technology, Ambisonics, to allow for sound scene generation over the spherical 'virtual loudspeaker' array. This combination of Ambisonics and binaural is ideal for VR/AR and the SADIE project also presented optimised Ambisonic surround sound decoders for VR/AR to work with the HRTF measurements.

The SADIE research project further led to the development of optimisation algorithms for the

binaural filters at York by McKenzie, Murphy and Kearney, such as in [3.3] that created better overall binaural sound quality. Further work by Rudzki and Kearney, in collaboration with Google, also considered the deployment platform not only for local binaural rendering in mobile devices but also streaming services over the web [3.4].
Consequently, the SADIE project developed underlying supporting spatial audio technology to VR/AR that opened up avenues of exploration that go beyond the strong entertainment value, for example, into the realms of audio for health and well-being, social inclusivity and accessibility. One such application is Johnston, Egermann and Kearney's work into the use of immersive VR based soundfields in the treatment of children with auditory hypersensitivity in autistic spectrum disorder (ASD) [3.5]. Here, children with ASD are given controlled exposure to soundfields that they find challenging in the everyday world via a gamified experience that utilises SADIE technology.

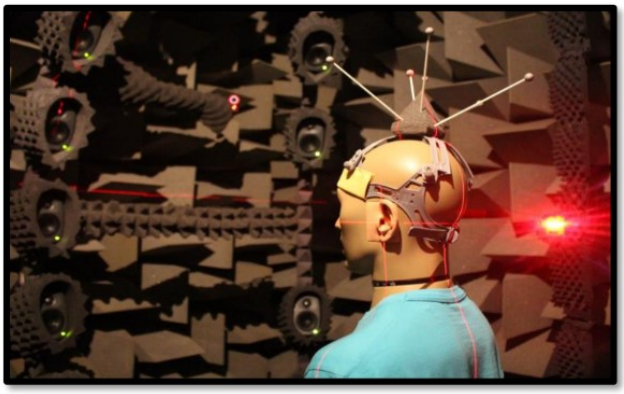

Figure 2: Binaural head measured as part of SADIE database [3.2].

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

3.1. G. Kearney, "SADIE Virtual Loudspeaker Database", 2016, University of York, https://www.york.ac.uk/sadie-project/database.html, doi:10.15124/89aac2f4-2caa-4c01-8dcb-6771635e1a1c
3.2. C. Armstrong, L. Thresh, D. T. Murphy, and **G. Kearney**, "A Perceptual Evaluation of Individual and Non-Individual HRTFs : A Case Study of the SADIE II Database," *Applied sciences*, vol. 8, iss. 11, 2018. doi:10.3390/app8112029
3.3. T. McKenzie, D. Murphy, and **G. Kearney**, "Diffuse-field equalisation of Binaural Ambisonic Rendering," *Applied sciences*, vol. 8, iss. 10, 2018. doi:10.3390/app8101956
3.4. T. Rudzki, I. Gomez-Lanzaco, J. Stubbs, J. Skoglund, D. T. Murphy, and **G. Kearney**. "Auditory Localization in Low-Bitrate Compressed Ambisonic Scenes." *Applied Sciences* vol. 9, iss. 13, 2019. 2618. doi:10.3390/app9132618
3.5. D. Johnston, H. Egermann, and **G. Kearney**, "Innovative computer technology in music based interventions for individuals with autism moving beyond traditional interactive music therapy techniques," *Cogent psychology*, p. 1554773, 2018. doi.org/10.1080/23311908.2018.1554773

[3.2] [3.4] Returned to REF2021; [3.2 - 3.5] Peer reviewed publications

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

Google Adoption of SADIE Research
In 2016, the datasets of binaural filters and Ambisonic decoders measured for the SADIE project were made publicly available on the project website www.york.ac.uk/sadie-project/.This included HRTFs from 18 human subjects and two binaural heads. The database has recently been updated to high resolution versions of the datasets [3.2].
In 2017, Google began to work with Dr. Kearney in defining the appropriate HRTF set for their VR pipeline. Dr. Kearney has a six year track record of working with Google and has been awarded a Google research Faculty Research award, a Chrome Media Award, a Google VR

research award and a YouTube award to continue his work on spatial audio quality in binaural based Ambisonics [5.1].
Google commissioned an independent study with Danish consultancy firm Delta Senselabs to evaluate the overall spatial audio quality of the SADIE database in comparison to their own THRIVE HRTF dataset [5.1]. This included a panel of 53 experienced listeners, 20 of whom were expert assessors. They found that the SADIE KU100 dataset demonstrated the best audio quality over all HRTFs and significantly outperformed their own dataset overall all test scenarios. The results are given in Figure 3. These show a comparison of the perceived overall spatial audio quality of audio rendered using the SADIE KU100 dataset vs. the Google THRIVE dataset. It is clear that for all different sound types tests (synthetic, natural and musical sounds) that the SADIE dataset significantly outperforms Google's own filters.

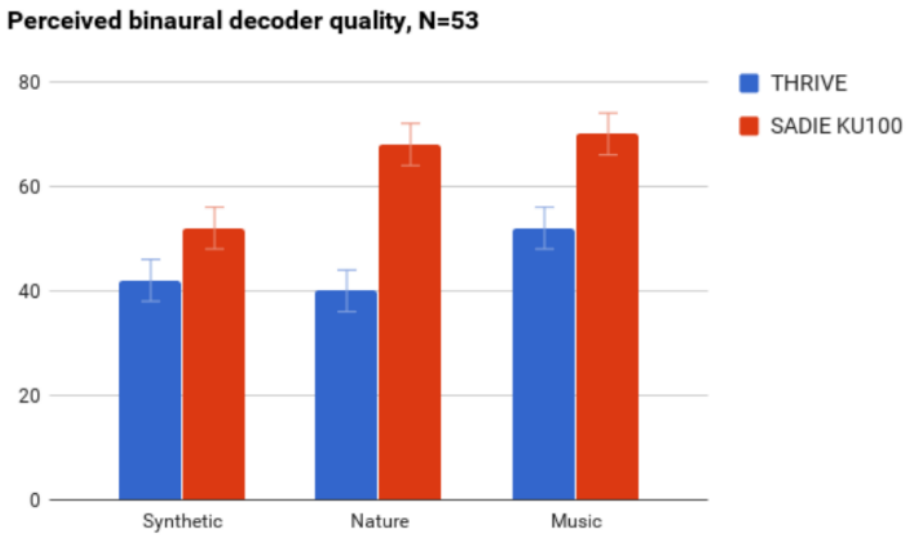

Figure 3. Comparison of spatial audio quality of SADIE vs Google THRIVE HRTFs [5.3].
In April 2017, Google announced the switch from THRIVE to SADIE filters for spatial audio playback in Google VR SDK, YouTube 360/VR, and Omnitone [5.2]. In November 2017, Google further announced Resonance Audio, a cross-platform spatial audio solution for VR utilising the SADIE binaural filters and decoders [5.3].
Resonance audio allows for app development over a range of game engines and sound design tools, including Unity, Unreal, FMOD, Wwise and also facilitates spatial audio on Android and iOS platforms as well as in music and sound editing workstations that support VST plugins, such as Cubase, Nuendo and Reaper. The Director of Video Infrastructure, YouTube, comments on the audio quality and industry adoption of the SADIE filters: *"We undertook an independent evaluation… The SADIE filters had significantly better spatial audio quality which led to their formal integration into the GoogleVR pipeline. Since then, SADIE filters have become the industry benchmark for spatial audio"* [5.1].

Scope of the Impact

YouTube VR acts as a deployment platform for VR content created with Resonance audio tools and utilises the SADIE filters on VR-enabled platforms, including mobile. In the first 19 months of the platform's launch over 350,000 hours of YouTube videos in VR were consumed [5.4] and by 2017 over 160 million Cardboard-enabled app downloads had been made and 10 million cardboard headsets have been shipped [5.5]. To date, the YouTube VR channel has 3.43 million subscribers [5.6].
Whilst it is difficult to gauge how many gamers are currently using SADIE filters, it is useful to consider the impact of even one title created using Resonance Audio. EPIC games *Fortnite Battle Royale* (https://www.epicgames.com/fortnite/en-US/home) is one such example. The title gained more than 125 million players in its first year of release (2017), earning the company hundreds of millions of dollars per month and is now the world's largest game with over 350 million accounts [S4]. A testimonial on the importance of spatial audio in the game's success comes from the Chief Strategy Officer at Epic Games, and is included with this case study. He states: *"Without high quality spatial audio, the Epic audio team feels it would not have been able*

to deliver the immersive experience that the game demands. The SADIE filters are high quality". He also adds how *"competitive play-testers were "blown away" with the quality"* [5.7].
Resonance Audio has now been fully integrated with a number of game engines so the number of downloads of the original repository is not very informative. If however we consider the VST plugin for Resonance, which is *just* the SADIE filters with no other resonance tools, the total number of downloads to date is 5,747. This means that there are approximately 5,000 sound designers globally who utilise the SADIE filters in the creation of immersive content. These sound designers range from bedroom producers through to highly influential commercial production houses. This latter aspect is corroborated by the Head of Audio Products at Abbey Road Studios and founder of the Abbey Road Spatial Audio Forum (of which Dr Kearney is a member). He states *"At Abbey Road we have to ensure that we deliver superior sound quality in all aspects of our productions. Before the integration of the SADIE filters into Resonance, we were not happy with the quality of the spatial audio delivery on platforms like YouTube as they didn't live up to our standards."* He mentions how they have developed immersive experiences at Abbey Road using Google Resonance for material from artists such as the Beatles, Rod Stewart and Jeff Beck *"with the sound quality it deserves"* [5.8].

Beyond Entertainment

The impact has not only been in the entertainment industry, however. The original intent of the SADIE filters and decoders was to be utilised as research tools to stimulate VR and AR enabled research throughout the sector. In our own work, the application of the underlying spatial audio technologies has enabled us to create impact within the UK health services. The work already mentioned on VR audio for treating auditory hypersensitivity disorders [3.5] has been used with 50 autistic children across the UK, in partnership with the charity Accessible Arts and Media and the Child Orientated Mental Health Intervention Centre (a partnership with Leeds and York NHS Trusts and the University of York). It has proven that using SADIE binaural audio to create realistic sound environments significantly improves the treatment of auditory hypersensitivity over standard stereo reproduction enabling shorter treatment times.

In conclusion, the SADIE filters now represent the benchmark for binaural audio reproduction in virtual and augmented reality due to the high quality, adoption by Google, and use within the VR and AR creative sector. Consequently, the SADIE project has demonstrated strong impact on immersive technologies and applications reaching well beyond the entertainment impact avenue originally intended, both nationally and globally.

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

5.1. Corroboration Letter: Director of Video Infrastructure, YouTube, Google Inc., California, US, 2021
5.2. Google Spatial Audio SDK: https://github.com/google/spatial-media/tree/master/spatial-audio
5.3. Resonance Audio: https://resonance-audio.github.io/resonance-audio/
5.4. Google Keyword Blog: VP of Virtual & Augmented Reality, Google LLC: https://blog.google/products/google-ar-vr/unfolding-virtual-journey-cardboard, 2016.
5.5. Google Keyword Blog: VP of Business & Operations, Google LLC: https://blog.google/products/google-ar-vr/more-ways-watch-and-play-ar-and-vr, 2017.
5.6. YouTube VR Channel, https://www.youtube.com/vr, (accessed 29 January 2021).
5.7. Corroboration Letter: Chief Strategy Officer, EPIC Games, California, US, 2020
5.8. Corroboration Letter: Head of Audio Products, Abbey Road Studios London, UK, 2020