1st Annual COG-MHEAR IAB Report - online copy

COG-MHEAR (EPSRC Grant no. EP/T021063/1) is a cross-disciplinary 4-year research programme awarded under the EPSRC's Transformative Healthcare Technologies for 2050 funding Call. It includes academic partners from 7 UK Universities and a User Group comprising global hearing-aid manufacturers, clinical collaborators, and end-user engagement organisations.
COG-MHEAR receives independent advice from a distinguished International Advisory Board (IAB) through annual meetings and informal interactions.

[This report covers the period: 1st March 2021 - 31st January 2022]

Contents

1. Introduction

Currently, only 40% of people who could benefit from hearing aids have them, and most people who have the devices don't use them often enough. COG-MHEAR aims to change this.

Hearing loss is a major public health issue affecting at least 1.5 billion people globally, including 12 million people in the UK. It is associated with poorer communication, cognitive, mental, and social outcomes in older adults. Hearing aids (HAs) are the most widely used devices for compensating the majority of hearing losses. For cochlear implant (CI) users, combining electric and acoustic signals through the use of a HA and CI together can provide the highest level of speech understanding and 'more natural' sound quality, with an improved binaural ability to locate a sound, and the end-user feeling "balanced" between the ears.

Due to advances in miniaturised sensors and power consumption, we now have the potential to monitor not only sound, but many parameters (e.g. visuals) to help improve intelligibility. However, only a limited number of research developments in speech enhancement have been implemented into commercial HAs. Recent technological advances have enabled low-latency, high data rate wireless solutions for in-ear hearing devices, which have primarily reformed the current innovation direction of the hearing industry. Nevertheless, even sophisticated commercial HA devices, including latest Bluetooth-enabled HAs, are based on audio (A)-only processing, and remain largely ineffective in restoring intelligibility in environments where overwhelming noise is present.

Barriers to HA uptake are multifaceted but can include: social stigma; cost; a lack of understanding of hearing loss interventions; and limitations of current hearing assistive technology. COG-MHEAR aims to transform hearing care, by completely rethinking the way HAs are designed. Our approach, for the first time, draws on the cognitive principles of normal hearing. Listeners naturally combine information from both their ears and eyes: we use our eyes to help us hear.

We aim to create "multi-modal" (**MM**) aids which not only amplify sounds but contextually use simultaneously collected information from a range of sensors to improve speech intelligibility. For example, a large amount of information about the words spoken by a person is conveyed in visual information: in the movements of the speaker's lips, hand gestures, and similar. This is ignored by current commercial HAs and could be fed into the speech enhancement process by designing a new-generation of MM or audio-visual (**AV**) HAs. We can also use wearable sensors (embedded within the HA itself) to estimate listening effort (or cognitive load) and its impact on the person, and use this to tell whether the speech enhancement process is actually helping or not.

2. Vision and major research challenges

2.1 Motivation

Human performance in everyday noisy situations is known to be dependent upon both aural and visual senses that are contextually combined by the brain's multi-level integration strategies. The MM nature of speech comprehension is well established, with listeners known to unconsciously lip read to improve the intelligibility of Speech in noise (**SIN**). Lip reading has been shown to help people tolerate an extra 4-6 dB of noise (1 dB of signal to noise ratio (SNR) gain can be equivalent to 10-15% better intelligibility) [1][2]. Further, looking at a speaker makes speech more detectable in noise; as if audio cues are being visually enhanced. **We envisage transformative, privacy-preserving MM HAs by 2050, that will seamlessly mimic the unique human cognitive ability to focus hearing on a single speaker,** effectively ignoring background distractor sounds regardless of their number and nature.

Our overall goal is to develop, test and evaluate real-time MM HA demonstrators, including hardware and software implementations, that will autonomously adapt to the nature and quality of their visual and acoustic environmental inputs, leading to enhanced intelligibility in noise, with potentially reduced listening effort or cognitive load. This requires us to holistically address a formidable range of technical, privacy and usability challenges. The open research challenges are aligned with our full work programme (presented in Section 4), comprising three major interlinked work packages (WP1-3). The latter are mapped to an end-user driven minimum viable product (**MVP**) development plan shown in Figure 1, below. The MVP represents our provisional roadmap for developing the world's first real-time MVP Demonstrator of AV HAs.

2.2 Overview of COG-MHEAR work programme and MVP Roadmap

There is a considerable adventure in our research, which is reflected in the highly iterative nature of the three WPs (see Section 4 for details). In overview, each set of WP tasks is designed as a series of individual, collaborative research projects. WP1.1 and WP1.2 are aiming to deliver more generalised, privacy-preserving and low-latency neural network based MM speech enhancement (SE) algorithms. WP1.3 is exploring more brain-inspired low-energy deep neural networks for MM SE. WP1.4 and WP1.5 are aiming to ambitiously explore wireless lip reading and cognitive load prediction models for integration with MM speech enhancement models (from WP1.1-WP1.3).

WP2.1 is delivering an off-chip real-time prototype of 5G-IoT enabled MM HA through design of an IoT Transceiver (TRx) and a next-generation communication network solution: 5G

Cloud-Radio Access Network (CRAN). This will be integrated with context-aware smart networking being developed in WP2.2. WP2.3 is initially aiming to address computational complexity and real-time processing issues associated with MM speech enhancement operations by offloading and running them in the background, in the Cloud. At the same time, we plan to explore ‘functionality split’ (during and beyond the project’s duration) by taking account of our new low-latency and low-energy deep neural networks (DNNs) being developed in WP1.1-1.3 and WP2.5, with more processing moved from the Cloud/Edge to full system on-chip software/hardware processing. The latter will be used with software defined radio (SDR) for real-time evaluation.

Our vision for 2050 is to go beyond 5G-IoT and internet connectivity constraints, and explore internet-independent, brain-like, on-chip MM HA processing to comprehensively address HA size, power, budget, communication and cybersecurity. Developed outcomes from WP1 and WP2 will be evaluated in WP3 through ongoing development of a new open evaluation framework and smart home testbed, with support from our industrial partners, clinicians and end users. WP3 is scheduled such that end-user requirements and preliminary testbed evaluations are fed back to WP1-2, to continuously optimise outcomes.

To facilitate end-user evaluations, we will explore the possibility (with our key industrial partner Sonova) of our initial MM HA prototypes augmenting commercial audio-only HAs (as sound delivery units). The contextual AV processing could serve as an add-on to improve system-steering, through a (e.g. smart glass-like) off/on-chip 5G-IoT transceiver and cloud/mobile-based MM HA implementations. Beyond the programme duration, technical and clinical validation of our prototypes could pave the way for delivering real-time, internet-independent, full-system on-chip, non-visible MM HA options.

***Background References:*:**
[1] Middelweerd M.J, Plomp, R., Effect of speechreading on speech reception threshold in noise,JASA,82.6:2145-47,1987
[2] MacLeod A, and Summerfield Q, A procedure for measuring auditory and AV SRT, British journal of audiology, 1990, 4(1), pp.29-43.

3. Research Team

The Research Team consists of several interdisciplinary groups, each working on an individual project (WP Task) that contributes to the overall programme goal. Fifteen investigators from seven partner Universities provide specific technical input required to various WP Tasks/projects. Each WP Task/project is led by one of the investigators as project lead (PL), working with at least one other investigator as project co-lead (co-PL), project postdoctoral researchers and/or match-funded PhD students (see Section 4).

The COG-MHEAR team works alongside a strong User Group comprising industrial and clinical collaborators, and end-user engagement organisations (see Section 5).

4. Progress Report on Programme Activities

Since the start of the COG-MHEAR programme in March 2021, significant progress has been made in several of our key projects. We present year 1 progress and year 2 plans for programme activities, followed by an overview of complementary COG-MHEAR activities and outputs from collaborative research funded by other sources. Finally, the impact of ongoing COG-MHEAR programme activities is outlined. Figure 1 presents a high-level schematic of our minimum viable product (MVP) development plan. Work Packages (WPs) 1-3 are integrated with typical high-end conventional hearing-aid signal processing that incorporates the COG-MHEAR development of a MM assistive hearing system.

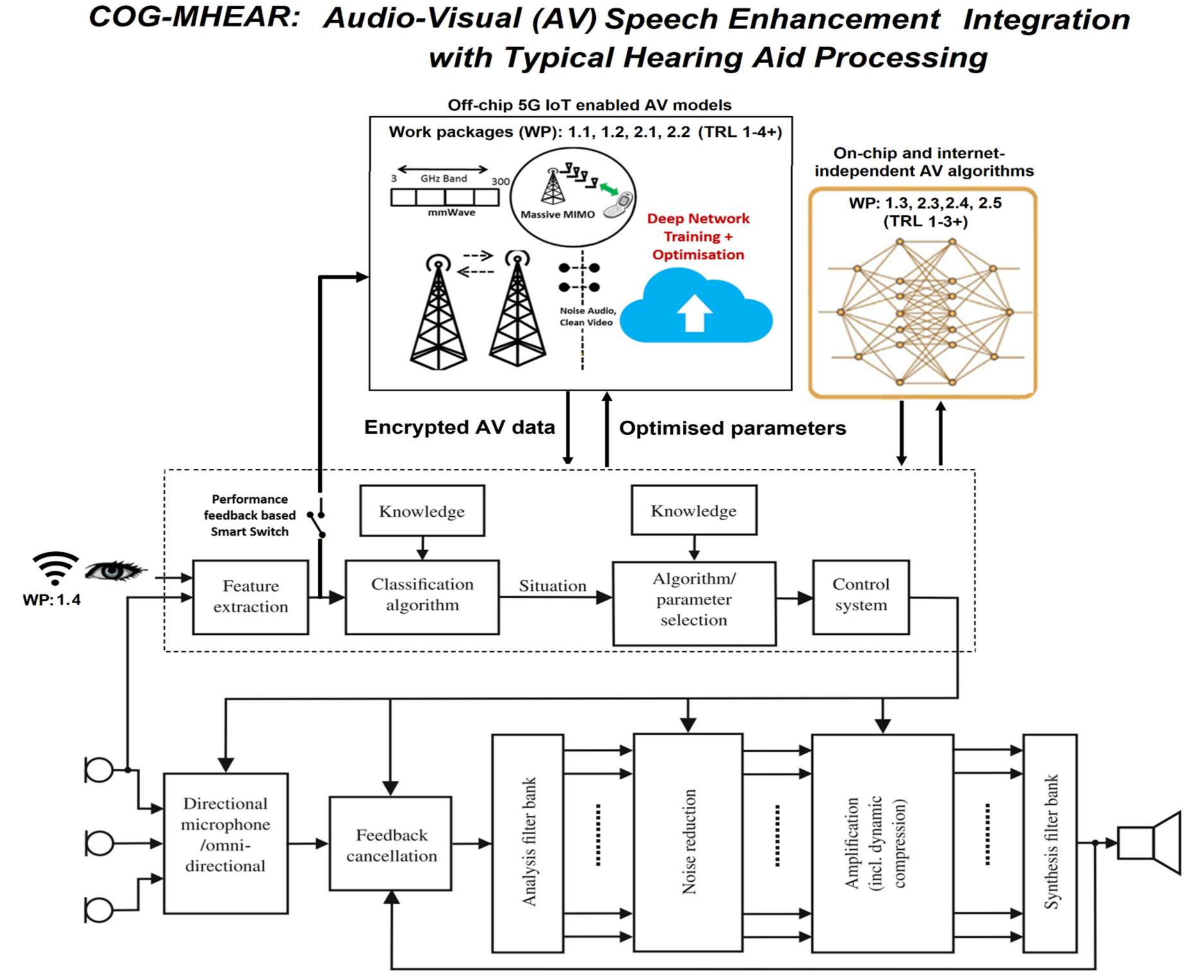

Figure 1: Minimum Viable Product (MVP) Development Plan (including schematic integration of AV Speech Enhancement with typical High-end Hearing Aid processing)

4.1 Details of each Work Package (WP) (including current and target Technology Readiness Levels (TRLs))

WP1.1 (Real-time robust AV speech enhancement algorithms). *PL:UoE(PB,SR); ENU(AH); UoW(AA), Sonova:* This has developed an initial, first of its kind, real-time deep neural network (DNN)-based Audio-only MVP demonstrator [O1]. It has been shown to exhibit significantly reduced latency compared to state-of-the-art speech enhancement algorithms (~12ms vs ~30ms) in a range of constrained web-based communication environments. Latency-performance trade-offs are being optimised, and visual (lip-reading) cues integrated to deliver a transformative AV MVP demonstrator. The latter is underpinned by a groundbreaking real-time AV framework based on a generative adversarial network (GAN) for low-latency speaker-independent AV speech enhancement. This can generalise to a range of visual and acoustic noises, by addressing the practical issue of visual imperfections in real environments [O2]. **At TRL2 and moving towards TRL3**

WP1.2 (Privacy-preserving AV speech enhancement models) *PL: ENU(AH,WB,EH); UoW (AA), UoE(PB,SR).* This has initially built on state-of-the-art privacy-preserving encryption algorithms including AES (Advanced Encryption Standard) (which is normally used to encrypt small amounts of data) and our benchmark Lightweight Chaos-Based Encryption scheme. Initial results of a quantitative cross-comparison, in collaboration with UoE and UoW show that lightweight chaos-based encryption schemes perform best in case of both Audio and Video encryption [O9]. In light of feedback from User Group workshops (see Section 10), we are pursuing collaborative work with UoG to explore more ambitious privacy-preserved AV speech enhancement models based on wireless lip reading (including in the presence of face masks) and smart context estimation (as part of WP1.4, WP2.2). Preliminary collaborative results are being published (e.g. [O10] as part of WP2.2). **At TRL0 and moving towards TRL1**

WP1.4 (Wireless-based privacy-preserving MM Lip-Reading models) *PL:UoG(QA); UoW(AA); ENU(AH,WB); Sonova:* An initial survey of non-contact sensing focusing on small-scale body movements has been conducted [O13], and innovative techniques have been developed based on SDR and RADAR technologies. Pilot results demonstrating the potential of this privacy-preserving approach have been published in [O14]. **At TRL1 and moving towards TRL2**

WP1.5 (Wireless-based MM models for cognitive load detection and prediction) *PL: UoE(TA); UoG(QA); ENU (AH), UoW (AA), UoN(MA); Sonova:* With the recent appointment of a PhD student, a literature review is being carried out, in collaboration with ENU, on current work on cognitive load and its links to hearing loss and dementia. An overview paper [O12] is exploring the interrelationship of hearing loss, cognitive load and dementia, including challenges and opportunities for wireless detection and monitoring with wearable microwave sensors. **At TRL0 and moving towards TRL1**

WP2.1 (Off-chip real-time 5G-IoT AV HA prototyping): *PL:UoE(TR), ENU(AA); HW(MS), ENU(AH):* AI demo is available at [O20] describing an initial stage of a transceiver frame structure for a 5G-IoT enabled HA prototype. We have developed a transceiver frame structure for our envisaged cognitively inspired 5G-IoT enabled HAs using LabVIEW NXG. **At TRL1 and moving towards TRL2**

WP2.2 (Context-aware, smart scalable network connectivity to improve energy efficiency and Quality of Experience) *PL: UoG(MI,QA); ENU(AH,EH); UoW(AA), HW(MS):* Initial work has focused on designing and utilising the world's first smart 5G-enabled sensing system (operating at 3.75GHz) for multi-subject activity monitoring [O14]. This offers a viable alternative to existing approaches for environmental context estimation and can potentially fulfil needs of smart network connectivity to improve energy efficiency and quality of experience. **At TRL1 and moving towards TRL2**

WP1.3 and WP2.3 (Internet-independent brain-like AV speech enhancement architectures and real-time on-chip prototyping) *WP1.3 PL: UoW(AA); ENU(AH); Alpha Data; WP2.3 PL: UoE(TA); UoM(AC); UoW(AA); ENU(AH); Alpha Data.* Going beyond well-established leaky integrate-and-fire (LIF) point neuron-inspired computer architectures (e.g., Intel's Loihi, IBM's TrueNorth, Manchester's SpiNNaker, and our prior DCNN work), this work has demonstrated for the first time a transformative computational potential of the two-point layer 5 pyramidal cell (L5PC) for internet-independent on-chip training of deep networks. It is shown that the proposed approach can process large amounts of real-world data using far less energy. **At TRL1 and moving towards TRL2**

WP3.1 (Eliciting end-user requirements and real-world AV corpus development) *PL: MA (UoN), ENU(AH), UoW(AA), HWU (MS,LB):* Due to COVID-19 restrictions, real world AV data was not collected in the first year. However, extensive evaluation was carried out using our previously collected, benchmark AV ASPIRE and VISION corpora to comparatively evaluate and optimise both the Audio-based and AV speech enhancement models in WP1. Further, an "in-the-wild" AV dataset has been collected from broadcast/YouTube style content using a fully engineered pipeline (developed as part of WP1.1). The pipeline is currently being integrated with the AV MVP and will be used to evaluate the AV speech enhancement models.

WP3.2 and WP3.3 (Open evaluation framework and Smart Assistive/Care Home Testbed)
WP3.2 PL: UoN(MA); ENU(AH); UoW(AA); HWU(MS,LB); Sonova; AoHL. WP3.3 PL: HW(MS,LB); UoE(TR,TA,PB); ENU(AH); UoN(MA); Sonova.
WP3.2 and WP3.3. are due to start in Year 2 of the COG-MHEAR research programme. Tentative plans with required facilities and personnel are in place. The work centres on the development of new evaluation approaches that will be required for the AV MVP. A review of SIN tests is being carried out to identify challenges and opportunities [O29].

4.2 Complementary COG-MHEAR programme activities

Complementary activities over the past year involved COG-MHEAR researchers working with collaborators (see Section 9) in a number of key related projects (funded by other sources), whose outputs are feeding into relevant WPs outlined below.

4.3 Programme Activities

Impact: Our impact strategy aims to shorten the time to translation for our pioneering research work; ensuring the fundamental research performed is ultimately relevant to health practice and care. Within this, we aim for broad engineering, AI, health and social care impact.

The first year's research has included work applicable to healthcare areas of economic and social importance, including computer vision, speech and natural language dialogue systems, and wireless systems engineering. This has also led to follow-on funding in these areas (see Section 7). Ongoing future work is likely to be of benefit in cochlear-implant signal processing, adaptive hardware engineering, and clinical, computational, cognitive and auditory neuroscience.

In order to maximise COG-MHEAR impact, we have focussed our efforts on:

1. User engagement activities and interactions with the COG-MHEAR User Group (see Section 4.3.1)

2. Social impact, dissemination and public engagement (see Section 4.3.2)

3. Exploitation and Commercialisation: The programme's direct training and development impact is also being realised through COG-MHEAR researchers and match-funded PhD students networking and working on collaborative projects with external partners (see Section 4.3.3).

4.3.1 End User engagement activities

Highlights of key COG-MHEAR User Group activities include (see Section 10 for details)

- Two Workshops organised by the User Group as part of our participatory co-design programme. Specifically, an industry Workshop on 23 June 2021 to solicit early feedback from industry experts on MVP design and evaluation, followed by a Multi-stakeholder User Workshop on 16 Nov 2021 to solicit end user feedback to inform our planned ongoing research (see Section 10).

- Continuous recruitment of User Group members to gain a variety of stakeholder perspectives. New team members and advisors who have joined include a GP with interest in audiology, a hearing-aid user, and a clinical audiologist. Continuing end user engagement will help further understand end-user privacy issues and maximise usability and uptake prospects.

4.3.2 Dissemination and public engagement activities

Over the past year, we have organised/planned a number of interdisciplinary workshops/conferences, special sessions, journal special issues, competitions, end user and public engagement activities (see Section 10 for details of other outputs). Highlights to date include:

- Approval obtained from TED for use of TED talks dataset to organise our first COG-MHEAR AV Challenge and Workshop (for submission to IEEE SLT 2022).
- IEEE WCCI 2022 Special Session approved on: Explainable and Interpretable Deep Learning Approaches to address Health Challenges. This will help disseminate our (WP1) outputs and stimulate further research in the area to address shared challenges for development of explainable healthcare AI models.
- **IEEE EMBC 2022 Workshop on: "Challenges and Opportunities for Development of Transformative Multi-Modal Hearing Assistive Technologies". This will showcase our AV MVP demonstrator (being developed as part of WP1).**
- The OpenASR 2021 Special Session accepted to ISCA's Interspeech 2022 conference. This will disseminate our (WP1 related) work in weakly-supervised and unsupervised speech processing methods.
- Special Issue approved in IEEE Transactions on AI on: "Physics-informed Machine Learning". This will help promote interdisciplinary research into the physics of hearing (complementing WP1).
- Special issue approved in the Electronics journal on "Advanced Sensing Techniques for Intelligent Human Activity Recognition Using Machine Learning". This will showcase related outputs from WP1.4 and WP2.2 and stimulate further research in wireless RF sensing for human health and activity monitoring.
- Special Issue approved in the IEEE Transactions on Affective Computing, on "Neuro-symbolic Artificial Intelligence for Sentiment Analysis". This will promote interdisciplinary research in this area and inform our planned research in WP1 and 3.1
- The annual 2022 UK Speech Workshop to be held in Edinburgh. This will showcase COG-MHEAR research to the wider speech technology research community.

4.3.3 Research training, networking and collaborations

Opportunities to enhance interdisciplinary training, networking and collaborative research are being continually explored in priority COG-MHEAR areas. See Sections 9 and 10 for details. Highlights include:

- Monthly networking and training Workshops organised by COG-MHEAR postdoctoral researchers and match-funded PhD students.
- Match-funded PhD students benefit from interdisciplinary supervisory team arrangements.
- Developing existing and new collaborations with internationally-leading researchers and research groups to inform COG-MHEAR programme activities

- Strategic partnerships are being explored with world-leading research centres and programmes, including those funded through the UKRI's (£830M) Strategic Priorities Fund

5. Project Management and Governance

The COG-MHEAR **governance structure** comprises 3 key elements: an International Advisory Board, a strategic programme board, and Work Package Task/Project Leads.

Flexibility: Management of flexibility is an important aspect of COG-MHEAR organisation, which aims for an optimal balance between focused tasks and flexible strategic evolution of the overall programme. Each Work Package Task is a separate key challenge, with scope given to plan for new promising lines of investigation.

Risk management: A risk-based monitoring strategy is conducted at both programme and project levels. The PM maintains a risk register, which provides a method of logging, evaluating and tracking risks to the ongoing progress of the research programme.

Our work programme in Section 4 provides an outline of the current planned work for the first 2 years, though this is subject to change as per our flexible management approach. At the mid-term programme review meeting, deliverables for the second half of the programme will be finalised.

6. Activities related to Responsible Innovation

COG-MHEAR aspires to carry out high quality responsible research and innovation to transform HA technology. All research teams carry out rigorous, groundbreaking work with care and respect for those involved, and accountability to create a positive research environment, in line with the EPSRC framework for responsible innovation [https://epsrc.ukri.org/research/framework/], so we are taking all possible steps to anticipate potential problems, particularly through early-stage engagement of stakeholders at our User Workshops, and our use of a participatory co-design process to respond to user needs in an inclusive manner.

Specific activities include a careful consideration by our research team (as part of relevant WPs), both through closely working with respective institutional ethics teams and continuing engagements with our User Group, to address a full range of ethical and design issues, relating to:

- Privacy and security of AV data collection, processing, storage and sharing
- Recruitment of volunteers for prototype evaluation
- Ensuring the safest possible use of emerging technologies such as RF radiation, including 5G
- HA wearability concerns

6.1 Open innovation

To ensure the reproducibility of our research, and to benefit the widest range of stakeholders, we are strongly committed to COG-MHEAR outcomes being made available as open source. We also seek to promote activities to disseminate project outcomes through a wide variety of channels.

6.2 Covid impacts and opportunities

The COG-MHEAR programme has been carried out under varying levels of Covid-19 restrictions throughout the first year. The teams have adapted well to virtual work, however planned recruitment of project researchers, collection of AV data and evaluation with human volunteers have been delayed.

Meetings continue to be held in hybrid or online formats, facilitated by video conferencing facilities being increasingly used during the lockdown, including by HA users.

The COG-MHEAR research team has utilised opportunities to contribute to complementary research, directly addressing pandemic-related challenges. Specifically, with co-funding from the EPSRC IAA, the SDR radar system developed by the COG-MHEAR team, was used to transform subtle chest movements into actionable micro-doppler signatures to extract respiratory rates by exploiting a ResNet (Residual Neural Network) [O15]. The pioneering system was also optimised for a number of other small-scale movement monitoring applications, including detecting breathing patterns and abnormalities [O16-O19], broadening the impact of COG-MHEAR during the pandemic.

Further, as part of a follow-on Scottish Government CSO grant (see Section 7), COG-MHEAR researchers developed novel AI-enabled sentiment analysis methods to assess public attitudes on social media towards a number of COVID-19 topics of interest to policy makers, including vaccinations and Covid tracing apps ([O26-O28])

7. Sustainability

7.1 Ongoing sustainability of the research

Plans are in place to ensure that COG-MHEAR research continues to evolve, beyond the remit of the current research programme. The wide reach of our ambitious research aims to transform the HA landscape over the next decade. COG-MHEAR uptake will be maximised by convincing end users and stakeholders that the advances in privacy-assuring AI technologies, and their integration with next generation wireless technologies can have a positive and beyond expectation impact on improving the quality of their everyday lives.

Applications for funding complementary research and innovation activities are part of our sustainability strategy. Future joint funding applications with collaborators will help ensure ongoing sustainability of our research.

The COG-MHEAR user group ensures that end-users, clinicians, and HA industry representatives are included at all stages of research, as part of our interdisciplinary programme of participatory co-design. Accessible project updates are shared with user group members (through our website, social media, email and meetings) giving details of project progress and to invite input and feedback. Institutional pump priming is leveraged where possible.

7.2 Sustainability of the research products

Organisations such as the NHS are keen to ensure that products and processes are sustainably sourced, used and disposed of in line with a net-zero carbon emissions policy.

We aim to maximise sustainability of the COG-MHEAR research products through our commitment to low-energy and cost-effective MM HA designs.

8. ED&I (equality, diversity and inclusion)

There is significant ethnic diversity in the project team.

The gender balance in the group reflects the gender imbalance in the wider information technology research sphere, however the academic team does have three female co-investigators and three female postdoctoral researchers, including one joining the project in March 2022.

Diversity of experience is being increased through the appointment of a HA user and a clinical audiologist as PhD students on the research programme.

The HA users and their representatives, who are key to the project, are planned to be selected with a balance of genders, ages and ethnicities. Ongoing recruitment will be carried out with aims to maintain this.

Ongoing work on building an AV corpora will also ensure diverse subjects are selected for recording. This includes plans for a balanced gender distribution, a range of ages, different speech speeds (to account for communication differences), and diverse ethnicities and accents.

9. Networking and collaboration

Networking and collaboration activities are fundamental to the ongoing delivery of our ambitious vision (as highlighted in Section 4.3).

Key ongoing COG-MHEAR collaborations include:

- Industrial and clinical partners in the User Group, including with Sonova International (a leading provider of innovative hearing care solutions)
- Project partners and collaborators from around the world working in a wide range of complementary technologies
- The general public, including HA users and charities such as RNID (the Royal National Institute for Deaf People) and Deaf Scotland, representing enduser organisations in the User Group (end user engagement is discussed in Section 10)

Leading national and international researchers working in priority COG-MHEAR areas are also being involved in collaborative programme activities.

9.1 Advocacy for engineering and the physical sciences

The research team has a strong track record in engaging with policy makers and in engineering advocacy.

9.2 Website and Social Media

The COG-MHEAR website provides a platform for engagement and dissemination. The website has been visited by over 200 users since it was set up in summer 2021. A series of blogs are being published to provide an informal and engaging means of updating visitors. Initial blogs have summarised key points from the main workshops held in the first year of the project. Explanations of the developing HA technology and research will follow. The @cogmhear Twitter account provides another dissemination and networking channel for details of events, publications and opportunities to take part in the research. This is supplemented by a LinkedIn page that is under development. Continuing engagement through social media will enable the project to recruit further participants.

10. End user engagement

Participatory co-design is key to ensuring that the COG-MHEAR research is truly relevant to impactful healthcare. User engagement involves individuals with hearing loss, industry, clinical and academic partners, and the wider community. Focus groups are being used to elicit views on the proposed technology and the data collection strategy, to inform the requirements of WP3.

Accessible blog posts from both workshops were published on the COG-MHEAR website: COG-MHEAR Blog. Feedback from the second workshop has led to prioritising a potential option to help further address end-user privacy concerns, by keeping AV data and processing more local to MM HA users. Alternative ambitious wireless-based privacy-preserving approaches, and their innovative application to BSL recognition systems (suggested by User Workshops) are also continuing to be explored.

A planned workshop this year will explore how sensors can be worn as an additional part of a HA, which will be a requirement for the envisaged MM HA technology. The success of the user engagement strategy will continue to be gauged through the level of interaction with users during and after engagement events: directly and through COG-MHEAR website visit metrics (discussed in Section 9). Key recruits to the User Group to-date (noted in Section 4.3), include a HA user, an audiologist and a GP. We believe they will further contribute towards ensuring direct relevance of the COG-MHEAR research to HA users.

11. Outputs

Outputs to-date include:

- 7 honours/awards and 10 invited/keynote talks
- 1 patent (see Sections 11.1 and reference [O24] in Section 11.3)
- 2 demos (see Section 11.2, and and references [O1] and [O22] in Section 11.3)
- 3 journal Special Issues , 2 Workshops and 2 Special Sessions
- 26 papers (including 5 under review) resulting from COG-MHEAR programme activities (see Section 4.1 for details and Section 11.3 for a list of papers). These include:
    - 16 papers (11 published and 5 under review) linked to WPs in terms of methods and target applications
    - 10 linked to WPs through the development of methods also used in other application areas
- 9 complementary publications resulting from COG-MHEAR researchers collaborating on related projects funded by other sources - these are informing ongoing research in relevant WPs (see Section 4.1 for details, and Section 11.3 for a list of papers)
- 4 follow-on funding awards

11.1 Patents

Adeel A., Multisensory Cooperative Computing, Patent Application Number GB2119011.1, 2021

11.2 Demos

- Interactive COG-MHEAR AV (Audio-Visual) MVP (Minimum Viable Product) Demonstrator**:** http://demo.cogmhear.org
- COG-MHEAR IoT (Internet-of-Things) Transceiver Demo: https://vimeo.com/675527544

11.3 Publications

Note: Pre-prints referenced below are not yet peer-reviewed. Outputs [O1] and [O20] below are references to COG-MHEAR demos (Section 11.2), and [O24] is the reference for our patent (Section 11.1)

[O1] COG-MHEAR AV MVP demonstrator**:** http://demo.cogmhear.org

[O2] Gogate, M., Dashtipour, K. and Hussain, A., 2021. Towards Robust Real-time Audio-Visual Speech Enhancement. arXiv preprint arXiv:2112.09060.

[O3] Hussain, T., Wang, W. C., Gogate, M., Dashtipour, K., Tsao, Y., Lu, X., Adeel A., and Hussain A., "A novel Temporal Attentive Pooling based Convolutional Recurrent Neural Network For Acoustic Signal Enhancement,". arXiv preprint arXiv:2112.09060

[O4] Hussain, T., Gogate, M., Dashtipour, K. and Hussain, A., 2021. Towards Intelligibility-Oriented Audio-Visual Speech Enhancement. in: The Clarity Workshop on Machine Learning Challenges for Hearing Aids (Clarity-2021) https://claritychallenge.github.io/clarity2021-workshop/papers/Clarity_2021_paper_hussain.pdf

[O5] Passos L., Hussain A., Adeel A., Novel Multimodal Canonically-Correlated Graph Neural Network for Energy-Efficient Speech Enhancement in future Hearing-Aids, arXiv preprint arXiv:2202.04528

[O6] I. Spinelli, S. Scardapane, A. Hussain and A. Uncini, "FairDrop: Biased Edge Dropout for Enhancing Fairness in Graph Representation Learning," in IEEE Trans. on Artificial Intelligence, doi: 10.1109/TAI.2021.3133818 (2021)

[O7] Ieracitano, C., Mammone, N., Hussain, A. Morabito F.C,. A novel explainable machine learning approach for EEG-based brain-computer interface systems. *Neural Comput & Applic* (2021). https://doi.org/10.1007/s00521-020-05624-w

[O8] Zou X, Zhang X, Liu H, Li Z, Hussain A, Li J, A novel multimodal fusion network based on a joint-coding model for lane line segmentation, Information Fusion, Volume 80, 2022, Pages 167-178

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