Institution: University of Kent

Unit of Assessment: 11: Computer Science and Informatics

Title of case study: Advancing Severe Brain Injury Rehabilitation Care Practices, Quality of Care, and Patient Family Wellbeing Across Europe through an Innovative EEG Software Tool

Period when the underpinning research was undertaken: 2006-2020

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:
Howard Bowman	Professor of Cognition and Logic	1993-present
Srivas Chennu	Lecturer	2016-2020

Period when the claimed impact occurred: 2016-2020

Is this case study continued from a case study submitted in 2014? No

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

Srivas Chennu and Howard Bowman have developed a software tool for improving the diagnosis of conscious awareness in patients after severe brain injury, based on their research into using neural signal processing methods for quantifying human brain networks. Since 2016 the software tool has been deployed across two residential care homes in Cambridgeshire and Hertfordshire, a world-leading European assessment centre in Belgium, and a rehabilitation centre in Germany. Across these locations, it has been used to measure awareness at the bedside of 200+ patients. The EEG software has improved assessments by allowing clinicians to form a detailed profile of a patient's cognitive function, and as a bedside tool it has advanced care practice by averting the need for transportation, while also providing a digital visualisation of the brain's activity, which improves understanding amongst patients' families and carers. As highlighted by one clinician, the tool is 'significantly reducing the cost of care and specialist assessments by many thousands of pounds, while simultaneously improving timeliness and efficacy' **[c].**

2. Underpinning research (indicative maximum 500 words)

Overview

There is currently little reliable data on the number of patients in prolonged disorders of consciousness in the UK. Estimates vary widely, with between 4,000-16,000 patients diagnosed to be in a vegetative state, and three times as many in minimally conscious states. Because diagnosing and treating such patients poses a serious clinical challenge to neurorehabilitation specialists and clinicians, levels of consciousness can be misdiagnosed in as many as 40% of vegetative state patients.

Chennu and Bowman's research is transforming how such patients are assessed, managed and diagnosed. The team began researching computational methods for quantifying human brain networks in **2006 [R1]**. In **2010**, Chennu took up a postdoctoral research post elsewhere, while Bowman continued the work at Kent **[R2].** Following Chennu's return to Kent in **2016**, the pair continued to develop their research together, with support from a Kent team of a Research Associate and a PhD student. The work was also supported by a grant from the Engineering and Physical Sciences Research Council awarded to Chennu **[G1].**

Their research demonstrated that following non-invasive bedside measurements of electrical brain activity, computational analysis can uncover consciousness in patients who otherwise

might seem unaware **[R3, R4, R5, R6].** This research led Chennu and Bowman to develop a software tool for analysing electrical brain activity measured at the patient's bedside. The Kent team worked in collaboration with clinicians at a range of institutions who since **2017** have deployed the software tool and collected feedback data to further improve the tool.

Development of the underpinning research

Chennu and Bowman's research involves adapting neural signal processing methods for quantifying human brain networks. Human brain network activity is the basis for the quantification of consciousness and is central to the improvement of diagnosis and rehabilitation plans. The foundations for this research were published in **2009 [R1]** and since then the research has been refined and elaborated and the software tool developed.

Since **2016,** Chennu and Bowman have built upon this work, combining neural signal processing, machine learning, and computational analysis of electrical brain activity to characterise the interaction between attention and consciousness. The work was developed for clinical application by showing that analysis of electrical brain activity could uncover hidden awareness in some patients with so-called disorders of consciousness following severe brain injury, even though these patients might seem unresponsive at the bedside **[R3]**.

This computational methodology was validated in three complementary ways: first, using phase synchrony for the identification of consciousness states between coma and quasi-brain-death **[R2]**; then using large-scale datasets of brain activity acquired from clinical settings **[R3]**; and, most recently, using brain activity recorded during anaesthetic-induced unconsciousness **[R6]**. In particular, **[R6]** characterised the brain network's underlying transitions from full consciousness to reduced awareness. Across this network, brain-scale patterns of activation drive the signatures of awareness used, for example, in output **[R3]** to assess consciousness.

Application of the research through EEG software

Based on the findings of this underpinning research, between **2016** and **2017** Chennu and Bowman made advances towards developing a software tool for analysing electrical brain activity measured at the patient's bedside to index their level of consciousness automatically, without requiring any behavioural responses from the patient.

The software tool involves using high-density electroencephalography (EEG) to measure electrical brain activity at the patient's bedside; the software analyses these recordings and produces an assessment of the patient's brain function and a digital visualisation of the brain's activity. The results of the assessments can then be used to develop a detailed brain-based profile of the patient's state of awareness and cognitive function and to formulate an individualised care and therapy plan for the patient.

In **2018,** the EEG software tool was deployed in a clinical trial of therapeutic intervention to aid the recovery of patients after severe brain injury **[R4]**. During the trial, the tool was used to measure the efficacy of electrical stimulation therapy in individual patients by assessing them with the software before and after the stimulation.

More recently, research has demonstrated the viability of routine deployment of the EEG software tool in clinical rehabilitation centres for repeatable and regular assessments of patients **[R5]**. This later work demonstrated that the software can be valuable for augmenting standard behavioural assessments of consciousness in the clinic, by diagnosing current levels of awareness and predicting longer-term recovery.

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

[R1] **Chennu**, S., Craston, P., Wyble, B. & **Bowman**, H. (**2009**). 'Attention Increases the Temporal Precision of Conscious Perception: Verifying the Neural-ST2 Model'. *PLoS Computational Biology,* 5**,** e1000576. https://kar.kent.ac.uk/54653/.

[R2] Li, L., Witon, A., Marcora, S., **Bowman**, H., & Mandic, D. P. (**2014**). 'EEG-based brain connectivity analysis of states of unawareness'. In *36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 1002-1005. https://kar.kent.ac.uk/48649/.

[R3] **Chennu**, S., Annen, J., Wannez, S., Thibaut, A., Chatelle, C., Cassol, H., Martens, G., Schnakers, C., Gosseries, O., Menon, D. & Laureys, S. (**2017**). 'Brain networks predict metabolism, diagnosis and prognosis at the bedside in disorders of consciousness'. *Brain,* 140**,** 2120-2132. http://kar.kent.ac.uk/61849/.

[R4] Thibaut, A., **Chennu**, S., Chatelle, C., Martens, G., Annen, J., Cassol, H. & Laureys, S. (**2018**). 'Theta network centrality correlates with tDCS response in disorders of consciousness'. *Brain Stimulation*. https://kar.kent.ac.uk/69096/.

[R5] Bareham, C. A., Allanson, J., Roberts, N., Hutchinson, P. J. A., Pickard, J. D., Menon, D. K. & **Chennu**, S. (**2019**). 'Longitudinal assessments highlight long-term behavioural recovery in disorders of consciousness'. *Brain Communications*, 1, fcz017. https://kar.kent.ac.uk/76439/.

[R6] Witon, A., Shirazibeheshti, A., Cooke, J., Aviles, A., Adapa, R., Menon, D. K., **Chennu**, S., Bekinschtein, T. A., David Lopez, J., Litvak, V., Li, L., Friston, K., and **Bowman**, H. (**2020**). 'Sedation modulates fronto-temporal predictive coding circuits and the double surprise acceleration effect'. *Cerebral Cortex,* bhaa071. https://kar.kent.ac.uk/80568/.

Grants

[G1] Engineering and Physical Sciences Research Council (EPSRC) grant EP/P033199/1 (**2017-2019**). 'Reducing Misdiagnosis of Awareness after Severe Brain Injury'. PI: Srivas Chennu. Value £101,058.

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

The EEG software tool was first deployed in **2016**, on 40 patients at two residential care homes in Cambridgeshire (Askham Village Community, Doddington) and Hertfordshire (Gardens and Jacobs long-term residential rehabilitation centres in Sawbridgeworth) **[c, e, f, g]**. Since then, its rollout has gathered significant momentum, involving a further 160+ patients at the Coma Science Group in Liege, Belgium, (**2017-present**) **[b]**; and 26 patients at the Therapiezentrum Burgau rehabilitation centre in Germany (**2018-present**) **[d]**.

The results of the EEG software assessments allow clinicians to form a detailed brain-based profile of a patient's state of awareness and cognitive function. This allows more tailored care and therapy to best meet the needs of the individual patients. The tool has made a significant impact on clinicians, patients and their families in the UK and Europe, by:

- advancing the clinical approach to brain activity assessments,
- improving severe brain injury rehabilitation and care practices, and
- increasing understanding and involvement amongst patients' families.

The co-director of Europe's leading centre for clinical assessment, management and treatment of patients diagnosed with prolonged disorder of consciousness (Coma Science Group) explains how 'The adoption of the technology has informed our knowledge, patients' families understanding, and, most importantly, the overall care of the patients we treat' **[b].**

Advancing clinical assessments

Feedback from clinical staff indicates that the EEG software tool has had a significant practical impact on the assessment of brain activity in severely ill patients. For example, the Professor of Anaesthesia at Addenbrookes Hospital has described how the software has 'advanced the clinical practice of brain activity assessments, improving practitioners' and specialists' understanding of the recovery of consciousness after severe brain injury' **[c].**

One of the UK's leading clinical experts in neurorehabilitation has stated that not only is the technology 'helping to inform clinical practice in real-life settings across several specialist hospitals in the UK and Europe, with the potential for more on the horizon', but also noted that she has 'benefitted from its value in allowing me and those I work with to more accurately quantify the level of activity associated with consciousness' **[a].** She highlighted how the research 'has fostered new knowledge around how brain activity assessments can reduce the rate of misdiagnosis of consciousness' and is informing 'our current thinking for how to make the technology more readily available to patients and advance what we do in the future' **[a].**

Advancing rehabilitation and care practices

Prior to the uptake of the EEG software tool, many of the patients in the Cambridgeshire care setting were treated at Addenbrooke's during the acute period after an injury, before being transferred to the centre for prolonged rehabilitation. The transferral process made patient follow-ups more difficult as it required bringing them back for frequent assessments and intervention. In his supporting letter, the Professor of Anaesthesia from Addenbrooke's explains how the software has 'bridg[ed] this clinical and translational gap between acute and chronic stages of recovery after brain injury by facilitating a way to manage patients at their bedside and avert the need for transportation' **[c].** In addition, he states that: 'Using Dr Chennu's technology, clinicians have been able to identify the most useful time points during a patient's rehabilitation when they can benefit from such scans, thereby significantly reducing the cost of care and specialist assessments by many thousands of pounds, while simultaneously improving timeliness and efficacy' **[c].**

Describing the changes made to their clinical practice as a result of the EEG software tool, the co-director of the Coma Science group explains that 'the technology's capacity to assess patients alongside other brain-based assessments like magnetic resonance imaging [which] has improved and often guided the care of our patients, thereby also informing our clinical decision-making and its outcomes' **[b]**. He states that 'Dr. Chennu's research and expertise […] is useful to us as clinicians in informing how we can respond to the challenges faced in caring for patients with brain injury, as the tool that his work has led to is both easy-to-use and also improves the processes of our care' **[b].**

A survey of families of patients at two of the participating rehabilitation centres corroborates this impact on the care received by patients. Responses highlighted how 'It is much better to have the EEG at the bedside it does not interfere with the care of my relative,' and 'No disruption is caused to [the patient's] routine' **[h].**

Similarly, a survey of clinical staff across the two centres established that the software tool allowed clinicians 'to consider the patients conscious state in more depth and provide more beneficial interaction' and 'reduces risks for patients – risk of infection for transport/moving, pressure sores, more convenient, less disruption to patient's normal routine' **[i].**

Increasing families' understanding and involvement

By including a digital visualisation of the brain's activity in a way that previous methods could not, South Newton hospital's clinical expert believes that the EEG software tool 'improves both the clinician and patients' family and carers understanding of a patient's brain activity' **[a].** She confirms that the technology has 'enabled me and my colleagues to more easily communicate the meaning and impact of these assessments to the patients' family and carers. Further, it often increases the extent of their understanding of the patient's diagnosis/situation' **[a].**

This beneficial impact on families' involvement and understanding is supported by clinicians at the Coma Science Group**.** Because the software has identified a minimal state of conscious despite a patient's behaviour indicating an unresponsive wakeful state, for instance, not only have clinicians in Liege 'then proposed to intensify care' but also 'in such contexts, together with the family [they] have used the findings to inform and discuss' patient treatment options' **[b].** The technology, they argue, 'enhances the capacity for collaborative thinking with patient families and is a valued port of information amongst all parties, as it is often combined with the knowledge that patients' families have of the patient to establish a best cumulative purview of the whole situation' **[b].**

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

[a] Letter from the Consultant Neuropsychologist and Director of Clinical Development, Renovo South Newton Limited, UK, describing the impact that the Kent research has had on the role of bedside brain activity assessments in patients with disorders of consciousness (30 July 2020).

[b] Letter from the Clinical Research Scientist and Co-director of the Coma Science Group, University of Liège, Belgium, describing the positive impact that the Kent research has had on improving the detailed assessments on patients referred for specialist evaluation by clinical centres across Europe (16 August 2020).

[c] Letter from Professor of Anaesthesia, University of Cambridge, UK, describing the novel advance of technology from the Kent work for bridging clinical and translational gap between acute and chronic stages of recovery after brain injury (17 September 2020).

[d] Letter from the Chief Physician and Head of Department, Therapiezentrum Burgau, Germany, describing the successful use of the Kent high-density EEG brain activity assessments on 11 patients (25 June 2019).

[e] Letter from a General Practitioner, Sawbridgeworth Medical Services, UK, describing the positive response of Kent's EEG brain activity assessments on 28 patients, as indicated in the survey data from the patients and their family, as well as from staff at Gardens and Jacobs Neurological Centres (22 March 2019).

[f] Letter from the Operations Director, Askham Village Community, UK, providing support for conducting a patient study at Askham Village Community, UK (27 March 2015).

[g] Letter from the Corporate Neuro Clinical Lead, Ramsay Neurological Services, UK, providing a supporting statement for conducting a patient study at Gardens and Jacobs Neurological Centres, Sawbridgeworth, UK (27 March 2015).

[h] Report of a Family Questionnaire. To determine the acceptability and feasibility of the EEG healthcare technology developed, questionnaires were administered to consultees and families of patients assessed using the technology. Across two participating rehabilitation centres where patients were resident (in Sawbridgeworth and Doddington), 22 surveys were sent out and 11 patients' family members completed them (date of survey letter: 23 February 2017).

[i] Report of a Clinical Care Staff Questionnaire. To assess the clinical utility and feasibility of the EEG healthcare technology developed, questionnaires were administered to the clinical staff involved in the care and management of patients assessed using the technology. Across two participating rehabilitation centres where patients were resident (in Sawbridgeworth and Doddington), 17 of the 42 administered questionnaires were completed and returned (date of survey letter: 23 February 2017).