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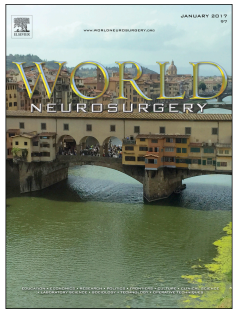

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Key words:

BCI, brain-computer interface, brain-machine interface, BMI, survey, acceptability, clinician, neurosurgical team.

Abbreviations:

BCI: brain computer interface

ECoG: Electrocorticography

EEG: Electroencephalography

FDA: Food and Drug Administration

IDEAL-D: Idea, Development, Exploration, Assessment, Long-term study – Device

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Author contribution statement:

Simon Williams MBChB – data curation; formal analysis; methodology; writing – original draft preparation; writing – reviewing and editing.

Hugo Layard Horsfall MRCS – formal analysis; formal analysis; methodology; writing – reviewing and editing.

Jonathan P Funnell MBBS – writing – reviewing and editing.

John G Hanrahan MBBS – writing – reviewing and editing.

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Andreas Schaefer PhD– supervision, writing – reviewing and editing.

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Hani J Marcus PhD FRCS – conceptualisation; methodology; writing – reviewing and editing; supervision.

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Hani J Marcus PhD FRCS – conceptualisation; methodology; writing – reviewing and editing; supervision.

Abstract:

Objective

Invasive brain-computer interfaces (BCIs) require neurosurgical implantation, which confers a range of risks. Despite this, no studies have assessed the acceptability of invasive BCIs amongst the neurosurgical team. This study aims to establish baseline knowledge of BCIs within the neurosurgical team and identify attitudes towards different applications of invasive BCI.

Method

A two-stage cross-sectional international survey of the neurosurgical team (neurosurgeons, anaesthetists, and operating room nurses) was conducted. Results from the first, qualitative, survey were used to guide the second stage quantitative survey, which assessed acceptability of invasive BCI applications. 5-part Likert Scales were used to collect quantitative data. Surveys were distributed internationally via social media and collaborators.

Results

108 qualitative responses were collected. Themes included the promise of BCIs positively impacting disease targets, concerns regarding stability, and an overall positive emotional reaction to BCI technology. The quantitative survey generated 538 responses from 32 countries. Baseline knowledge of BCI technology was poor, with 9% claiming to have a 'good' or 'expert' knowledge of BCIs. Acceptability of invasive BCI for rehabilitative purposes was >80%. Invasive BCI for augmentation in healthy populations divided opinion.

Conclusion

The neurosurgical team's view of the acceptability of BCI was divided across a range of indications. Some applications (for example stroke rehabilitation) were viewed as more appropriate than other applications (such as augmentation for military use). This range in views highlights the need for stakeholder consultation on acceptable use cases along with regulation and guidance to govern initial BCI implantations if patients are to realise the potential benefits.

Introduction

Brain-computer interfaces (BCI) can be categorised as stimulating or recording systems.[1] Recording BCIs are systems that detect cortical activity and, through data extraction and algorithmic analysis, cause an action from an effector.[2] In 1969, Fetz *et al.* showed that the cortical neural activity of rhesus macaques could be detected and used to trigger the dispensing of food.[3] Since this landmark study, interest in BCIs developed rapidly over the remainder of the 20th century, in tandem with an exponential rise in publications relating to BCIs at the turn of the millennium as technological capability aligned with theoretical knowledge.[2,4]

BCIs may be invasive (implanted directly onto the brain, as in electrocorticography (ECoG) or intracortical arrays) or non-invasive (placed on the scalp, such as in electroencephalogram (EEG) hardware).[2] In recent years, BCI development has rapidly progressed along with practical applications, examples of which include spelling computer systems,[5,6] controlling computer programmes,[7,8] moving robotic prostheses,[9,10] controlling wheelchairs,[11] or assisting with neurorehabilitation.[12] Simultaneous to the promise BCIs offer in healthcare, ethical concerns remain.[13] The application of BCI will likely be restorative, but in the future BCIs may have the potential to augment function of otherwise healthy patients,[1] such as enhancing human memory,[14,15] and creating "brain-to-brain" communication systems.[1,16] Additionally, invasive BCI implantation is associated with surgical risks including bleeding and infection[2] or damage to eloquent brain tissue,[17] which need to be considered when discussing the overall paradigm of BCIs. Neurosurgery has a rich history of driving the inception and development of novel technologies, [18] and as BCI research evolves, neurosurgeons and the neurosurgical team will be responsible for implantation of BCI systems.[1] As such, the neurosurgical team will have a vital role in the evolving paradigm of BCI, both technologically and ethically, and are therefore suitably placed to discuss the risk associated with this "disruptive" technology.[19]

To our knowledge, there has been limited research into the acceptability of BCI to the neurosurgical team.

We aimed to establish the neurosurgical team's baseline knowledge of BCIs and identify attitudes towards different applications of invasive BCI. This includes assessment of willingness to participate in the insertion of different applications of invasive BCI, and determining perceived appropriateness of different invasive BCI applications.

Methods

Overview of methods

A cross-sectional, 2-stage, mixed-method (qualitative and quantitative) survey was performed in keeping with the precedence within the literature (Figure 1).[20,21] The first stage qualitative survey (Table 1) assessed baseline understanding and attitudes of the neurosurgical team towards BCIs. Thematic analysis led to the emergence of themes, used to generate the second stage quantitative survey (Table 2), which presented scenarios and assessed participant acceptability of proposed BCI implementation. Survey methodology and distribution adhered to recommended practice[22] and this survey has been reported in accordance with Consensus-Based Checklist for Reporting of Survey Studies (CROSS).[23] Ethical approval was not required for this study as no patient or clinical data were collected, and the study was performed to plan and advise on future research.[24]

Participants

Participants were invited to participate internationally and included members of the neurosurgical team who would be directly involved in the surgical implantation of invasive BCIs. The "neurosurgical team" included neurosurgeons, anaesthetists, and operating room nurses.[20] Trainee and consultant grades were included, whilst student and non-training roles were excluded.

Distribution

Surveys were created (GoogleForms) and distributed via a network of international collaborators. Local collaborators were provided with study information sheets and sought responses from their individual units. Collaborator status was achieved if local recruits were able to collect 23 responses in total, with guidance advising to collect three responses for the qualitative survey, and twenty responses for the quantitative survey. The qualitative survey was distributed exclusively via local collaborators. To encourage participation, the quantitative survey was distributed both via local collaborators and via social media (Twitter, Facebook). The qualitative survey was live for two weeks (November 2021), and the quantitative survey live for four weeks (November and December 2021). Data for both surveys were collected independently as two individual cluster sampling surveys.

First stage qualitative survey

Participant demographics and occupation were collected, followed by two open questions regarding their current understanding of BCIs. An introduction to BCI was provided, followed by two further open questions relating to the perceived advantages and concerns of BCIs (Table 1; Supplemental Material 1). Answers were thematically analysed and coded to identify core themes, which were used to guide the questions and scenarios posed in the second stage quantitative survey.

Second stage quantitative survey

Demographics including age, gender, country of residence, and occupation were recorded. Current understanding of BCIs was recorded prior to a series of six case scenarios regarding intracranial BCIs (Table 2; Supplemental Material 2). For each case vignette, participants were asked two questions: "Do you agree or disagree that this is an appropriate use of BCI?", and "Would you be happy to be involved as a member of the surgical team in this example of a BCI?". Answers were recorded using a 5-point Likert scale (1 = Strongly Disagree; 2 = Disagree; 3 = Neither Agree nor Disagree; 4 = Agree; 5 = Strongly Agree; identical ranking for baseline understanding response). The Likert scale was designed in accordance with existing recommendations.[25]

Data analysis

Qualitative survey data was thematically analysed to identify themes, in accordance with existing guidance on thematic analysis.[26] Free text answers were screened for themes, and coded to facilitate data analysis. Data from the quantitative survey were analysed using GraphPad Prism5 software (GraphPad Software, Inc.). Data from all respondents was analysed, followed by subgroup analysis for occupation and age. Inferential statistics for quantitative data were conducted in accordance with current accepted statistical theory.[27] Our quantitative data was discrete, ordinal data and values were assigned a numerical rank; (1 = Strongly Disagree; 2 = Disagree; 3 = Neither Agree nor Disagree; 4 = Agree; 5 = Strongly Agree). Median response was reported as a measure of central tendency. Statistical analysis of responses between two data sets used Mann-Whitney U, whilst analysis between three or more groups used Kruskal-Wallis test, with a p value <0.05 denoting statistical significance. Where Kruskal-Wallis test was used, Dunn's Multiple Comparison Test was subsequently used to compare individual groups. Quantitative data is also presented using descriptive statistics.

Results

First stage qualitative survey

A total of 108 responses were collected from participants in 23 countries (Figure 1). Most respondents were male (79/108; 73%). The modal age group was 30–39 (47/108; 44%), followed by 20–29 (31/108; 29%), 40–49 (16/108; 15%), 50–59 (6/108; 6%), and ≥60 (3/108; 3%). Occupation was reported as neurosurgeon (43/108; 40%), anaesthetist (39/108; 36%), and operating room nurse (26/108; 24%). BCIs had been encountered in a range of settings by other respondents, including in scientific literature (31/108; 29%), media including social media, television, and the internet (20/108; 19%), and clinical practice (6/108; 6%). Half of respondents (54/108; 50%) had not encountered BCIs before in any context.

Participants were asked about their current understanding of BCIs (Table 1; Supplemental Material 1) and 56% reported a poor baseline knowledge of BCI. The responses were coded into four main themes: (1) basic understanding; (2) potential applications; (3) implications for neurosurgery; (4) emotional reaction to BCI.

Respondents were able to identify that BCIs *"…allow their users to communicate or control external devices"* and that BCIs used *"signals from the brain"*. No participants were able to describe in detail the mechanisms of BCI data extraction or command output. Respondents noted numerous potential applications of BCI, including controlling *"…muscle groups, prosthetics, or an external thing like a cursor [to] allow users to communicate or control external devices"*. Several respondents also highlighted the potential for BCIs to be used in certain disease targets, such as in neurodegenerative disease, paralysis, or in amputees. A small proportion of respondents mentioned that BCIs may improve the safety of neurosurgical operations, interestingly focusing on the use of BCI from the surgeon's perspective rather than that of the patient. One participant noted the wide-ranging effects that BCI may have upon neurosurgery, writing *"…a new era of human future life minimising disability and improving life quality"*. Numerous participants exhibited positive emotive reactions including listing BCIs as "*good*", a "*great thing*", a "*highly promising field*", and technology that "*can help hugely*".

Participants were asked about the anticipated advantages of BCIs (Table 1; Supplemental Material 1). Many named at least one proposed benefit of BCIs (95/108; 88%). The most common theme of BCI advantages was disease targets, including spinal cord injury, locked-in syndrome, and traumatic brain injury. Other reported uses included restorative movement, use of prostheses, restoration of special senses, and promotion of neuroplasticity and rehabilitation. Another theme for BCI advantages was intraoperative assistance, including intraoperative cortical mapping and patient assessment. Anaesthetic respondents highlighted how BCIs may be used as a technological adjunct in *"assessment of neural activity during or after surgery, [and] assessing anaesthetic depth"*. Several participants mentioned the technical advantages that invasive BCI confers over its non-invasive counterparts, such as constant monitoring of neural activity compared to when users must wear surface electrodes. Another reported advantage of BCI was the impact on quality of life; one respondent commented that BCI may *"…support users with disabilities in everyday* *and professional life, and increase collaboration in building their communities."*, whilst others mentioned the significant impact that BCI may have in *"improvement in quality of life…particularly around regaining independence"*.

Over half of respondents (58/108; 54%) expressed concerns when questioned about insertion of a BCI system in the final open question (Table 1; Supplemental Material 1). Thematic analysis of potential concerns derived four themes: (1) short-term complications; (2) long-term complications; (3) lack of experience with BCI technology; (4) ethics, security, and other concerns. Respondents frequently mentioned immediate intraoperative and postoperative complications such as infection, bleeding, seizures, delayed recovery, and the effect of BCI implantation upon anaesthetics. Long-term complications reported included the effect of BCI implant upon brain tissue, migration and longevity of BCI implants, and the potential need for reoperation. Central to the complications was the subjective inexperience with such a novel technology and a lack of surgical experience inserting BCIs. One respondent summarised many responses by writing *"…because its [BCIs] theoretical and not widely tested…we still don't know what complications could arise; in the short-term or long-term, neurologically"*. Other concerns related to the 'hype' around BCIs, noting that they may not live up to their suggested promise, or have little clinical impact. Ethical concerns related to data security such as the hacking of hardware and access to personal data, which patient groups would be permitted BCI, and who would make that decision. It should be noted that almost half of respondents (50/108; 46%) did not highlight any concerns.

Second stage quantitative survey

A total of 538 responses from 32 different countries were obtained (Figure 1; Table 3). Most respondents were male (334/538; 62%), with the modal age group being 30–39 (200/538; 37%). Baseline understanding of BCI from the 538 respondents was poor, similar to the first stage survey (Figure 2). The proportion of respondents with a 'good' or 'expert' understanding of BCIs was low amongst all specialties: neurosurgeons (15%); anaesthetists (9%); operating room nurses (6%). The difference in baseline knowledge of BCIs between specialty groups was found to be statistically significant ($p < 0.0001$, Kruskal-Wallis test), with neurosurgeons having a statistically significantly greater rank than anaesthetists (Dunn's Multiple Comparison Test, $p<0.05$), who in turn had a greater rank than operating room nurses (Dunn's Multiple Comparison Test, $p<0.05$).

The second stage quantitative survey posed six different scenarios detailing different applications of invasive BCI (Table 2). For each scenario, participants answered two questions: "Do you agree or disagree that this is an appropriate use of BCI?", and "Would you be happy to be involved as a member of the surgical team in this example of a BCI?" (Supplemental Material 2). Scenarios 1-3 related to rehabilitative applications of BCI in patients with a deficit. Scenarios 4-6 related to augmentative BCI applications in healthy individuals.

The respondents were largely in agreement for BCIs relating to rehabilitative purposes (83% "agree" or "strongly agree"), compared to a BCI for the augmentative application in healthy individuals (38% "agree" or "strongly agree") (Figure 3). Although there was overall agreement for the rehabilitative BCI applications (scenario 1-3), there remained a minority (4%) of the neurosurgical team that "strongly disagree" or "disagree" with this application (Figure 3). Further, the augmentative applications of BCI evoked a higher percentage of "strongly disagree" and "disagree" for an augmentative BCI to control computer software (scenario 4; 38%), a BCI developed by a private social media company (scenario 5; 48%), and a BCI developed for military use (scenario 6; 38%).

The degree to which members of the neurosurgical team were happy to place an implant mirrors the agreeability for the intended application of the discussed BCI (Figure 4). Respondents were happier to be involved with the neurosurgical team for rehabilitative BCI implantation (scenarios 1-3), than for augmentative BCI implantation (scenarios 4-6). For example, 84% of respondents "agreed" or "strongly agreed" that they would be happy to insert the BCI to assist with speech following a stroke as part of a cranioplasty operation, compared to 45% of respondents who "disagreed" or "strongly disagreed" to be a part of the team inserting an augmentative BCI developed by a private social media company (Figure 4).

Willingness of the neurosurgical team to participate in BCI insertion differed by specialty (Figure 5). Neurosurgeons were happier to insert rehabilitative BCIs than anaesthetists and operating room nurses as demonstrated by the highest proportion of "strongly agree" or "agree" across scenarios 1 – 3 (Figure 5). For these scenarios, neurosurgeons responded with an average of 86% "strongly agree" or "agree" to involvement as a member of the neurosurgical team, compared to 78% of anaesthetists, and 77% of operating room nurses. Anaesthetists were more willing to be involved in insertion of augmentative BCIs (average 44% "strongly agree" or "agree") than neurosurgeons (39%) and operating room nurses (36%).

Subgroup analysis by age group did not reveal any significant trends. Respondents from older age groups were more likely to have heard of BCIs, 50% of <20, and 43% of those aged 20–29 reporting never having heard of BCIs, compared to 35% of ≥60 year olds, and 31% of those aged 50 – 59 (Supplementary Figure 1). Age did not significantly affect perception of appropriateness of BCI application (Supplementary Figure 2) nor willingness to participate in surgical insertion.

Subgroup analysis by reported level of BCI understanding revealed that individuals who reported having a 'Good' or 'Expert' understanding of BCIs were statistically significantly more willing to participate in BCI insertion compared to those who had 'Never heard of BCIs' ($p < 0.05$, Mann Whitney U) (Supplementary Figure 3). This significant difference was true for all cases.

Discussion

Key findings

To our knowledge, this study presents the most comprehensive cross-sectional analysis of international neurosurgical teams' attitudes towards BCIs to date, with over 600 participants from 32 countries. Our two-stage survey elicited qualitative viewpoints regarding invasive BCIs, followed by a quantitative analysis of baseline knowledge, assessment of BCI applications, and willingness to participate in implantation of BCIs.

A key finding from the first stage qualitative survey was the limited baseline understanding of BCIs amongst the neurosurgical team. Only 10% of neurosurgeons had a subjective "good" or "expert" understanding of BCIs. However, respondents were generally aware of the potential benefits like the positive impact on disease targets, such as spinal cord injury, locked-in syndrome, traumatic brain injury and rehabilitative medicine. Further, respondents felt that BCIs had the potential to impact psychosocial aspects of patients' lives and empower such patients to engage meaningfully in society. Respondents reported their concerns relating to the short- and long-term complications, their lack of experience with BCI technology including surgical technique, and the ethics and data security of BCIs.

The second stage quantitative survey presented six scenarios describing rehabilitative and augmentative applications of BCIs to the neurosurgical team. Respondents ranked the appropriateness of the BCI application and their willingness to be a part of the team inserting such BCIs. Scenarios were derived from real-world and anticipated examples of BCI technology, including speech assistance,[28–30] prosthesis control,[9,31] control of computer software, gaming and social media use,[32,33] and military use.[34] Respondents were agreeable to rehabilitative BCI applications, such as for speech generation and prosthesis control, and this was reflected in their willingness to be part of the surgical team inserting such BCIs (>80% for each role). However, respondents were much less agreeable to augmentative BCI applications, such as military use and private social media companies. The data suggests that the neurosurgical teams concern about being involved in BCI implantation correlates primarily with their ethical stance on the morality of the procedure. Furthermore, our data suggests that limited knowledge of BCIs correlates with unwillingness to participate in BCI insertion.

BCIs are a novel technology which divides the opinion of clinicians. Even the least controversial BCI applications have a significant minority disagreeing with their applicability, such as the rehabilitative use of a BCI to aid speech restoration following a stroke. Scoping clinician acceptability for BCI application is essential, as private industry battles to advance the BCI market.[1] However, clinicians must engage with the decision-making process, as currently clinician input has been limited. For example, the Asilomar Survey surveyed 145 BCI researchers, of whom only a small proportion were clinicians.[35] Further, recent literature detailing the IDEAL-D (Idea, Development, Exploration, Assessment, Long-term study-Device) framework for device innovation states that device perspectives, patient perspectives, and systems perspectives, in addition to the clinicians perspective must be considered.[36] Further work must address the ethical considerations of BCI technology, and will likely require international collaboration to undertake patient public involvement involving legislators, social scientists, medical ethicist – indeed society as a whole. Similarly, regulatory legislation must keep up with the speed of development. The US Food and Drug Administration (FDA) published non-binding, regulatory guidance for implantable BCIs to help accelerate medical uses of the technology.[37] This is the first example of a regulatory agency focusing explicitly on BCIs, however regulation regarding augmentative BCIs in crucially missing. Future guidelines and regulations must also consider the ethical approaches to novel device innovation to enable safe advancement, whilst providing a regulatory environment that encourages innovation and drives forward BCI technology.[38,39]

Comparison with the literature

There have been few studies examining clinician acceptability of BCIs, and none specifically examining invasive BCI. Letourneau *et al*. give the most detailed account of clinician views to date, in their cross-sectional survey of 137 physicians directly caring for patients with severe neurological disability in Canada, assessing clinician knowledge and potential impact of BCIs.[40] Amongst their findings was a general lack of knowledge regarding BCIs, coupled with prediction from participants that BCIs stand to positively impact a large number of patients.[40] Nijboer *et al*. published results from their Asilomar Survey in 2011, a qualitative survey conducted at an international BCI conference in the United States, drawing upon views from a wide range of the multidisciplinary team including PhD students, computer scientists, neuroscientists, and engineers - a small proportion of respondents were clinicians.[35] Grubler *et al*. surveyed BCI professionals, including researchers, patients, and three clinicians, and identified themes such as concerns regarding consent and data breaches, high expectations of BCIs, and concerns about the use of BCI in non-medical contexts.[41] Whilst such publications provide valuable insight, they do not dissect the views of the core team responsible for the surgical implantation of BCIs. Other publications have not focused on clinicians.[35,42,43]

At present, the tariff of disease states BCIs stand to positively impact is largely unknown, with real-world applications limited to only a few practical applications. Letourneau *et al*. aimed to calculate the scope of disease states that may benefit from BCI.[40] Their team focused on a pre-defined set of diseases in order to calculate potential impact.[40] Based on their criteria, an estimated 13,000 – 32,000 individuals in Canada stand to benefit from BCIs (approximately 3.6 – 8.9 per 10,000 when extrapolated to their population).[40] However, whilst this *a priori* assessment of disease targets may undoubtedly benefit from invasive BCI, numerous potential applications may have gone undetected. These "unknown unknowns" mean that the scope of BCI applicability may be undervalued. Furthermore, as the authors note, their estimates for prevalence of certain neurological disease targets was below nationwide prevalence reports, again suggesting that the impact of BCI may be greater than expected.[40] As previously discussed, the neurosurgical team are uniquely placed to evaluate the risk-benefit ratio of BCI insertion, given their frontline experience of complications. These findings are key in the clinical translation of BCI technology – research has demonstrated that clinician acceptability plays a significant role in the clinical impact of a technology, and has wider implications for the direction of research.[44,45]

Strengths and limitations

This survey is the largest exploration of the neurosurgical team towards BCI acceptability. It adheres to robust methodology following precedence from the literature[20,21]. We also consider the multidisciplinary team of neurosurgeons, anaesthetists, and operating room staff, who will be responsible for the implantation of BCI.

This study has several limitations. Both qualitative and quantitative surveys were distributed in English language only, which may result in selection bias, and makes true international review unattainable. Similarly, geographic response rate was not proportionate across continents, with a marked predominance of responses from Asia (42%) and Europe (34%). Whilst sampling of respondents was random, those with an interest in BCI may have been more likely to complete the survey, resulting in responder bias. However, our findings were largely consistent with existing data on BCI acceptability which suggests a certain degree of external validity.

Conclusion

To our knowledge, this is the most comprehensive assessment of the neurosurgical team relating to BCIs. The neurosurgical team has limited baseline understanding of BCIs but are aware of the potential benefits. The neurosurgical team were agreeable to rehabilitative applications of BCI. Augmentative BCI applications remain more controversial than rehabilitative applications, yet our data highlights a significant proportion of the neurosurgical team are open to augmentative BCI. The range of views on which BCI use cases were appropriate highlights the urgent need for stakeholder consultation to guide BCI implantations in their infancy. Government, regulators and professional bodies should engage with patient groups and the public to draft regulation and guidelines to govern BCI implantation as it moves forward.

Disclosures of interests

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Data statement

Raw data is available to access on request.

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Figure 6 was produced by Amy Warnock at the Wellcome / EPSRC Centre for Interventional and Surgical Sciences, University College London.

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Figure Legend

Figure 1: study methodology flow diagram.

Figure 2: Baseline understanding of BCIs amongst the neurosurgical team: *"How would you rate your current understand of brain-computer interfaces?"*

Figure 3: Responses of participants to the question *"Do you agree or disagree that this is an appropriate use of BCI?"* for BCI case vignettes

Figure 4: Responses of participants to the questions *"Would you be happy to be involved as a member of the surgical team in this example of a BCI?"* for BCI case vignettes

Figure 5: Responses by speciality to the question *"Would you be happy to be involved as a member of the surgical team in this example of a BCI?"* for BCI case vignettes

Figure 6: schematic overview of invasive and non-invasive BCI with existing outputs.

Supplementary Figure 1: Baseline understanding of BCIs amongst the neurosurgical team by age group: *"How would you rate your current understanding of brain-computer interfaces?"*

Supplementary Figure 2: Responses by age group of participants to the question *"Do you agree or disagree that this is an appropriate use of BCI?"* for BCI case vignettes

Supplementary Figure 3: Responses by baseline knowledge of BCIs to the questions *"Would you be happy to be involved as a member of the surgical team in this example of a BCI?"* for case vignettes.

* = $p < 0.05$, Mann Whitney U

Table 1. Qualitative survey blank space questions.	
Q1	Have you encountered brain-computer interfaces (BCIs) before, and if so, in what context? (Clinical practice, scientific literature, newspapers and magazines etc.)
Q2	What is your current understanding of BCIs?
Short explanation on BCIs (see Supplemental Material 1).	
Q3:	What do you think the main advantages of intracranial BCIs in neurosurgery may be? Can you give any examples?
Q4:	Would you have any concerns if your team was asked to insert an invasive BCI? If yes, what would they be?

Table 2. Quantitative survey case vignettes.	
Case 1:	*A patient undergoes a decompressive craniectomy following a malignant cerebral infarct and is now unable to verbally communicate. The patient is scheduled for cranioplasty (replacement of the bony defect with a titanium plate). An invasive BCI is planned to be inserted during the same operation. The invasive BCI will detect neural signals and help the patient communicate through 'thought-to-speech'.*
Case 2:	*A patient who has suffered a stroke is unable to verbally communicate. An invasive BCI is planned for insertion to help this patient communicate. Electrode grids will be placed over the patient's cerebral cortex which detect neural signals associated with speech, which will then be decoded to generate an audio output, in a 'thought-to-speech' mechanism. Insertion will require a general anaesthetic and drilling through the skull to access the brain.*
Case 3:	*An amputee plans to have an invasive BCI inserted to assist in control of a prosthesis. Neural signals corresponding to the specific desired movements will be detected and interpreted, resulting in coordinated movement of a forearm and hand prosthesis. Insertion will require a general anaesthetic and drilling through the skull to access the brain.*
Case 4:	*A healthy individual is planned to have a commercial invasive BCI fitted that enables them to control and interact with computer software using neural activity. Insertion will require a general anaesthetic and drilling through the skull to access the brain.*
Case 5:	*A social media company develops an invasive BCI which better enables users to access and interact with numerous software, including enhanced interaction with online games, social media, and virtual reality environments. Insertion will require a general anaesthetic and drilling through the skull to access the brain.*
Case 6:	*An invasive BCI is developed to enable military personnel to communicate with one-another without verbalising speech. Insertion requires general anaesthetic and drilling through the skull to access the brain.*

Table 3. Quantitative survey baseline characteristics	
Gender	
Male	334/538 (62%)
Female	192/538 (36%)
Prefer not to say	7/538 (1%)
Non-binary	4/538 (1%)
Occupation	
Neurosurgeon	237/538 (44%)
Anaesthetist	153/538 (28%)
Operating Room Nurse	148/538 (28%)
Age group	
<20	12/538 (2%)
20 – 29	157/538 (29%)
30 – 39	200/538 (37%)
40 – 49	113/538 (21%)
50 – 59	39/538 (7%)
≥60	17/538 (3%)
Response by Continent	
Asia	224/538 (42%)
Europe	182/538 (34%)
Africa	94/538 (17%)
North America	35/538 (7%)
South America	3/538 (1%)

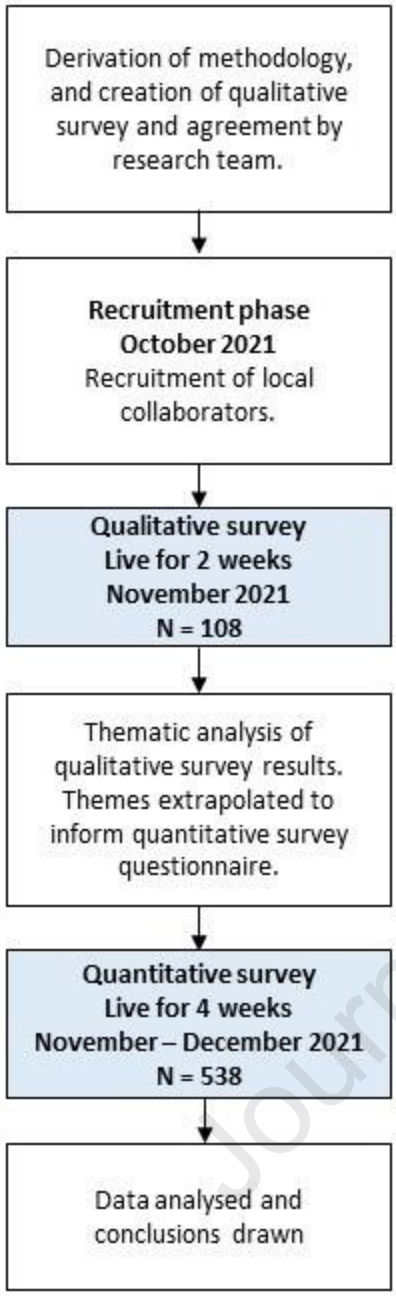


Figure 1: study methodology flow diagram.

Figure 2: Baseline understanding of BCIs amongst the neurosurgical team*: "How would you rate your current understanding of brain computer interfaces?"*

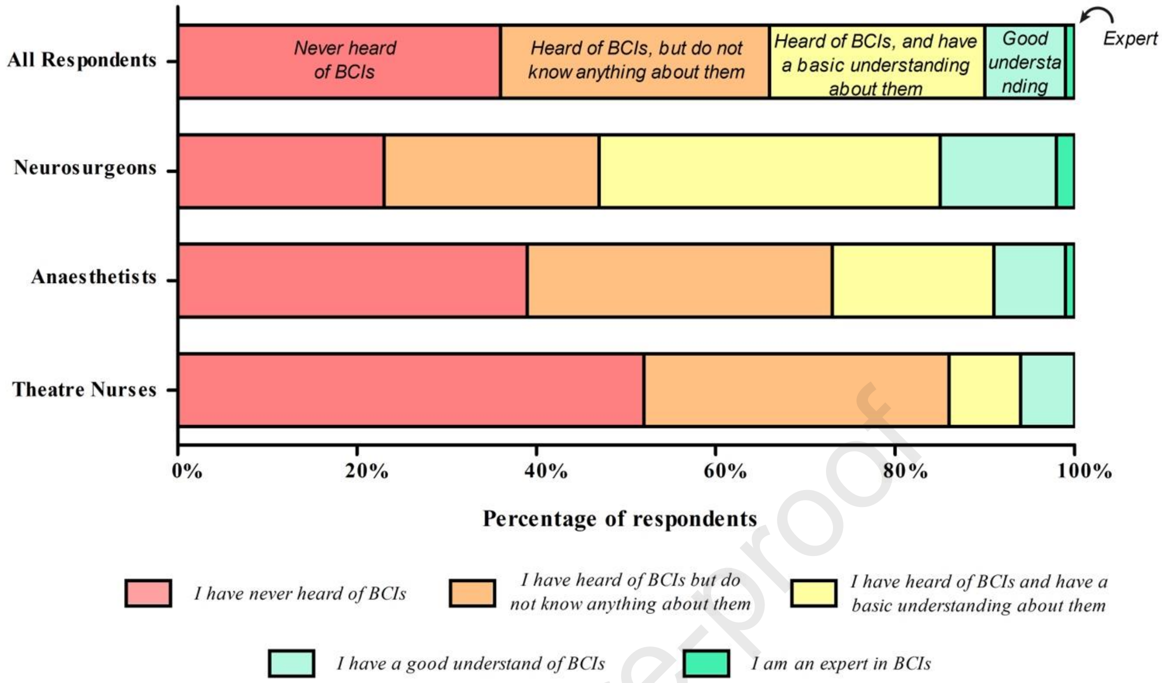


Figure 3: Responses of participants to the question *"Do you agree or disagree that this is an appropriate use of BCI?"* for BCI case vignettes

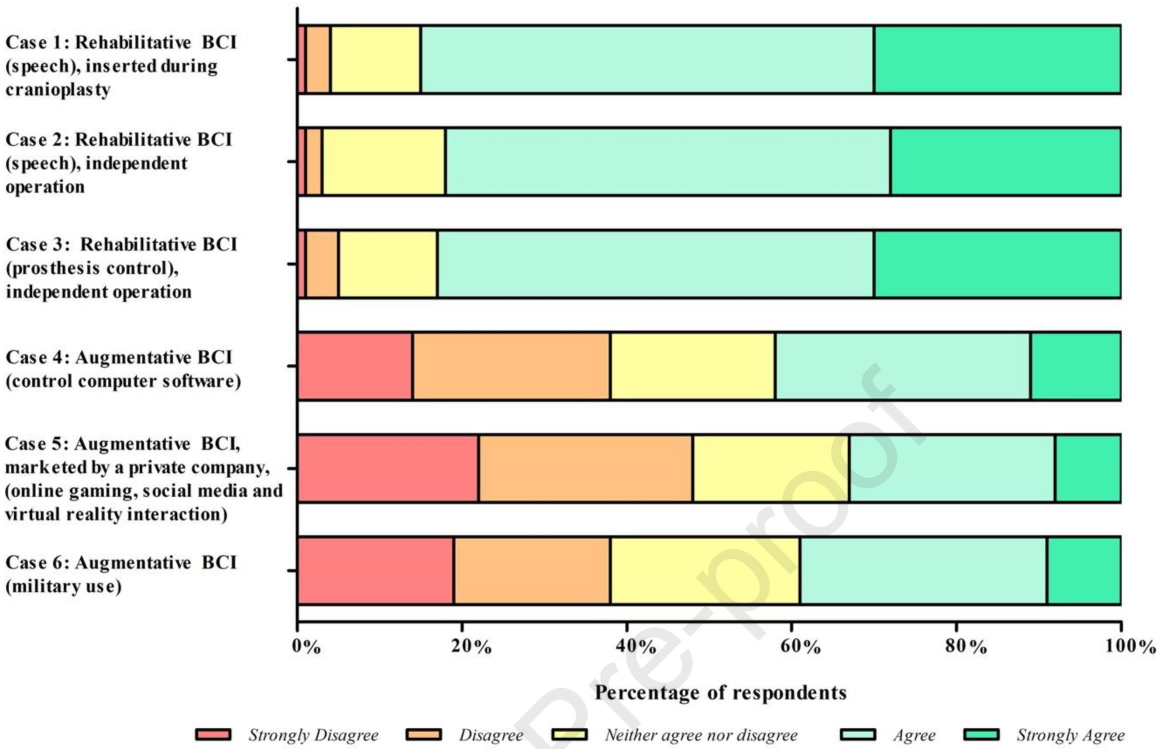


Figure 4: Responses of participants to the question *"Would you be happy to be involved as a member of the surgical team in this example of a BCI?"* for BCI case vignettes

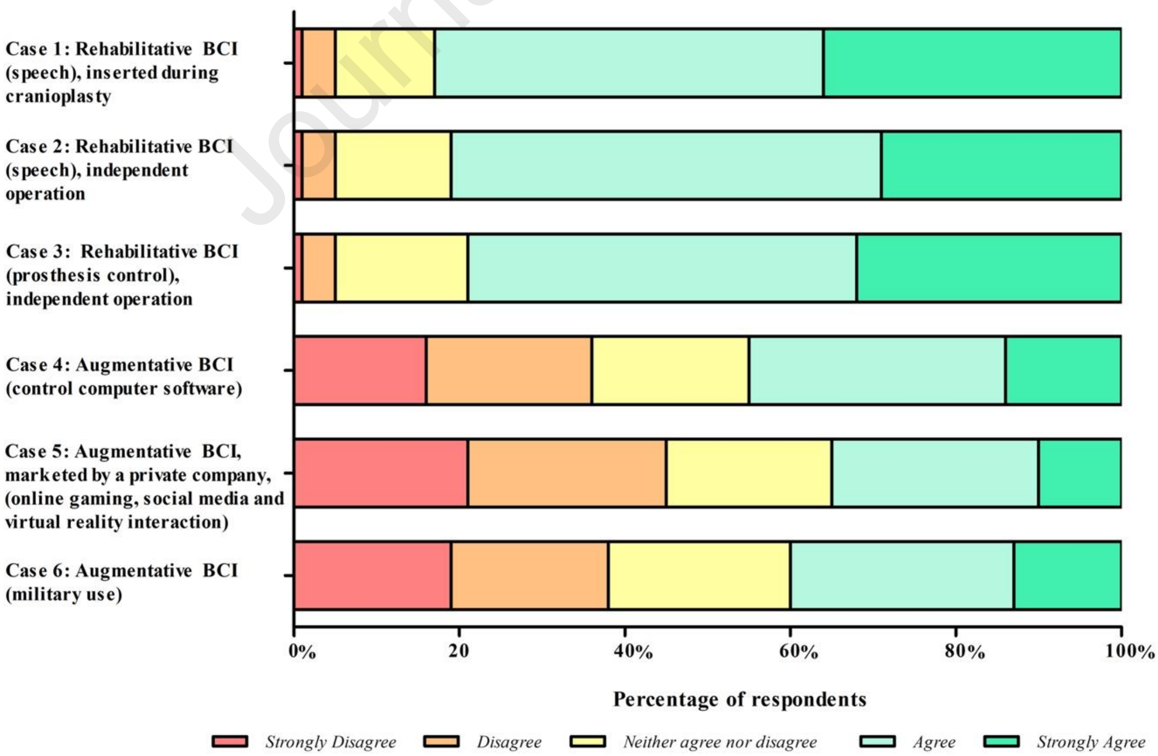
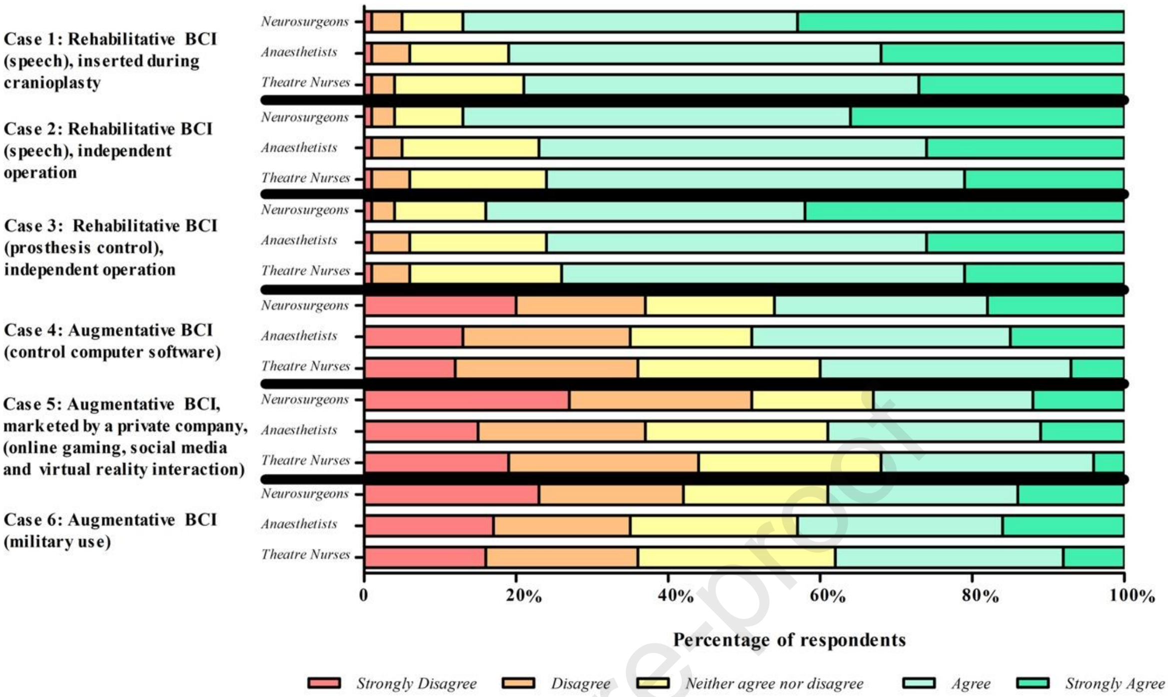


Figure 5: Responses by speciality to the question *"Would you be happy to be involved as a member of the surgical team in this example of a BCI?"* for BCI case vignettes



Abbreviations:

BCI: brain computer interface

ECoG: Electrocorticography

EEG: Electroencephalography

FDA: Food and Drug Administration

IDEAL-D: Idea, Development, Exploration, Assessment, Long-term study – Device

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