Editor summary:

On the centenary of the first human EEG recording more than 500 experts reflect on the impact this discovery has had on our understanding of brain and behaviour.

100 years of EEG for brain and behaviour research

Faisal Mushtaq[1,2†], Dominik Welke[1], Anne Gallagher[3,4], Yuri G. Pavlov[5], Layla Kouara[1], Jorge Bosch-Bayard[6], Jasper J. F. van den Bosch[1], Mahnaz Arvaneh[7], Amy R. Bland[8], Maximilien Chaumon[9], Cornelius Borck[10], Xun He[11], Steven J. Luck[12], Maro G. Machizawa[13,14], Cyril Pernet[15], Aina Puce[16], Sidney Segalowitz[17], Christine Rogers[18,19], Muhammad Awais[20], Claudio Babiloni[21,22], Neil W. Bailey[23], Sylvain Baillet[18], Robert C. A. Bendall[24], Daniel Brady[25], Maria L. Bringas-Vega[26], Niko Busch[27], Ana Calzada-Reyes[28], Armand Chatard[29,30], Peter E. Clayson[31], Michael X. Cohen[32,33], Jonathan Cole[34], Martin Constant[35], Alexandra Corneyllie[36], Damien Coyle[37,38], Damian Cruse[39], Ioannis Delis[40], Arnaud Delorme[41,42], Damien Fair[43], Tiago H. Falk[44], Matthias Gamer[45], Giorgio Ganis[46], Kilian Gloy[47], Samantha Gregory[48], Cameron Hassall[49], Katherine Hiley[1], Richard B. Ivry[50], Karim Jerbi[51,52], Michael Jenkins[53], Jakob Kaiser[54], Andreas Keil[55], Robert T. Knight[50], Silvia Kochen[56], Boris Kotchoubey[5], Olave Krigolson[57], Nicolas Langer[58], Heinrich R. Liesefeld[59], Sarah Lippé[51], Raquel E. London[60], Annmarie MacNamara[61], Scott Makeig[62], Welber Marinovic[63], Eduardo Martínez-Montes[28], Aleya A. Marzuki[64], Ryan K. Mathew[65,66], Christoph Michel[67], José d. R. Millán[68,69], Mark Mon-Williams[1], Lilia Morales-Chacón[70], Richard Naar[71], Gustav Nilsonne[72], Guiomar Niso[73], Erika Nyhus[74], Robert Oostenveld[75,72], Katharina Paul[76], Walter Paulus[77,78], Daniela M. Pfabigan[79], Gilles Pourtois[80], Stefan Rampp[81,82], Manuel Rausch[83,84], Kay Robbins[85], Paolo M. Rossini[86], Manuela Ruzzoli[87,88], Barbara Schmidt[89], Magdalena Senderecka[90], Narayanan Srinivasan[91], Yannik Stegmann[45], Paul M. Thompson[92], Mitchell Valdes-Sosa[28], Melle J. W. van der Molen[93], Domenica Veniero[94], Edelyn Verona[31], Bradley Voytek[95], Dezhong Yao[26,96], Alan C. Evans[18,19], Pedro Valdes-Sosa[26,28]

[1]School of Psychology, University of Leeds, Leeds, UK, [2]NIHR Leeds Biomedical Research Centre, Leeds, UK, [3]Université de Montréal, Montreal, Canada, [4]Sainte-Justine University Hospital Research Center, Montreal, Canada, [5]Institute of Medical Psychology and Behavioral Neurobiology, University of Tübingen, Tübingen, Germany, [6]Facultad de Psicología, Universidad Autonoma de Madrid, Madrid, España, [7]Department of Automatic Control and Systems Engineering, University of Sheffield, Sheffield, UK, [8]Department of Psychology, Health and Social Care, Manchester Metropolitan University, Manchester, UK, [9]Institut du Cerveau, CNRS, Sorbonne Université, Paris, France, [10]Institute of Medical History and Science Research, Universität zu Lübeck, Lübeck, Germany, [11]Department of Psychology, Bournemouth University, Bournemouth, UK, [12]Center for Mind and Brain, UC Davis, California, USA, [13]Xiberlinc Inc., Tokyo, Japan, [14]Tokyo Medical and Dental University, Tokyo, Japan, [15]Neurology and Neurobiology Research Unit, Copenhagen University Hospital, Copenhagen, Denmark, [16]Department of Psychological and Brain Sciences, Indiana University, Bloomington, Indiana, USA, [17]Department of Psychology, Brock University, Ontario, Canada, [18]Montreal Neurological Institute, McGill University, Montreal, Canada, [19]McGill Centre for Integrative Neuroscience, McGill University, Montreal, Canada, [20]School of Computing Sciences, University of East Anglia, Norwich, UK, [21]Department of Physiology and Pharmacology, Sapienza University of Rome, Rome, Italy, [22]Hospital San Raffaele Cassino, Cassino, Frosinone, Italy, [23]School of Medicine and Psychology, The Australian National University, Canberra, Australia, [24]School of Health and Society, University of Salford, Salford, UK, [25]School of Computer Science, University of Sheffield, Sheffield, UK, [26]The Clinical Hospital of Chengdu Brain Science Institute, University of Electronic Science and Technology of China, Chengdu, China, [27]Institute of Psychology, University of Münster, Münster, Germany, [28]Cuban Center for Neuroscience, Playa, Havana, Cuba, [29]Universite´ de Poitiers, Poitiers, France, [30]Centre National de la Recherche Scientifique, France, [31]Department of Psychology, University of South Florida, Florida, USA, [32]Sincxpress Education, [33]Donders Institute, Nijmegen, The Netherlands, [34]University Hospital Dorset, NHS Foundation Trust, Poole, UK, [35]Faculté de Psychologie et des Sciences de l'Education, Université de Genève, Geneva, Switzerland, [36]Lyon Neurosience Research Centre, Lyon, France, [37]The Bath Institute for the Augmented Human, University of Bath, Bath, UK, [38]School of Computing, Engineering and Intelligent Systems, Ulster University, Ulster, UK, [39]School of Psychology, University of Birmingham, Birmingham, UK, [40]School of Biomedical Sciences, University of Leeds, Leeds, UK, [41]Swartz Center of Computational Neuroscience, UC San Diego, California, USA, [42]Centre de Recherche Cerveau et Cognition, Toulouse III University, Toulouse, France, [43]Institute of Child Development, University of Minnesota, Minneapolis, Minnesota, USA, [44]INRS-EMT, University de Quebec, Quebec, Canada, [45]Department of Psychology, University of Würzburg, Würzburg, Germany, [46]School of Psychology, University of Plymouth, Plymouth, UK, [47]Institute of Psychology, University of Bremen, Bremen, Germany, [48]School of Health & Society, University of Salford, Salford, UK, [49]Department of Psychology, MacEwan University, Edmonton, Alberta, Canada, [50]Department of Psychology, UC Berkeley, California, USA, [51]Psychology Department, Université de Montréal, Montreal, Canada, [52]UNIQUE, Quebec & Mila, Quebec, Canada, [53]School of Medical and Life Sciences, Sunway University, Kuala Lumpur, Malaysia, [54]Department of Psychology, Ludwig Maximilian University Munich, Munich, Germany, [55]Department of Psychology, University of Florida, Florida, USA, [56]Studies in Neuroscience and Complex Systems (ENyS), CONICET, Buenos Aires, Argentina, [57]Centre for Biomedical Research, University of Victoria, Victoria, BC, Canada, [58]Department of Psychology, University of Zurich, Zurich, Switzerland, [59]Department of Psychology, University of Bremen, Bremen, Germany, [60]Department of Experimental Psychology, Ghent University, Ghent, Belgium, [61]Institute for Neuroscience, Texas A&M University, Texas, USA, [62]Swartz Center for Computational Neuroscience, UC San Diego, California, USA, [63]School of Psychology, Curtin University, Perth, Australia, [64]Department for Psychiatry and Psychotherapy, University of Tübingen, Tübingen, Germany, [65]School of Medicine, University of Leeds, Leeds, UK, [66]Leeds Teaching Hospitals NHS Trust, Leeds, UK, [67]Departments of Clinical and Basic Neurosciences, University of Geneva, Geneva, Switzerland, [68]Department of Electrical & Computer Engineering, The University of Texas at Austin, Austin, Texas, USA, [69]Department of Neurology, The University of Texas at Austin, Austin, Texas, USA, [70]International Center for Neurological Restoration, Havana, Cuba, [71]Institute of Psychology, University of Tartu, Tartu, Estonia, [72]Department of Clinical Neuroscience, Karolinska Institutet, Stockholm, Sweden, [73]Cajal Institute, CSIC, Madrid, España, [74]Department of Psychology, Bowdoin College, Maine, USA, [75]Donders Institute for Brain, Cognition and Behaviour, Radboud University, Nijmegen, The Netherlands, [76]Faculty of Social Sciences, University Hamburg, Hamburg, Germany, [77]Department of Neurology, Ludwig-Maximilians University Munich, Munich, Germany, [78]University Medical Center Göttingen, Göttingen, Germany, [79]Department of Biological and Medical Psychology, University of Bergen, Bergen, Norway, [80]Faculty of Psychology and Educational Sciences, Ghent University, Ghent, Belgium, [81]Department of Neurosurgery, University Hospital Erlangen, Erlangen, Germany, [82]University Hospital Halle (Saale), Halle, Germany, [83]Faculty Society and Economics, Rhine-Waal University of Applied Sciences, Kleve, Germany, [84]Department of Psychology, Catholic University of Eichstätt-Ingolstadt, Eichstätt, Germany, [85]Department of Computer Science, The University of Texas at San Antonio, Texas, USA, [86]Department of Neuroscience & Neurorehabilitation, IRCCS San Raffaele Roma, Rome, Italy, [87]Basque Center on Cognition Brain & Language, San Sebastian, España, [88]Basque Foundation for Science, Bilbao, España, [89]Institute of Psychosocial Medicine, Psychotherapy and Psychooncology, Jena University Hospital, Jena, Germany, [90]Institute of Philosophy, Jagiellonian University, Kraków, Poland, [91]Department of Cognitive Science, Indian Institute of Technology Kanpur, Kanpur, India, [92]Keck School of Medicine, University of Southern California, California, USA, [93]Institute of Psychology, Leiden University, Leiden, The Netherlands, [94]School of Psychology, University of Nottingham, Nottingham, UK, [95]Department of Cognitive Science, UC San Diego, California, USA, [96]Center for Information in Medicine, School of Life Science and Technology, University of Electronic Science and Technology of China, Chengdu, China

[†]Correspondence can be addressed to Faisal Mushtaq (email: f.mushtaq@leeds.ac.uk) and Pedro Valdes-Sosa (email: pedro.valdes@neuroinformatics-collaboratory.org)

Standfirst (360 characters): On the centenary of the first human EEG recording more than 500 experts reflect on the impact this discovery has had on our understanding of brain and behaviour. We document their priorities and call for collective action focusing on validity, democratization and responsibility, to realise the potential of EEG in science and society over the next 100 years.

On 6 July 1924, psychiatrist Hans Berger found himself in an operating room in Jena, Germany, with the neurosurgeon Nikolai Guleke. Here, Berger made the first recording of spontaneous electrical activity from a human brain, which would lead to the development of modern electroencephalography (EEG; see Box 1). One hundred years later, we surveyed over 500 experts from over 50 countries (https://www.eeg100.org/survey), asking them to reflect on the impact of EEG on our understanding of brain function and dysfunction and where the community should prioritise efforts to maximise the impact of EEG. We also prompted them to speculate on EEG's evolving role in neuroscience and society for the next 100 years. Our commentary draws upon these responses and ends with a call to action, pushing for collective action to realise EEG's full potential.

History & Impact

In an era where physiologists worked at the level of cells and fibres, placing two electrodes on the brain's surface seemed an absurd endeavour. Berger, engaged in a lifelong search for biomarkers of "mental energy", was undeterred and, after years of toil, he made his breakthrough.

While 1924 marked the year of discovery, a self-doubting Berger did not publicly reveal it to the world until 1929[1]. In the intervening period, he undertook hundreds of experiments, extending his observations from direct recordings from the brain to the scalp. While the scientific community hesitated to embrace the discovery, the popular press wasted no time, coining the term "brain script" ("Hirnschrift") to describe the waveforms captured by Berger's galvanometer. Public discourse in the Weimar Republic reflected their excitement, with fantastical ideas on its potential—from telepathy to judging a horse's temperament[2]. Perhaps, above all, the discovery brought an expectation that this unprecedented empirical access to a living human brain might help unravel the mysteries of the mind.

It was, however, left for Lord Adrian, Nobel laureate and physiologist extraordinaire, to turn the scientific doubters into believers. Together with B.H.C. Matthews, Adrian replicated Berger's experiments in 1934[2], lighting the torch for a new field of study. Soon after, new laboratories started pushing boundaries. The neural characteristics of sleep were quickly defined, with Einstein as a famous subject in these early studies[2]. Similarly, epilepsy, previously seen as a personality trait, was repositioned as a disorder of electrophysiological brain activity. This work, pioneered by William Lennox, and Erna and Frederic Gibbs, was a considerable success for developing biomarkers of neurological disorders[3]. Quantitative analysis of EEG (qEEG) was born when Mary Brazier and Norbert Wiener modelled the EEG as a stochastic process using analogue computers[3]. These approaches were quickly superseded by digital computers, which opened the way for evoked potentials, (time-)frequency analysis, artifact rejection, and progress on topics currently popular such as brain age and normative modelling.

Reflecting on its history, our survey respondents reported that clinical diagnosis is where EEG has had its most significant impact. Today, EEG is supported by well-established scientific and professional societies that foster its use across the globe[4]. Indeed, it is often the only neuroimaging modality available in resource-limited clinical settings and remains the only imaging modality shown to be successful for mass screening of brain dysfunction[5].

--- INSERT FIGURE 1---

--- INSERT BOX 1---

The Future

To predict EEG's impact over the next century, we generated a list of potential developments, breakthroughs, and achievements, covering what we assumed to be critical to progress through to the highly improbable. Our respondents gave an estimate of when (if at all) each statement would be fulfilled.

Responses suggest that most predictions will be realised within the next couple of generations **(Figure 1)**. Some near-term ambitions have already been fulfilled within specific quarters. For example, EEG contributes to the diagnosis of sleep disorders and there are established standards and automatic analysis approaches for some clinical applications[3].

Other predictions seem only a few years away. The idea that consumer-grade hardware will become common, and that EEG could be used for reliable detection of brain abnormalities and pharmacological interventions are ostensibly within reach. Personalised neuromodulation therapies also seem a promising avenue for improving brain function in disease and accelerating learning and skill acquisition in healthy individuals. Moreover, there is an expectation that progressive diseases including neurodegenerative dementias, which initially manifest at the synaptic level, will find in advanced EEG techniques a tool for early detection.

As expected, the two boldest predictions, deciphering the contents of dreams and reading the contents of our long-term memory from EEG, elicited the most pessimistic responses.

--- INSERT FIGURE 2---

Priorities

Another objective of the survey was to identify the priorities of the EEG community for guiding future efforts.

All our proposed priorities reached a median rating of at least moderately important (**Figure 2**). Of these, improvements in qEEG tools (artifact cleaning, recording hardware, and analysis software) ranked highest. Standardisation emerged as another urgent priority, with a need for consensus on the protocols used for data acquisition as well as for signal processing and data analysis in basic and clinical science. Hardware manufacturers and software developers have an important role to play here, with interoperability across devices and packages needed to support the adoption of standards.

We propose that these priorities, together with the above predictions, should form a roadmap for the coming decades: technological advances will need to go hand in hand with community-agreed standards to optimise the future of EEG.

--- INSERT FIGURE 3---

A Call to Action

In addition to rating priorities and estimating predictions, we also invited survey respondents to offer their insights through free-text responses. Their comments indicate a degree of optimism that emerging technologies are opening exciting new possibilities for EEG. Increasingly affordable hardware, coupled with advances in AI, virtual reality, and brain-computer interfacing, holds immense potential for advancing our understanding of brain-behaviour relationships. These technologies could also fundamentally transform our interactions with the physical and digital world and contribute to addressing the global burden of brain disorders[7]. However, there was also a sense of frustration with slow progress. Although our respondents were generally confident that EEG's low cost, non- invasive nature, portability, and temporal resolution will secure its long-term future, it is striking that the development of EEG-based biomarkers for global brain health was seen as a more distant possibility. From the free-text responses, we also heard concerns—ranging from a lack of adherence to agreed standards and protocols for clinical and scientific practice to ethical questions created by novel commercial applications and the lure of 'neuroenhancement'.

We propose that for EEG to survive and thrive deep into the 22nd century and beyond, right now we must focus on the following aspects:

(i) **Validity**, established by ensuring our work is robust, reliable, replicable, and as reproducible as possible in both basic research and clinical settings;

(ii) **Democratization**, delivered through recognizing the importance of diversity of data to advance fundamental neuroscience and automation of processes to support the development of inclusive health policies;

(iii) **Responsibility**, considering issues of equity in access, privacy, and sustainability.

We elaborate on this manifesto below.

Validity

EEG has already proven its worth in several clinical settings. However, the lack of large open datasets annotated by experts has hindered the development and validation of new automated techniques and splintered the consolidation of research findings (but see[8]). In other fields such datasets have provided a foundation for machine learning and the application of AI—developments only starting in EEG. In research, large-scale investigations of EEG phenomena are underway[9]. Clinically oriented efforts, hampered by the progressive loss of clinician-academics specialising in EEG, are needed to generate large reproducible datasets that will be central to improving the diagnostic accuracy of new methods to address some of the highest priority items identified by our respondents. As such, it is surprising to see mixed perspectives towards open science practices. Solutions for sharing and archiving data ranked low but such efforts will be central to realising the most urgent priorities of improving methods and developing standards that are widely adopted.

We recommend:

- Pooling resources to generate large annotated open data repositories to facilitate discovery science and improve diagnostic applications.
- Continuing and accelerating community-driven efforts to implement standardised protocols for data collection, processing, and analysis to support reproducibility and improve replicability.

Democratization

Despite EEG being the most widely used direct measure of brain function, it is still not accessible to most of the world[4] and much of the scientific data come from a small number of countries and a small section of the population from therein. The EEG community, as elsewhere in science and society, is beginning to recognise the limitations that this lack of diversity brings. Recognizing the potential for bias, we sought to distribute the survey as widely as possible by extending beyond our personal networks, asking societies and device manufacturers to distribute the survey to their mailing lists to ensure broad and diverse participation. Despite this, the demographic of our final sample is noteworthy: most respondents work in universities in North America or Europe while lower and middle-income countries are poorly represented, participants in senior positions are generally male and only few participants are clinical workers or hard- and software engineers. If our sample is a reasonable reflection of the demographics of the EEG community, then such underrepresentation could have potentially negative consequences for the scientific and clinical importance of EEG, from understanding fundamental processes to interventions and evidence-based health-related policies[10].

The good news is that the field is well-positioned to tackle these challenges. Devices are becoming cheaper, more portable, and user-friendly. This is allowing scientists and clinicians to engage with communities traditionally excluded from EEG research. AI-driven automation, based on large representative datasets, could also help overcome the substantial barriers to accessing training and expertise to support interpretation in clinical settings. We believe these innovations will be important drivers in the acceptability and inclusivity of future applications of EEG and are excited by their potential to support our understanding of mechanisms of brain function in health and disease that represent all of society. The time is ripe for growing a more inclusive and diversified field of neuroscience.

We recommend:

- Leveraging the affordability and portability of new EEG devices to work with minoritised communities.
- Supporting international collaborations, networks and initiatives that can facilitate the global expansion of clinical and research activity; foster training programs, and resource sharing to build local expertise and infrastructure.

Responsibility

Ongoing and potential future developments also raise new ethical questions that resonate with pressing societal challenges. EEG has significant promise as a tool for supporting the delivery of population brain health for all[5]. Moreover, our collective predictions suggest that EEG may become embedded in everyday commercial technology within a generation.

Concerns around cognitive freedom and mental privacy must be addressed through regulation that prioritises protection from harm without limiting the benefits of open data[11].

With the expected proliferation of large-scale data that new low-cost and easily accessible consumer-oriented devices will bring, we must also consider the environmental costs of large-scale data acquisition (including waste management) and computing resources required for storing and processing those data and arrive at an approach that supports the long-term sustainability of our planet.

> We recommend:
>
> - Funders, institutes and individuals advocate for the development and use of environmentally friendly technologies and methods for data acquisition, storage, and processing, as well as for sharing and reuse of already recorded data to minimise EEG's ecological footprint.
> - The development of ethical guidelines and regulations to support equitable access to brain data as well as the protection of sensitive personal information.

Next Steps

While it is unlikely that any of the current authors will be around to evaluate the success of our predictions in one hundred years, we trust that the present work and accompanying survey data will serve as a time capsule in the scientific record. At the same time, we recognise that these results capture only a partial picture of perspectives. We welcome more: as a homage to the years between the discovery and public release, the survey will remain open for the next 5 years and responses will be made publicly available. As we move through this fourth industrial revolution, we hope this will provide an outlet for new and seldom-heard voices to share their hopes, concerns, and priorities.

More immediately, we invite the full spectrum of the neuroscience community—from academic, clinical and industry settings—to take up our call for action and commit to promoting robust, ethical, inclusive, and sustainable practices that will help realise a century of potential for EEG in science and society.

Acknowledgements: This work was supported by the UK Research and Innovation Biotechnology and Biological Sciences Research Council (BB/X008428/1), the National Institute for Health and Care Research (NIHR) Leeds Biomedical Research Centre (NIHR203331) and the German Research Foundation (PA 4005/1-1) and is the result of a partnership between the #EEGManyLabs (https://eegmanylabs.com) project, EEGNet (Brain Canada Foundation #4940); and the Global Brain Consortium (https://globalbrainconsortium.org/). The latter is funded by Grant Y0301902610100201 of the University of Electronic Sciences and Technology of China, STI 2030-Major Projects Grant Number: 2022ZD0208500 and the Chengdu Science and Technology Bureau Program Grant Number: 2022GH02-00042- HZ. We would like to thank the organisations, societies and researchers supporting (see[6] for full list) and all participants.

References

1. Berger, H. Über das Elektrenkephalogramm des Menschen. *Arch. Für Psychiatr. Nervenkrankh.* **87**, 527–570 (1929).
2. Borck, C. *Brainwaves: A Cultural History of Electroencephalography*. (Routledge, Abingdon, 2018).
3. *Niedermeyer's Electroencephalography: Basic Principles, Clinical Applications, and Related Fields: Sixth Edition*. (Wolters Kluwer Health, 2012).
4. Bringas-Vega, M. L., Michel, C. M., Saxena, S., White, T. & Valdes-Sosa, P. A. Neuroimaging and global health. *NeuroImage* **260**, 119458 (2022).
5. World Health Organization. *Measures of Early-Life Brain Health at Population Level*. https://www.who.int/publications-detail-redirect/9789240084797 (2023).
6. Welke, D., Mushtaq, F. & van den Bosch, J. #EEG100: Supplementary Materials. osf.io/qv38p (2024).
7. Steinmetz, J. D. *et al.* Global, regional, and national burden of disorders affecting the nervous system, 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021. *Lancet Neurol.* **23**, 344–381 (2024).
8. Beniczky, S. *et al.* Standardized computer-based organized reporting of EEG: SCORE – Second version. *Clin. Neurophysiol.* **128**, 2334–2346 (2017).
9. Pavlov, Y. G. *et al.* #EEGManyLabs: Investigating the replicability of influential EEG experiments. *Cortex* **144**, 213–229 (2021).
10. Webb, E. K., Etter, J. A. & Kwasa, J. A. Addressing racial and phenotypic bias in human neuroscience methods. *Nat. Neurosci.* **25**, 410–414 (2022).
11. Jwa, A. S. & Poldrack, R. A. Addressing privacy risk in neuroscience data: from data protection to harm prevention. *J. Law Biosci.* **9**, lsac025 (2022).

Competing Interests

Author M G Machizawa is the CEO of Xiberlinc Inc., a neurotechnology company. Author D Coyle is Founder and CEO of NeuroCONCISE Ltd, a wearable EEG company. Author R K Mathew is a shareholder in RBM Healthcare Ltd and an Advisory Shareholder for Opto Biosystems Ltd, a neurotechnology company. The remaining authors declare no competing interests.

Box 1. What is EEG?

Electroencephalography (EEG) is a non-invasive neuroimaging technique used to record electrical activity of the brain via electrodes placed on the scalp. The recorded signal, the electroencephalogram (which shares the acronym EEG), is the product of synchronized synaptic activity in populations of cortical neurons (pyramidal cells organized along cortical columns). Voltage fluctuations at each electrode site reflect a differential measurement between the active and reference electrodes that is amplified and recorded as an EEG trace. These electrical changes can be captured with high temporal resolution, offering a window into the time course of brain activity in the submillisecond range.

EEG has proven particularly useful in a clinical setting because certain cases of abnormal brain function evoke relatively consistent EEG patterns that can be detected. Such applications have been facilitated by quantitative EEG (qEEG), the application of mathematical techniques to extract numerical features of the EEG trace to support signal interpretation. EEG traces provide a canonical test for epilepsy and can be used to identify sleep problems, determine whether the brain is alive or dead, or probe certain disorders of consciousness. Visual evoked potentials have been used in diagnosing multiple sclerosis, a disorder that leads to demyelination, and auditory evoked potentials detect abnormalities in the hearing of newborns.

By time-locking the signal to a response or an external stimulus and averaging the signal over many trials, the neural activity that is specifically related to the sensory, motor, or cognitive event that evoked it can be extracted. This technique is regularly applied in studies monitoring brain maturation across development, in mental ill health and examining neural change following behavioural and pharmacological treatments. In academic research, EEG, through averaging the signal, and more recently, single trial analysis, has been used extensively to explore fundamental questions related to cognitive processing, including in the study of attention, emotion, memory, and decision-making.

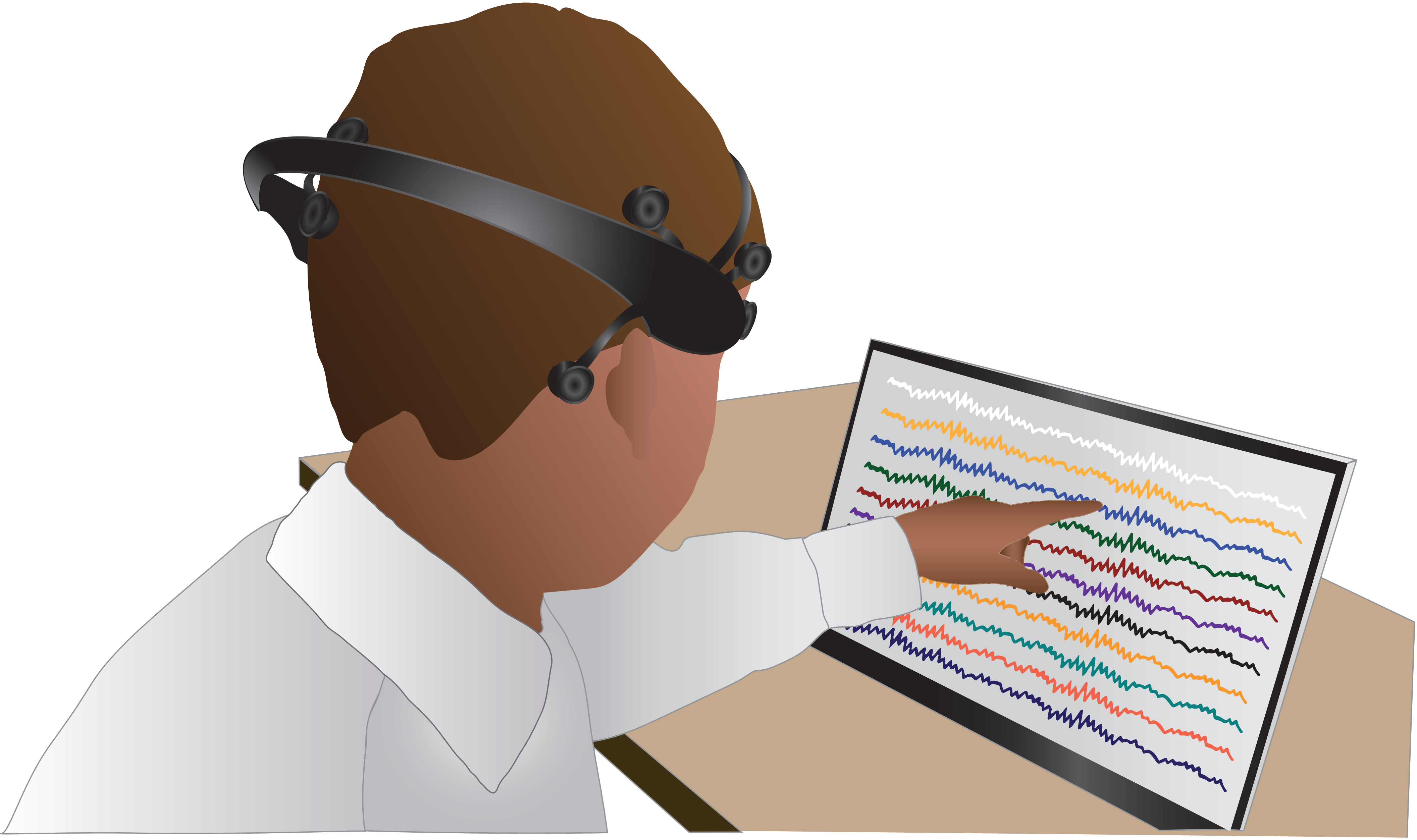
With its portability and low cost, EEG is increasingly being used in real-world settings, with communities and in environments where other neuroimaging tools are either too expensive or logistically impractical. Commercial applications leveraging EEG are also on the rise, making brain monitoring accessible to the public. Its integration with other technologies including artificial intelligence and virtual and augmented reality is creating new possibilities to interact with the digital and physical world. Advances in brain-computer interfaces (BCIs) show EEG can be used to control prosthetics and communication devices, to deliver neurofeedback training and promote physical rehabilitation.

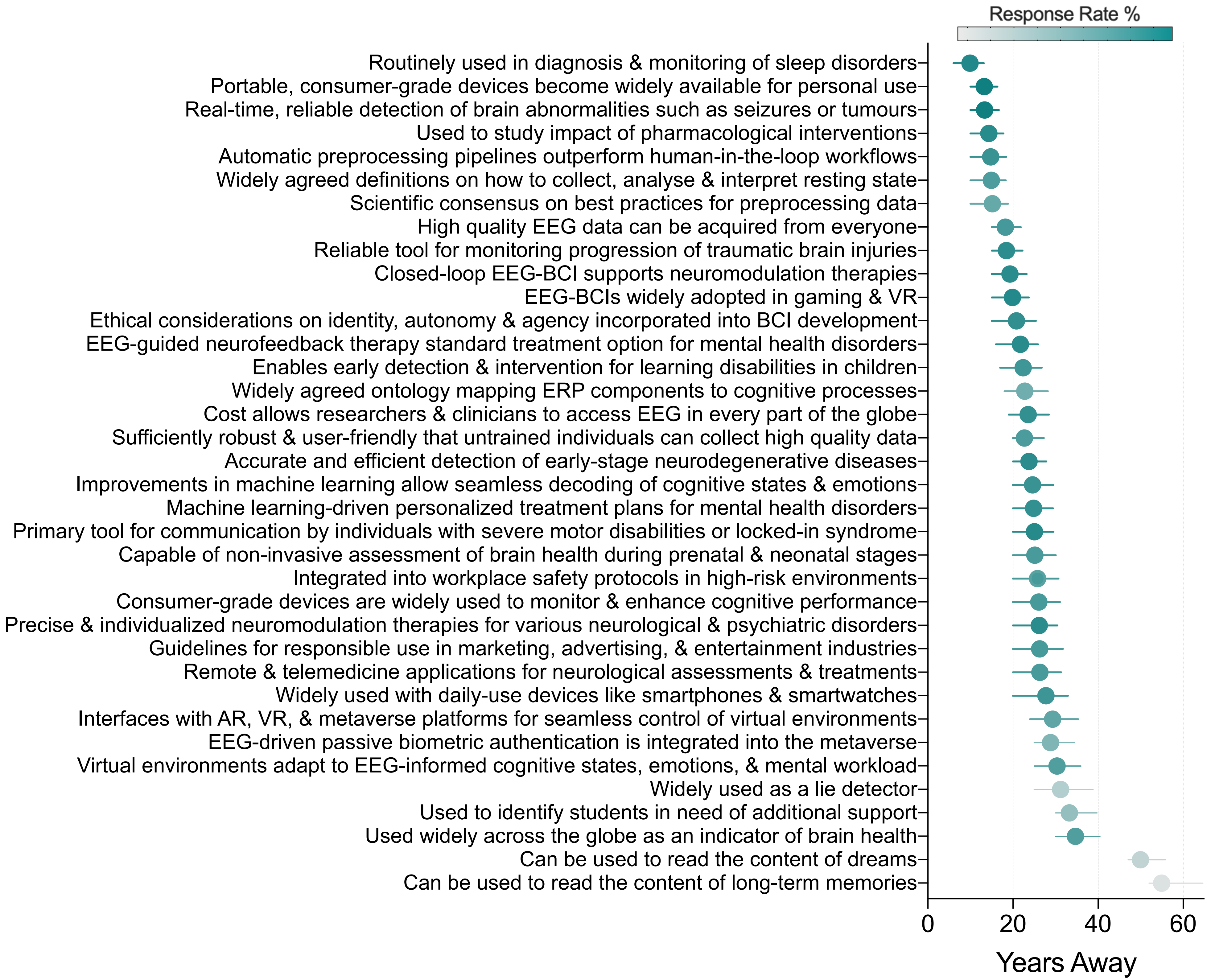
Figure Titles and Captions

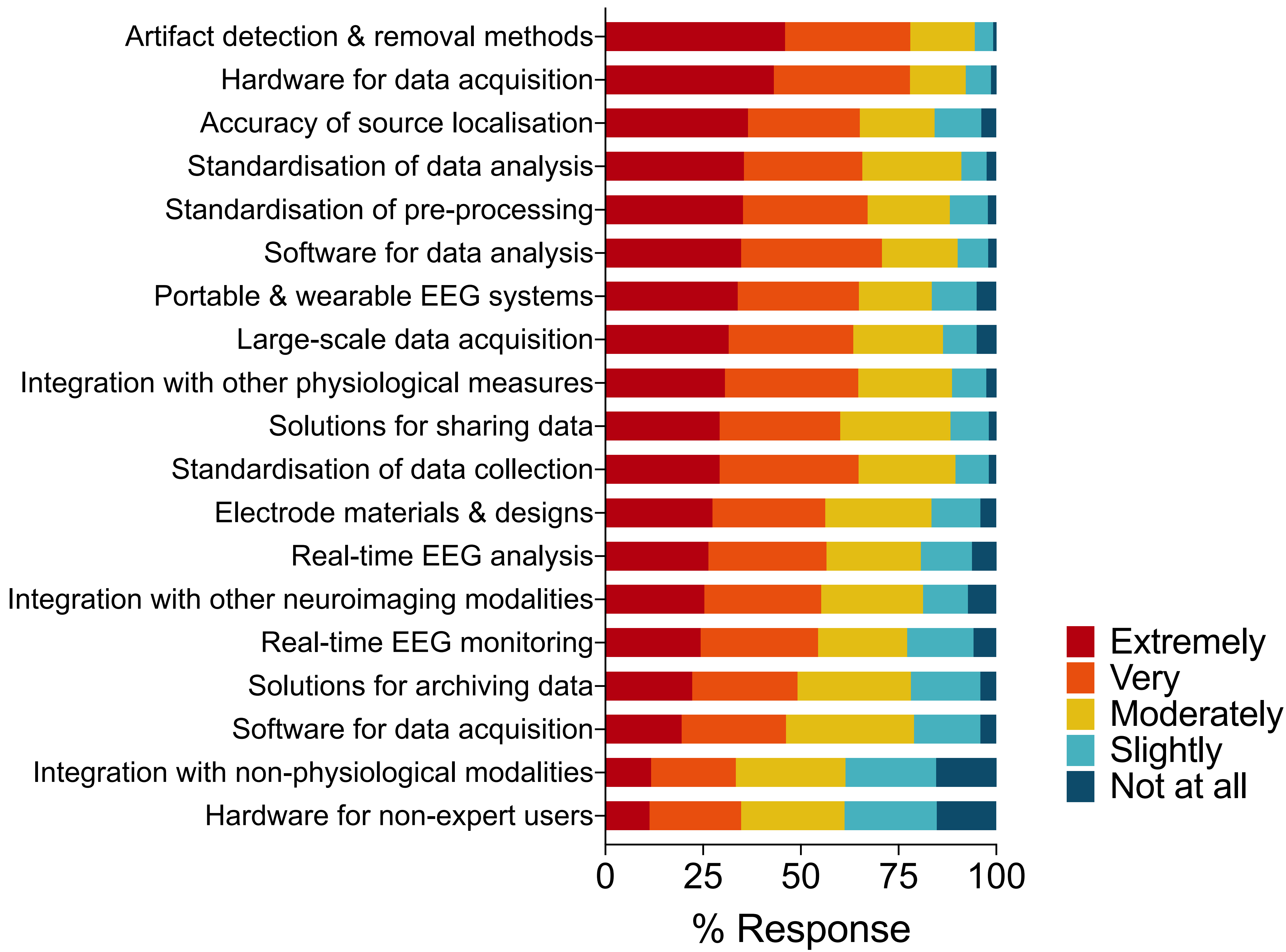
Figure 1: An EEG recording in 2024.
An illustration of a young participant wearing a modern wireless headset recording EEG outside of the laboratory in a school classroom setting. The signal displayed on the screen, repeated across rows, is an adaptation of an early recording taken by Hans Berger from his son Klaus[1], showing a sinusoidal 10-Hz activity, which he referred to as the "alpha rhythm".

Figure 2: Predicting Future Milestones of EEG
Survey respondents (n = 515, from 51 countries) with 6,685 years of collective experience rated when the EEG community might widely accept the listed statements as being achieved. Here we present rank-ordered median averages of all responses (error bars represent 95% confidence intervals of the mean). Statement labels are shortened for presentation (see[6]). Participants could opt out of making predictions if their uncertainty was too high. The percentage of response per statement is indicated by colour, ranging from teal (88%) to light grey (37%). Stratification of predictions by respondent characteristics is available through our web application (https://www.eeg100.org/survey/).

Figure 3: Priorities for Progressing EEG.
Participants rated how important major developments and advancements in various domains of EEG research would be to their work. The priority list is ordered by the frequency of "Extremely Important" ratings.




Response Rate %
Routinely used in diagnosis & monitoring of sleep disorders
Portable, consumer-grade devices become widely available for personal use
Real-time, reliable detection of brain abnormalities such as seizures or tumours
Used to study impact of pharmacological interventions
Automatic preprocessing pipelines outperform human-in-the-loop workflows
Widely agreed definitions on how to collect, analyse & interpret resting state
Scientific consensus on best practices for preprocessing data
High quality EEG data can be acquired from everyone
Reliable tool for monitoring progression of traumatic brain injuries
Closed-loop EEG-BCI supports neuromodulation therapies
EEG-BCIs widely adopted in gaming & VR
Ethical considerations on identity, autonomy & agency incorporated into BCI development
EEG-guided neurofeedback therapy standard treatment option for mental health disorders
Enables early detection & intervention for learning disabilities in children
Widely agreed ontology mapping ERP components to cognitive processes
Cost allows researchers & clinicians to access EEG in every part of the globe
Sufficiently robust & user-friendly that untrained individuals can collect high quality data
Accurate and efficient detection of early-stage neurodegenerative diseases
Improvements in machine learning allow seamless decoding of cognitive states & emotions
Machine learning-driven personalized treatment plans for mental health disorders
Primary tool for communication by individuals with severe motor disabilities or locked-in syndrome
Capable of non-invasive assessment of brain health during prenatal & neonatal stages
Integrated into workplace safety protocols in high-risk environments
Consumer-grade devices are widely used to monitor & enhance cognitive performance
Precise & individualized neuromodulation therapies for various neurological & psychiatric disorders
Guidelines for responsible use in marketing, advertising, & entertainment industries
Remote & telemedicine applications for neurological assessments & treatments
Widely used with daily-use devices like smartphones & smartwatches
Interfaces with AR, VR, & metaverse platforms for seamless control of virtual environments
EEG-driven passive biometric authentication is integrated into the metaverse
Virtual environments adapt to EEG-informed cognitive states, emotions, & mental workload
Widely used as a lie detector
Used to identify students in need of additional support
Used widely across the globe as an indicator of brain health
Can be used to read the content of dreams
Can be used to read the content of long-term memories
0
20
40
60
Years Away



Artifact detection & removal methods
Hardware for data acquisition
Accuracy of source localisation
Standardisation of data analysis
Standardisation of pre-processing
Software for data analysis
Portable & wearable EEG systems
Large-scale data acquisition
Integration with other physiological measures
Solutions for sharing data
Standardisation of data collection
Electrode materials & designs
Real-time EEG analysis
Integration with other neuroimaging modalities
Real-time EEG monitoring
Solutions for archiving data
Software for data acquisition
Integration with non-physiological modalities
Hardware for non-expert users
0
25
50
75
100
% Response
Extremely
Very
Moderately
Slightly
Not at all