

Sustainable neuroscience through open science

Lara M. C. Puhlmann, Alina Koppold, Gordon B. Feld, Tina B. Lonsdorf, Kirsten Hilger, Susanne Vogel, Çağatay Gürsoy, Alexandros Kastrinogiannis, Louisa Kulke, Alexander Lischke, Anett Müller-Alcazar, Julian Packheiser, Matthias F. J. Sperl, Yu-Fang Yang, Laura Bechtold, Sebastian Ocklenburg & Helena Hartmann



Neuroscience is crucial for understanding human behaviour. Yet, its resource-intensive methods contribute to the climate crisis. We call on neuroscientists to align their research with ecological sustainability goals across the research cycle and propose three key steps: replace unfocused data collection, reduce excessive emissions and refine imprecise methods.

Imagine a simple magnetic resonance imaging (MRI) experiment with 30 participants, who undergo one scan each. Recent life-cycle assessments estimate that an MRI scan generates roughly 22.4 kg CO₂e (CO₂-equivalent greenhouse gases¹) in its use phase, equivalent to driving a new European car for 145 km. This still excludes scanner standby power, which accounts for 40% of MRI-related emissions². On this basis, even a small MRI study produces around 940 kg CO₂e, comparable to driving 6,000–6,500 km. Yet, these emissions usually yield only a single publishable research paper that describes a select population. In an ideal world, sharing data publicly changes everything: now, the same data can fuel replication studies, reanalyses with new research questions, large-scale meta-analyses, methods benchmarking or training datasets for machine learning, which often results in several additional publications without any further data collection. And this is only the tip of the iceberg. If the data remain unpublished or inaccessible, however, nearly a metric tonne of CO₂e and the opportunity for downstream discovery is simply lost. This asymmetry highlights a central point in neuroscience: FAIR (findable, accessible, interoperable and reusable) open data multiply scientific value while holding environmental cost optimally near constant.

Following the ‘Decade of the Brain’ in the 1990s, neuroscientific research has grown exponentially, often motivated by the promise of solving pressing issues in health and clinical science. This has led and continues to lead to a better fundamental understanding of why humans think and behave as they do, which paves the way for improvements in clinical and other applied settings. Yet, simultaneously, the rapidly escalating climate crisis poses an existential threat to human well-being and demands urgent reductions in greenhouse gas emissions, including in research. Here, we address this conflict and call on the scientific community to responsibly implement open science practices to reduce the carbon footprint of neuroscience.

Compared to other scientific fields that study human behaviour, neuroscience relies on tools with a particularly strong effect on the

environment. For example, functional MRI (fMRI) requires substantial amounts of electricity for data collection and processing, and neuroscientific animal models rely on large research and breeding facilities that are energy-intensive and waste-intensive. At the same time, neuroscience is highly instrumental in reducing human suffering in the long run, such as by enabling innovative insights into mental health. This unquestionable contribution, together with its resource use, implies a heavy responsibility to carefully balance the costs and benefits of neuroscientific projects. Although this responsibility initially mainly lies with decision-makers, institutions and governments that shape funding streams and incentives, there are important opportunities for each individual scientist to contribute to the critical cost–benefit ratio across the research cycle.

We therefore call on the neuroscientific community to consider the ecological impact of their research when assessing its societal impact. Some environmental costs are certainly justified by the expected benefits to science and society. However, unsustainable research practices that generate excess emissions without sound justification (Fig. 1) can and must be reduced. Several institutions and funders – such as the European Union and the German Research Foundation (Deutsche Forschungsgemeinschaft (DFG)) – have already incorporated sustainability principles into their mission statements (for example, the Horizon Europe Green Charter and the DFG 2023 sustainability guidelines for resource-efficient research), and acknowledge the urgent need to reconsider the scientific process in light of the climate crisis. Yet, how scientists can effectively implement more sustainable research practices remains open, and only few practical guidelines exist. Here, we argue that open science practices, if responsibly implemented, can make an important contribution to tipping the cost–benefit scale towards conducting sustainable human neuroscience. Such responsible implementation relies on clear guidelines and resources on how to implement them in research practice.

Research in neuroscience proceeds in repetitive cycles of six major steps: starting and planning a project, data collection, data analysis, manuscript writing and dissemination of findings – which then informs new projects and cycles (Box 1). Accordingly, all of these steps should be considered in a sustainable research cycle. Finding appropriate resources for each step can be challenging at all career levels. Based on the ARIADNE framework³, a curated resource navigator for transparent and reproducible science across the full research cycle, below we offer practical, step-by-step guidance to support sustainable neuroscientific research from planning a scientific project to disseminating its findings. Recommendations involve three core principles that are inspired by the ‘three Rs’ of animal research: replace unfocused data collection with open data or simulations, whenever possible; reduce emissions by focusing on more efficient hypothesis-driven research;

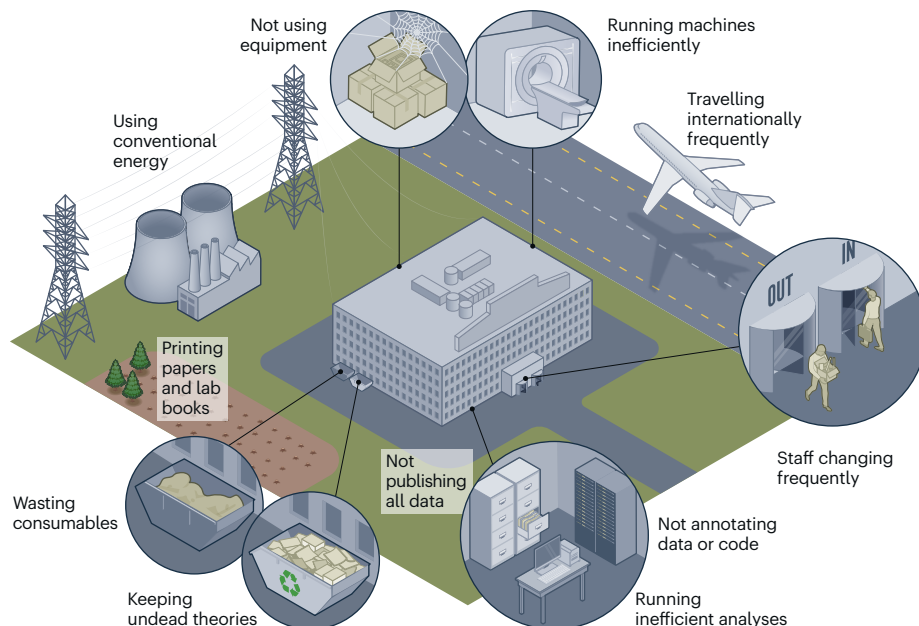


Fig. 1 | Unsustainable research practices in neuroscience. Neuroscience research carries a substantial ecological footprint that is due to energy-intensive methods, inefficient workflows, underused equipment and unsustainable dissemination, as well as research based on ‘undead theories’ (models or

concepts that were once popular but do not hold up to modern, often empirical scrutiny). Additional negative effects stem from poor data and/or code sharing, international travel and high staff turnover, which highlights the urgent need for more sustainable practices.

and refine methods through more precise measurements and optimized statistics. Although general recommendations for sustainable research practices exist, we here focus on specific recommendations for the field of neuroscience. An extended version of this Comment is available as a preprint⁴.

Start and plan your research responsibly and precisely

The largest environmental costs of neuroscience result from the initiation of a study per se and the associated data collection. First, neuroscientists should consider the potential short-term and long-term benefits (societal, academic and otherwise) against the costs of a research project. To maximize the cost–benefit ratio of a novel study, unnecessary data collection needs to be prevented and the reuse of existing or potentially openly accessible data (such as those available on [OpenNEURO](#)⁵) needs to be considered, whenever possible. If this is not possible, any new data collection should be planned according to open science principles and should adopt sustainable research practices.

Generally, a sustainable study and data collection plan should include responsible sharing of the often-cost-intensive neuroscientific equipment, obtaining ethical approval and participant consent for sharing their data as openly as possible, and ensuring the acquisition of valid data by means of thorough methodological considerations based on consensus guidelines and sufficient piloting. Further, for all neuroscientific research methods, the preregistration of projects – including an a priori power analysis for an optimal sample size – are central for optimizing the cost–benefit ratio of a study. Notably, later reviewers should be mindful that a preregistration is a plan rather than a prison: it presents a time capsule of the researchers’ thoughts and plans before data collection (as detailed as is necessary and possible) that often needs to be transparently adjusted later. Moreover, as formal power analyses for many neuroscientific methods are not

straightforward, other sample size justifications that take into account, for example, informational value versus resource allocation should be carefully considered and transparently reported⁶. Given the often protracted nature of neuroscientific studies, a timely and publicly available preregistration of the planned work is crucial for keeping other groups from unknowingly working on the same question in parallel. The need for preregistration is especially urgent for biomedical animal research, for which the number of registered protocols is still very low compared to human research.

Collect data according to a cost–benefit analysis

When acquiring novel data, the suitability of resource-intensive methods to answer a given research question should be carefully weighed against other, cheaper methods. A sustainability-conscious researcher should consider whether a research question can be answered by a relatively energy-efficient method such as electroencephalography (EEG) or whether it truly requires more resource-intensive methods such as animal research, MRI or fMRI. This means we want to specifically address the unfortunate situation in which a researcher has a hammer (an MRI scanner) and thus every research question becomes a nail (an MRI study), in contrast to the reverse situation in which the specifics of a research question may, after careful consideration, require the use of resource-intensive methods. Although the energy use for fMRI peaks sharply during scanning, the requirement to maintain the scanner permanently also consumes energy and makes its underutilization especially problematic. On average, the annual energy cost of a 3T MRI is around 80 to 90 MW⁷, which translates to 31,000–35,000 kg CO₂e per scanner. Measurement precision should be maximized to limit the number of participants and/or trials required for sufficient statistical power⁸ and thus energy-consuming measurement time, especially where large amounts of data are required (for example, for individual

BOX 1

Guidelines for sustainable neuroscience

Considering these steps will help you to make conscious choices throughout the research cycle and ensure sustainable neuroscience by replacing, reducing and refining.

Starting (step 1)

Start with a meaningful question, use existing data where possible and weigh benefits versus ecological cost.

- Identify a useful research question
- Check for availability of existing data
- Perform a cost–benefit analysis

Planning (step 2)

Plan for precision, use power analyses and adopt realistic timelines.

- Establish a realistic time schedule
- Determine an informative sample size
- Ensure methodological precision

Collecting data (step 3)

Collect data mindfully and minimize energy use and consumables.

- Consider energy demands
- Use biodegradable reagents where possible
- Use consumables responsibly

Analysing (step 4)

Analyse efficiently, avoid wasteful computations and archive data after preprocessing and other steps that require considerable computing resources.

- Check for errors early in the analysis process
- Use computational resources responsibly
- Save preprocessed data

Writing (step 5)

Write transparently and share both findings and sustainability measures taken.

- Document the environmental impact of the research
- Report all experiments conducted
- Write accessibly

Disseminating (step 6)

Disseminate for reuse and make data, code and materials FAIR and well-documented to prevent unnecessary duplication.

- Ensure data are available for reuse
- Provide adequate documentation for reuse
- Share only necessary data

difference research). Finally, reducing waste by choosing responsible manufacturers of consumables (for example, checking whether they have recycling programmes and use renewable energy) as much as possible for the collection of biological samples, which are commonly assessed in neuroscientific studies, can reduce their particularly high carbon footprint substantially.

During the acquisition period, data quality must also be consistently checked to swiftly recognize problems and thus avoid the costly acquisition of erroneous or even useless datasets. Core facilities offer a good model to increase the efficient usage of scientific machinery. Moreover, dedicated, trained staff in permanent positions are critical to avoid mistakes and ensure efficient data management. Relatedly, proper documentation of data collection from the beginning on is critical for long-term usability of research data. This involves detailed metadata, clear data dictionaries and comprehensive recording of methodologies, which should be shared together with the publication.

Minimize environmental impact in analysis and writing and disseminate openly

Following data collection, data analysis has further environmental impacts, especially when using computationally advanced methods. These methods already make up almost half of all energy costs in information technology and are at the same time becoming increasingly popular in modern neuroscience owing to their ability to handle complex datasets and exploratory analyses. By streamlining data processing techniques, optimizing code for efficiency and using low-power computing resources, the environmental impact of neuroscientific research can be considerably reduced. Furthermore, preregistration of preprocessing steps and analyses may substantially reduce the number of reanalyses of the same data⁹. Tools such as those provided

by the Green Algorithms project¹⁰ can assist researchers in estimating the carbon footprint of their measurement software and algorithms.

In light of the costs of neuroscientific research and analysis, the transparent reporting of all conducted experiments (including null findings) is essential. Neuroscientific research is always a substantial resource investment on the side of the researcher as well, which can create substantial pressure to spin or selectively report results. Yet, every study and experiment that remains in the file drawer is a waste of resources, even (or, perhaps, especially) if the results are nonsignificant or deemed inconclusive. Their publication helps to avoid unnecessary replications and is key to identifying and unrooting ‘undead theories’ (models or concepts that were once popular but do not hold up to modern, often empirical scrutiny). For maximum availability to the public, findings should be made accessible to as many individuals as possible by, for instance, publishing them as preprints or open access. Compared to other disciplines, open access journals in neuroscience have grown exceptionally over the past decade and also include ‘top-tier’ journals, which makes open publishing a highly attractive choice. Early dissemination through preprints (for example, *bioRxiv* and *medRxiv*) has become commonplace in modern neuroscience laboratories and substantially speeds up the spread of information as well as its availability, even if the research later ends up in a ‘closed’ journal.

Following study completion, publicly sharing research data and materials has clear and indisputable advantages for society and science. Beyond the facilitation of reuse, it allows estimating the validity of scientific measures and varying data-processing methods, as well as helping to avoid statistical errors in future research. Finally, to date, many publicly available neuroscientific datasets are not readily reusable owing to the lack of adherence to existing publishing and documentation standards or of generally agreed-upon standards in the first place. Such underused data and materials that have been

shared nonetheless consume resources and energy, therefore building a ‘digital data cemetery’. The prospects of dissemination thus rely on the adherence to the so-called FAIR principles.

Take action to implement sustainable practices

With the climate crisis posing an existential threat to human physical and mental wellbeing, neuroscience stands at a turning point. Although neuroscientific research is crucial for understanding the function of the human brain in health and disease, there is an urgent need to reduce resource consumption and to make neuroscience more ecologically sustainable. To address and balance this critical trade-off, we propose three key steps: replace unfocused data collection, reduce emissions and refine methods for analysis and new data collections whenever they are sensible (that is, the benefits of new data collection outweigh the costs). Most importantly, however, individual researchers cannot themselves solve this issue looking forward. Rather, institutions, policy-makers and funders must join forces and take action to enable and reliably fund practices that are integral to sustainable neuroscience, from infrastructure to long-term continuity in projects and contracts.

Lara M. C. Puhlmann^{1,2,27} ✉, Alina Koppold^{3,27},
Gordon B. Feld^{4,5,6,7,27}, Tina B. Lonsdorf^{3,8}, Kirsten Hilger^{9,10},
Susanne Vogel^{11,12}, Çağatay Gürsoy¹³, Alexandros Kastriogiannis¹³,
Louisa Kulke¹⁴, Alexander Lischke^{11,15}, Anett Müller-Alcazar^{11,12},
Julian Packheiser^{16,17}, Matthias F. J. Sperl^{18,19,20,21}, Yu-Fang Yang²²,
Laura Bechtold²³, Sebastian Ocklenburg^{11,12,24,27} & Helena Hartmann^{25,26,27}

¹Clinical Psychology and Behavioural Neuroscience, Faculty of Psychology, Technische Universität Dresden, Dresden, Germany.

²Leibniz Institute for Resilience Research, Mainz, Germany.

³Biological Psychology and Cognitive Neuroscience, Department of Psychology, University of Bielefeld, Bielefeld, Germany. ⁴Department of Clinical Psychology, Central Institute of Mental Health, Medical Faculty Mannheim, University of Heidelberg, Mannheim, Germany.

⁵Department of Psychiatry and Psychotherapy, Central Institute of Mental Health, Medical Faculty Mannheim, University of Heidelberg, Mannheim, Germany.

⁶Department of Addiction Behavior and Addiction Medicine, Central Institute of Mental Health, Medical Faculty Mannheim, University of Heidelberg, Mannheim, Germany.

⁷Department of Psychology, University of Heidelberg, Heidelberg, Germany. ⁸Institute for Systems Neuroscience, University Medical Center Hamburg-Eppendorf, Hamburg, Germany.

⁹Department of Psychology, University of Würzburg, Würzburg, Germany.

¹⁰Department of Psychology, Vinzenz Pallotti University Vallendar, Vallendar, Germany. ¹¹Department of Psychology, MSH Medical School Hamburg, Hamburg, Germany. ¹²Institute for Cognitive and Affective Neuroscience, MSH Medical School Hamburg, Hamburg,

Germany. ¹³Department of Neurology, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany. ¹⁴Department of Developmental Psychology with Educational Psychology, University of Bremen, Bremen, Germany. ¹⁵Institute for Clinical Psychology and Psychotherapy, MSH Medical School Hamburg, Hamburg, Germany. ¹⁶Social Neuroscience, Medical Faculty, Ruhr University Bochum, Bochum, Germany. ¹⁷Research Center One Health Ruhr of the University Alliance Ruhr, Ruhr University Bochum, Bochum, Germany. ¹⁸Department of Clinical Psychology and Psychotherapy, University of Siegen, Siegen, Germany. ¹⁹Department of Clinical Psychology and Psychotherapy, University of Marburg, Marburg, Germany. ²⁰Department of Clinical Psychology and Psychotherapy, University of Giessen, Giessen, Germany. ²¹Center for Mind, Brain and Behavior, Universities of Marburg and Giessen (Research Campus Central Hessen), Marburg, Germany. ²²Division of Experimental Psychology and Neuropsychology, Department of Education and Psychology, Freie Universität Berlin, Berlin, Germany. ²³Faculty of Mathematics and Natural Sciences, Institute for Experimental Psychology, Department for Biological Psychology, Heinrich Heine University Düsseldorf, Düsseldorf, Germany. ²⁴Biopsychology, Institute of Cognitive Neuroscience, Ruhr University Bochum, Bochum, Germany. ²⁵Department of Neurology, University Hospital Essen, Essen, Germany. ²⁶Center for Translational Neuro- and Behavioral Sciences (C-TNBS), University Hospital Essen, Essen, Germany. ²⁷These authors contributed equally: Lara M. C. Puhlmann, Alina Koppold, Gordon B. Feld, Sebastian Ocklenburg, Helena Hartmann.

✉ e-mail: lara.puhlmann@lir-mainz.de

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Competing interests

The authors declare no competing interests.