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Leveraging neuroscience for climate change research

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Anthropogenic climate change poses a substantial threat to societal living conditions. Here, we argue that neuroscience can substantially contribute to the fight against climate change and provide a framework and a roadmap to organize and prioritize neuroscience research in this domain. We outline how neuroscience can be used to: (1) investigate the negative impact of climate change on the human brain; (2) identify ways to adapt; (3) understand the neural substrates of decisions with pro-environmental and harmful outcomes; and (4) create neuroscience-based insights into communication and intervention strategies that aim to promote climate action. The paper is also a call to action for neuroscientists to join broader scientific efforts to tackle the existential environmental threats Earth is currently facing.

The world is facing a potentially catastrophic problem in the form of human-caused global warming[1,2]. Researchers in the social and behavioural sciences are therefore increasingly focusing their attention on understanding how to mitigate and adapt to the climate crisis[3,4]. Surprisingly, the various techniques, frameworks, research findings and methodologies from the field of neuroscience are only beginning to be applied in this context[5–8]. Here we integrate and expand on this work to outline how neuroscience can contribute to these efforts by investigating the impacts that a changing climate has on the brain, and the neural mechanisms underlying psychological and behavioural phenomena that may have a positive or a negative impact on the state of the environment.

We argue that findings from different neuroscientific domains such as environmental, health, decision, social or affective neuroscience can advance our understanding of the reciprocal relationships between the environment and the brain (Fig. 1). We present a succinct overview of how neuroscientific research can provide insights on (1) what a changing climate means for human health and well-being, and (2) how to identify promising strategies to help adapt to and mitigate climate change. This Perspective integrates and highlights already existing neuroscientific contributions[6–8], and presents a roadmap to organize and prioritize impactful future research in this domain. We moreover discuss how neuroscience can be helpful in the context of climate policy-making by providing an evidence-based foundation that objectively quantifies both the impact of climate change on the brain and the benefits of adaptive strategies and technologies that aim to buffer these effects. This evidence can support the work of, for example, policymakers and urban planners, and may increase acceptance of robust climate policy by the general public. Finally, we discuss the importance of considering the balance between the considerable environmental impact of conducting neuroscience and the benefits of the potential insights that stand to be gained.

A brief history of environmental neuroscience

Stretching back to research from the late 1940s, neuroscientists have investigated how the physical environment affects the brain and

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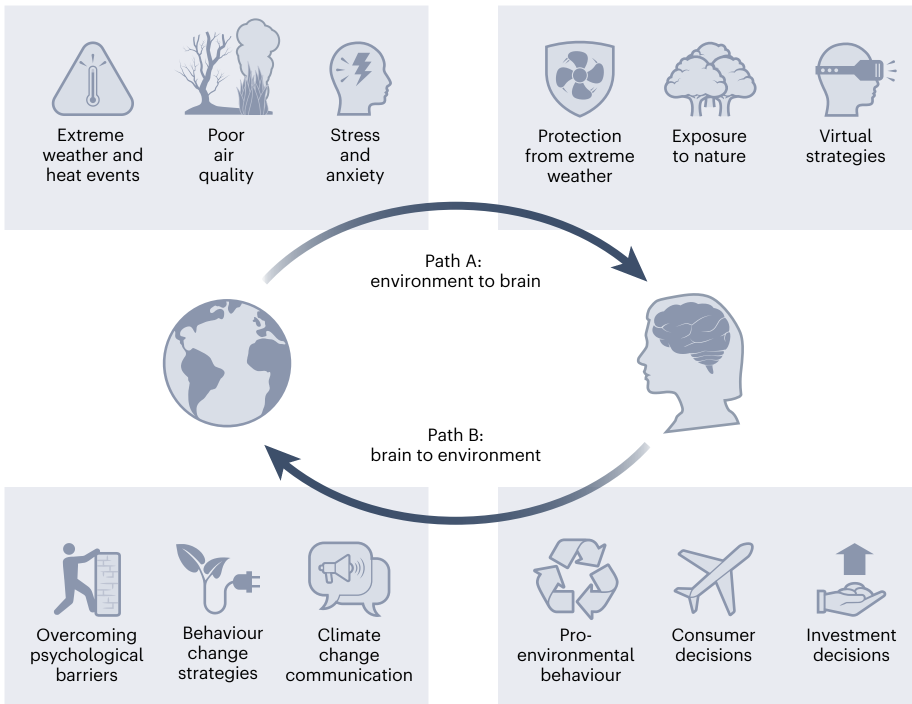

Fig. 1 | Reciprocal relationships between the brain and a changing environment. The illustration outlines the reciprocal relationships between the changing environment and the brain, highlighting the main contributions that neuroscience can make to this understanding. Path A aims to answer two main questions: (1) "How does climate change affect the brain?"; and (2) "Can neuroscience help with climate change adaptation?". Path B aims to answer two main questions: (1) "What drives environmental behaviour at the neural level?"; and (2) "How can neuroscience inform climate-relevant behaviour change and communication strategies?". Credit: Earth icon, KindPNG; all other icons, except the brain icon, adapted from the Noun Project.

behaviour[9,10]. Observational studies showed that rodents raised in enriched environments learned faster than rodents raised in sterile laboratory settings[11]. These behavioural effects were linked to a neuronal reorganization resulting in changed brain morphometry induced by the content of the environment[12]. This early environmental neuroscience work demonstrated for the first time, albeit in non-human animals, the profound impact that environmental features can have on the development and plasticity of the brain.

Today, environmental neuroscience investigates the reciprocal relationships between organisms, particularly humans, and their environment, with a focus on neural and psychological processes[9,10]. Features of modern environments, such as access to green spaces or other aspects of urban development, impact neural and psychological function[10]. Environmental neuroscience research investigates how brains undergo functional and structural changes in response to environmental changes, illustrating how factors that determine access to specific environments (for example, socioeconomic status[13]) and factors that result from exposure to specific environments (for example, exposure to pollutants[14]) can have a profound impact on human brain development.

Neuroscientific approaches thus provide a unique perspective on the interactions between organisms and their environments by identifying the neural substrates and mechanisms underlying these interactions. They can identify biologically plausible candidates for the cause–effect relationships between changing environmental features and changes at the behavioural level. For example, growing up in a household of low socioeconomic statushas long been associated with poor health outcomes and impaired cognitive and emotional development[13,15]. Neuroscience has identified neural processes by which factors related to low socioeconomic status result in specific neural disturbances in cognitive and affective systems, including lack of cognitive stimulation, exposure to toxins, poor nutrition and heightened childhood stress[13]. Once the underlying neural mechanisms were understood, targeted intervention strategies could be developed to buffer against these negative environmental impacts, and intervention efficacy could be evaluated using neuroscientific data. For example, a training programme targeting preschoolers and their parents increased selective attention as measured via electrophysiological assessment and resulted in cognitive improvements[16]. Of course, there are complex constellations of structural factors that influence inequities surrounding socioeconomic status that need to be considered (similar to the complex inequities that surround climate change). Nevertheless, neuroscientific methodologies contributed to a better understanding of the neural and cognitive implications of poverty, allowed for identification of negative consequences that can potentially be reversed, and enabled the development and evaluation of powerful targeted interventions.

Similarly, we believe that neuroscience has considerable promise in the context of climate change[17]. To fulfil this promise, more evidence is needed about how the already occurring and projected environmental changes caused by climate change influence the brain. Research in the social and behavioural sciences has begun cataloguing the substantial effects of a changing climate on human cognition, affect, behaviour and health[18–23]. Neuroscience can substantially contribute to the understanding of the effects of climate change on the brain and behaviour. This would require expanding the focus of current environmental neuroscience research to address issues related to climate change adaptation, climate change mitigation, environmental protection and justice, and sustainability. Neuroscientists can apply their methodological and conceptual skills towards these issues and refine them working alongside climate scientists, meteorologists, healthcare professionals, biologists, psychologists, sociologists, environmental and social justice scholars, communication experts, political scientists and citizen science projects, to understand and quantify how the changing environment impacts the brain and vice versa. A similar transformation of scope has occurred in environmental psychology, the 'sister discipline' of environmental neuroscience (Box 1).

Reciprocal relationships between the brain and environment

In the following sections, we discuss how neuroscientists can make substantial contributions to climate change research. We illustrate this approach along two interconnected pathways reflecting the reciprocal causal influences between the brain and environment (Fig. 1).

Path A environment to brain

Neuroscientists can investigate how the effects of climate change impact the brain and leverage this knowledge to develop strategies to protect it or make it more resilient against these negative effects. Multiple helpful insights can already be gleaned from subdisciplines of neuroscience, particularly environmental neuroscience, to understand how the environment influences the brain[9,10]. For example, as climate change worsens, humans will be exposed to more extreme weather events including heatwaves, droughts and hurricanes, and associated forest fires and floods. Neuroscientists can quantify how these factors impact the brain in terms of structure, function and overall health, and evaluate how this may explain changes in well-being and behaviour[22]. They can also investigate the neural substrates of psychological and behavioural responses to climate change, such as heat-related increases in anxiety and conflict[20,21]. In turn, these insights may help improve strategies to adapt to the consequences of climate change.

Path B brain to environment

Neuroscientists can investigate the neural substrates of the cognitive and affective processes that result in pro-environmental or environmentally harmful behaviours[6–8]. Research along this pathway can be informed by neuroscientific subdisciplines such as neuroeconomics or social neuroscience and should aim to identify the neural correlates of human emotions, cognitions, decisions and behaviours that positively or negatively impact the environment. Many human judgements and decisions related to climate change are influenced by psychological barriers, cognitive biases and heuristics that are not necessarily accessible to conscious introspection (Box 1)[5,8,24,25]. Neuroscientific approaches have the potential to uncover the neural correlates of these judgements, choices and behaviours[26,27]. Capturing motivationally relevant signals that reliably predict future behaviour may help identify barriers preventing people from showing pro-environmental behaviours, and develop and improve intervention strategies to promote these actions[5,19,28,29]. To illustrate, previous neuroimaging research into health communication campaigns has shown that neural activation towards campaign messages outperforms focus group evaluations as a predictor of campaign success at both the individual and population levels[30]. Neuroscientific approaches may ultimately also inform and improve strategies and policies aiming to motivate pro-environmental choices and behaviours[4,5,7].

Importantly, these two pathways should not be considered in isolation, but as complementary routes with complex reciprocal feedback loops. For example, many consequences of climate change, such as heatwaves or wildfires, will result in people staying indoors to avoid detrimental health effects. However, neuroscientific findings suggest that increased exposure to outdoor green spaces can have positive effects on the structure and function of the human brain[31,32]. Limiting time spent outdoors may thus have a detrimental impact on the brain. Psychological research has moreover found that increased exposure to nature and green spaces is associated with more pro-environmental behaviours[33]. Thus, exposure to nature may have the dual benefit of increasing well-being and having beneficial effects on neural plasticity (Fig. 1, path A), while also encouraging people to engage in more sustainable behaviours (Fig. 1, path B). Neuroscientists may

BOX 1

The proactive role of psychology in addressing climate change

Emerging at the same time as environmental neuroscience, environmental psychology initially focused on exploring how aspects of the built and natural environment affect human behaviour, productivity and well-being[98]. In the 1970s, research turned towards understanding the psychological factors underlying human influences on the biophysical environment (for example, air and noise pollution), and the negative effects of these changes on human health and well-being. Today, many environmental psychologists focus on finding ways "to change people's behaviour to reverse environmental problems while at the same time preserving human well-being and quality of life"[98], an approach often referred to as sustainability psychology. By combining and integrating: (1) a focus on the impact of the environment on the human mind; and (2) a focus on the impact of human behaviour on the environment, the field has uncovered promising bidirectional and reinforcing relationships between exposure to different environments and the promotion of pro-environmental cognitions and behaviours[99]. The American Psychological Association's Task Force on Climate Change has recently published an action plan outlining the multiple roles that psychologists can play when it comes to research, practice and advocacy related to the climate crisis[3]. They discuss two main challenges on which psychologists can focus their efforts. The first relates to climate change adaptation: psychologists (both psychological scientists and clinical practitioners) can help individuals, households and countries to understand how climate change will impact daily life and how to overcome or adjust to these impacts. This includes conducting research to understand psychological responses to climate change (for example, anxiety and depression), drivers of mental health conditions (for example, conflict and trauma), and developing interventions and therapies focusing on climate and the environment (for example, ecotherapy and resilience training). The second challenge relates to climate change mitigation: psychologists can help advance efforts to limit, prevent and counteract greenhouse gas emissions, for instance, by contributing to the design and evaluation of new technologies to reduce energy consumption and to increase their acceptance by the public[3]. Psychologists can contribute to transforming people's lives and environments to reduce energy consumption and emissions while ensuring their compatibility with human cognitive, emotional, cultural and social functioning[100]. This includes understanding the psychological factors underlying sustainable decisions, behaviours and practices that are aligned with emission reduction while making these changes compatible with human well-being. Given that multiple psychological barriers can impede decision-making and behaviour change in the climate and sustainability domains (for example, temporal discounting, uncertainty, learned helplessness and conflicting motivations), understanding how to overcome these barriers is a priority for psychological research in this domain[5,24].

The American Psychological Association's action plan is meant to inspire and motivate psychologists to devote attention to the impacts of climate change. We suggest that the field of neuroscience should similarly aim to expand its focus to respond to these urgent societal challenges by bringing its unique competencies and insights to the table.

contribute to investigating the biological mechanisms underlying these effects, and address questions such as whether the dual benefits of nature exposure can also be obtained with alternative strategies that can be implemented indoors, such as exposure to plants or animals, or immersive virtual nature scenarios.

In the following sections, we outline some relevant questions that neuroscientists can help address in the context of the two pathways. We highlight already existing findings and emphasize gaps in which new research may have the largest impact. While illustrative rather than exhaustive, these ideas are intended to orient and facilitate future research.

Key questions relating to path A

Neuroscientists can help understand the impact of climate change on the human brain and mind, and increase knowledge about the ways to adapt to the negative effects of climate change.

How does climate change affect the brain?

There are multiple ways in which climate change will impact living environments and ultimately affect the brain. We discuss several key outcomes and potential avenues for future research.

Extreme weather and heat events. A major detrimental effect of climate change is related to the impact of the increasing number of extreme weather events, particularly heatwaves[22], on the brain. Higher temperatures increase human and non-human mortality, decrease cognitive performance and ability to learn, decrease self-control, and have been associated with increases in crime rate and civil conflict[21,23,34,35]. Each standard deviation increase in temperature or extreme rainfall has been shown to increase the frequency of interpersonal violence by 4% and intergroup conflict by 14%[21]. While these results depend on the baseline weather in the population being studied, they provide poignant evidence highlighting the detrimental effect of weather-related phenomena. Increased heat can moreover worsen sleep conditions, which can further degrade cognition and behaviour[34]. Medical and biomedical research has focused on understanding the multiple ways that extreme heat exposure impacts the brain, for example, by increasing the permeability of the blood–brain barrier allowing damaging toxins and pathogens to infiltrate the brain, or by inhibiting the ability of cells and tissues to detoxify byproducts of oxygen metabolism[22,36]. However, relatively little research has focused on the neurocognitive implications of these impacts.

Given the variety of dysfunctions associated with extreme weather and heat (for example, decreased cognitive performance, worsening sleep and so on), there are many avenues by which neuroscience research can make substantive contributions to understanding how hotter environments impact the brain and behaviour. Importantly, some of these negative outcomes may be reversible, or at least mitigatable. A better understanding of the neural basis of these phenomena may be leveraged by psychologists and healthcare professionals to develop targeted interventions.

Poor air quality. Another negative consequence of climate change relates to its complicated association with air quality. While air pollution (for example, transport-related and factory emissions) directly contributes to climate change, this atmospheric warming can also increase ground-level ozone (a key component of smog), fine airborne particulate matter and exposure to allergens[36,37]. In addition, as climate change worsens, so does the increased frequency and severity of wildfires and bushfires, which relates to dangerous smoke events. These greatly degrade air quality and are associated with thousands of deaths per year, most of which are hundreds of kilometres away from the source[38].

Exposure to air pollution has profound negative impacts on brain health and cognitive functioning. For example, prenatal exposure to air pollutants was associated with decreased brain volume in the left hemisphere, which was also linked to decreased processing speed and attention deficit hyperactivity disorder symptoms in urban youth[14]. Increased exposure to fine particulate matter has been linked to reduced cognitive performance and different forms of cognitive decline, including dementia and Alzheimer's disease[39]. One extremely well-powered study ($N > 1.4$ million) found that each standard deviation increase in exposure to air pollutants resulted in a 16–42% increase in the risk of developing a brain infarct[40]. Such brain infarcts are typically asymptomatic but can be a precursor or an early warning signal of a more dangerous symptomatic stroke, or even early onset of dementia[41]. This work highlights an important benefit of utilizing neuroscientific approaches as they can help to detect problems before they are behaviourally observable.

Stress and anxiety. Another major consequence of climate change is related to increased levels of stress and anxiety[20,42,43]. Specifically, exposure to more frequent and powerful extreme weather events, reduced access to food and water resources, forced migration, and heightened conflict will result in increased societal stress levels. Exposure to natural disasters is strongly associated with high psychological distress and psychiatric disorders such as post-traumatic stress disorder (PTSD) and depression[44]. Specific neurobiological signatures of PTSD related to natural disasters have been identified, which are distinct from the signatures of PTSD related to other causes (Table 1)[45]. It follows that tailored treatments based on the origin of the trauma are needed[44,45], but research in this area is limited.

Research has also begun to track record levels of 'climate anxiety', particularly among young adults[20]. This is especially concerning as insights from clinical and psychiatric neuroscience have demonstrated how chronic stress during youth relates to permanent alterations in brain structure and the development of psychopathology later in life[46]. However, climate anxiety appears to be distinct from other forms of anxiety[43], which suggests that its impact on the brain may also be different. Even with comprehensive policy actions to combat climate change, global temperatures will continue to rise for the next 10–20 years[1], suggesting that levels of stress and climate anxiety may also increase. What is currently missing is a better understanding of how these impacts relate to changes in brain structure and function, and to what extent they are distinct from more general forms of stress and anxiety.

These empirical findings and emerging insights highlight the potential contributions that neuroscientists can make by adding to our understanding of how a changing climate impacts the brain. Importantly, many of these outcomes are likely to interact, magnifying their negative consequences. For example, extreme heat is not only linked to worse air quality (for example, via the increased frequency of wildfires), but also increases the permeability of the blood–brain barrier to more harmful neurotoxins[23]. Thus, health issues related to poor air quality are probably exacerbated in regions with warmer climates and/or more frequent extreme weather events. Further, the outcomes addressed above are probably interacting with many other factors not considered here, in complex ways. Careful investigation is needed to better characterize what these complex interactions mean for the brain and determine how we can adapt to, or at least reduce, these negative impacts of climate change.

In the next section, we will take these ideas one step further and discuss how neuroscience can support the development and evaluation of specific interventions to support human adaptation to climate change.

Can neuroscience help with climate change adaptation?

Integrating neuroscientific and biomedical approaches can inform and quantify the efficacy of specific climate change adaptation strategies. For instance, if during a heatwave a part of the concerned population is equipped with air-conditioning or fans, compared with

Table 1 | Non-exhaustive selection of cognitive and affective processes and the related brain regions that play a role in the context of climate change

	Relevance for climate change	Cognitive and affective processes	Possible neural substrates
Path A: environment to brain	Climate anxiety	Fear and anxiety[81,82]	Amygdala, periaqueductal gray
	Climate-related PTSD	Fear-conditioning and extinction[45]	Ventromedial prefrontal cortex, amygdala, insula
Path B: brain to environment	Awareness of future consequences of climate change	Mental simulations of future events[57,83]	Ventromedial prefrontal cortex, hippocampus, parahippocampal cortex
	Weighing of current costs of climate action versus future consequences of inaction	Temporal discounting[84,85]	Dorsolateral prefrontal cortex, posterior parietal cortex
	Awareness of the risks of climate action versus inaction	Risk perception and loss aversion[86,87]	Amygdala, insula, ventromedial prefrontal cortex, striatum
	Awareness of the collective nature of the climate change problem	Mentalizing and perspective-taking[69,70,88]	Temporoparietal junction, posterior cingulate, medial prefrontal cortex
	Evaluation of the reward value of specific actions; prediction of the population demand for sustainable products	Reward anticipation and processing[89–91]	Ventral striatum, ventromedial prefrontal cortex, amygdala, medial orbitofrontal cortex
	Integration of different costs and rewards related to behavioural options; prediction of the population effect of communication strategies	Value integration[91–94]	Medial prefrontal cortex, ventral striatum, anterior cingulate cortex, insula
	Translation of intentions into concrete actions	Cognitive control[95,96]	Dorsolateral prefrontal cortex, anterior cingulate cortex, parietal lobe

Note that the same brain region can be involved in several cognitive and affective processes. It is not possible to infer the involvement of a specific cognitive or affective process from the activation of a specific brain region alone, unless methodological precautions are taken[97].

a control group without this equipment, it would be possible to quantify the impact of heat on brain and body regarding a variety of neural and psychological mechanisms (for example, structural brain scans, resting-state analysis, cognitive tests, sleep analyses, medical exams). This would highlight and quantify the benefits of keeping the brain and body cool. Similarly, during wildfire smoke season, providing air quality sensors, purifiers and masks, and comparing brain scans and medical reports with a control group would allow for the quantification of the specific impact of wildfire smoke on the brain and body. Finally, researchers could utilize artificial and simulated environments that mimic the consequences of climate change (for example, heat suits), to investigate how the brain and cognitive functioning is affected. These approaches would offer evidence to governments, policymakers and the public about the dangers of heat, smoke exposure and the future negative impacts of climate change, and highlight and quantify the importance of interventions tailored to climate change adaptation.

At the same time, researchers need to keep in mind the costs and unintended environmental side-effects of specific adaptation strategies. For instance, technologies such as air-conditioning require substantial amounts of energy, which ultimately contributes to worsening climate change. Implementation of technology-based adaptation strategies should be complemented with information and education programmes that teach efficient usage and with technological adaptations such as outlet timers or motion detectors, to reduce the energy consumption of adaptation approaches. Researchers moreover should be attentive to the potential unintended neural and psychological side-effects of specific adaptation strategies. For example, if policymakers recommend that people stay indoors during a heatwave to reduce heat stress, this may result in reduced time outdoors in natural and social settings that promote well-being. For instance, a 60-minute walk in a green forest environment reduced stress-associated activity in the amygdala compared with a walk in an urban setting[47]. Neuroscientific findings like these are contributing to a growing evidence base that quantifies the benefits of expanding urban woodlands and creating accessible green spaces in cities[48]. Ultimately, this evidence should inform policymakers, urban planners and developers.

Findings on the restorative benefits of nature exposure have moreover motivated research on whether technological advances such as immersive virtual simulations of nature can convey some of the same restorative benefits when direct access to nature is not possible (for example, due to adverse impacts of climate change such as heatwaves)[49]. Exposure to virtual nature has indeed been found to confer similar benefits, including reduced boredom and pain, increased positive affect, and improved cognitive performance and well-being[50,51]. Future research may combine actual and virtual nature exposure with neuroimaging approaches to better understand the processes underlying the restorative impact of nature. Once these mechanisms are identified, virtual exposure techniques that can be used when access to nature is not possible can be identified and optimized.

Neuroscientists can contribute to identifying ways to make human (and non-human) brains more resilient towards the negative impact of climate change by better understanding the impact of adaptation technologies or the restorative effects of nature exposure. Neuroscientists can moreover contribute to investigating the adverse effects of other climate-change-related impacts such as increased flooding, drought, biodiversity loss and migration on populations across a range of different contexts globally, and help identify ways to protect against these impacts. Immersive virtual reality exposure to the consequences of climate change can also be used in this context to increase awareness of climate change and to motivate climate action[52,53]. Traditional classroom-based educational measures have also shown promising effects in promoting pro-environmental attitudes and behaviours[54]. Complementing these approaches with more realistic stimuli[53] as well as with pertinent findings about the adverse effects of climate change on brain and health may help improve existing educational interventions about climate change[52,55].

Key questions relating to path B

Neuroscientists in subfields such as neuroeconomics or social and affective neuroscience have become interested in understanding the neural underpinnings of complex human decision-making. This research has substantially increased the understanding of the interplay of different cognitive and affective brain regions that are important for human judgements and decisions, many of which are relevant in the context of climate change (Table 1)[6].

What drives environmental behaviour at the neural level?
Research specifically addressing these issues in the environmental domain is relatively sparse. A few studies have begun to explore how activity in specific neural circuits relates to judgements and behaviours that impact the environment[28,56,57]. For instance, research has tried to identify neural activation patterns specific to individuals with high concern for climate change and high levels of pro-environmental behaviours[58]. Similarly, research has investigated how personality traits relate to neural differences in the processing of climate change information[57], how the reward value of green consumer products is encoded[59], and how differences in brain morphology[60] as well as differences in brain activity in regions associated with cognitive processing and self-control explain differences in the frequency of pro-environmental behaviour[58,61].

Neuroscience has moreover provided insights into the neural representations of different types of action impacting the environment. For example, in one recent study[28], when instructed to think about ways to increase their pro-environmental behaviours (for example, taking the train), participants showed increased activity in brain regions involved in reward integration. Conversely, when those participants were instructed to think about decreasing environmentally harmful behaviours (for example, lowering the heating), they showed increased activity in regions involved in loss anticipation and cognitive control. Interestingly, they judged increasing pro-environmental behaviours to be more feasible than decreasing their environmentally harmful behaviours. This dissociation at the neural level may help to better understand why people are able to adopt new pro-environmental behaviours while simultaneously continuing to persist with environmentally harmful habits[29]. The dissociation may help get a better conceptual grasp on processes such as cognitive dissonance[8] and their role in the context of sustainable actions. It also supports the idea that different intervention strategies may be required when aiming to increase pro-environmental behaviours (for example, leveraging positive emotions[29]) compared with decreasing environmentally harmful behaviours (for example, leveraging different types of norm[62]).

This brief overview illustrates the potential of functional and anatomical neuroimaging data to illuminate the neural substrates of traits, judgements and decisions that relate to different types of environmental behaviour. Future research could investigate inter-individual and group differences in a more systematic and theory-driven manner. For example, neuroscientific research focusing on the neural markers of climate-change-related motivation and decision-making could investigate how and why specific groups tend to resist adopting sustainable lifestyles (for example, comparing conservatives and liberals, or vegans and omnivores). Do such groups systematically differ in the ways that they process climate-change-related information[63]? Are there structural differences that might shed light on how and why group differences occur? While still at its beginning, a neuroscience of sustainable decisions and behaviours can undoubtedly help to answer these questions.

How can neuroscience inform climate behaviour change and communication strategies?
Neuroscientific measures of the mechanisms underlying attitude and behaviour change may offer important new avenues for the design, selection and improvement of concrete intervention and communication strategies aiming to promote climate action. During the development stage of such interventions, the selection and design is frequently guided by focus groups or self-reported behaviour change intentions of survey participants. This can be problematic for two main reasons. First, self-reported reactions towards persuasive communication strategies may only partially reflect the impact of these stimuli, and self-reported intentions to change one's behaviour may not always be a good indicator of actual future behaviour (the intention–behaviour gap)[8,64]. This may be owing to implicit cognitive or affective processes not accessible to conscious awareness, demand characteristics, social desirability or the presence of other processes active during encoding that are not captured by summary ratings[7,8,59,64]. By complementing these approaches with brain recordings, a deeper understanding of the encoding process can be gained, which may help uncover drivers and barriers to behaviour change that are missed by relying on self-reports[26,64]. Second, explicit individual self-reports do not always accurately relate to group-level behaviour[26,30]. Neuroimaging research has shown that neural activation in specific regions outperforms self-reports in predicting population effects of health communication campaigns[30]. This finding points to the enormous potential of neuroscientific approaches, particularly as an implicit measurement, to help design and evaluate impactful strategies to motivate climate action and sustainable behaviour.

Research on the neural basis of decision-making has identified neural predictors of choices based on the considerations of gains versus losses and the integration of different types of value (for example, economic versus social)[6,25,65–67]. This approach has been leveraged to predict demand for products such as chocolate, music or movies[65,66,68], and can also be used to study purchase decisions for sustainable products at the individual level and, importantly, at aggregate and population levels[56,66,67]. For instance, individual neural responses in reward anticipation networks towards eco-labelled light bulbs predicted increased choices of these bulbs in individual participants as well as demand for eco-labelled bulbs at the population level in a national survey[56]. Importantly, this work suggests that neuroscientific insights can predict choice beyond what simple behavioural or psychological measures can[67].

Brain stimulation techniques moreover allow researchers to causally test psychological models of sustainable decision-making by experimentally manipulating the underlying neurocognitive processes. One recent study used transcranial brain stimulation to test the hypothesis that an inability to take the perspective of future generations generates a lack of sustainable behaviour. Consistent with this hypothesis, upregulating activation in a region involved in mentalizing increased sustainable decisions in an intergenerational economic dilemma task[69,70]. In contrast, inhibiting activation in regions involved in self-regulation processes did not influence sustainable choices in a similar task[71]. Neuroscientific approaches may thus provide causal insights into the mechanisms that do and do not underlie pro-environmental behaviour and may ultimately inform the development of more effective interventions.

Neuroimaging techniques may help to better understand sustainable decision-making mechanisms and inform climate change communication strategies and behaviour change interventions. For instance, the findings outlined above suggest that rather than strengthening self-control processes, imagining the plight of future generations may be a more effective way to increase sustainable decisions. Behaviour change interventions in the scanner can be fruitfully combined with virtual reality techniques (for example, by demonstrating the future consequences of climate change by showing rising sea levels in cities, or by assessing consumer decisions in more realistic simulated settings[53]), as more realistic environments will allow for a more ecologically valid evaluation of choices in experimental settings (for example, by reducing psychological distance)[24,52,57]. Using neural data to predict the success of specific interventions out-of-sample can yield important insights into how effective policy and communication strategies should be designed to encourage climate action.

Weighing the costs and benefits of climate neuroscience

While this article highlights the potential contribution of neuroscience to understanding and addressing climate change, it is important to consider that neuroscientific methodologies can exact considerable environmental costs. For instance, the amount of energy required to operate a Siemens Magnetom Prisma 3 Tesla MRI scanner 5 days a week is approximately 200 MWh per year[72], equivalent to the average energy consumption of 18 US homes per year[73]. Conference travel is another major contributor; travel emissions at one conference were estimated to be 1.3–1.8 tons of carbon per attendee[74]. Given that one of the most important neuroscience conferences welcomed 30,000 researchers in 2022, this means their footprint was equivalent to the energy usage of 5,857 US homes per year[73].

Neuroscience researchers interested in working on the questions and pathways discussed here must be mindful of ways to reduce their scientific carbon footprint. This can take on many forms. For example, the norms around virtual or hybrid conferences have shifted, and there are now multiple effective online platforms. Another viable option involves holding multi-site conferences with virtual links between them[74]. Academics can also help to mitigate their professional footprint by decreasing overconsumption of resources (for example, laboratory animals), directing the use of grant money towards companies that prioritize sustainability, participating in civil disobedience[75] and lobbying relevant societies (for example, the Society for Neuroscience) to help advance green policies and laws[76]. Additionally, coordinating efforts and collaborating between different research groups will ensure that multiple similar projects are not conducted at the same time, reducing the likelihood of wasting precious resources.

Moreover, researchers should consider how to maximize the impact of scientific contribution in climate change neuroscience. Most research questions on climate change do not need to be tackled with a neuroscientific toolkit. Surveys, lab-based methodologies and field experiments on their own greatly advance the understanding of different types of environmental behaviour[55,77]. Depending on the research question at hand, combining these approaches with neuroscientific measures can be a viable way to further understanding. With these considerations in mind, the neuroscientific community should focus on purposeful and impactful research[77]. Leveraging complementary approaches, divergent perspectives and interdisciplinary collaborations will help achieve this goal. Neuroscience might benefit from adopting big team science approaches, for example, by testing multiple interventions targeting the same dependent variable in multi-site collaborations (for example, megastudies, many-labs approaches[78] or ENIGMA-style projects[79]).

Finally, researchers and editors need to be measured when disseminating neuroscientific results, and be aware and transparent about the claims that they realistically can or cannot make. This is especially important in the neuroscience domain, as merely including brain images in scientific discourse has been shown to increase the persuasive influence and allure of the research towards laypeople[80]. Researchers should avoid overselling and overstating results, and clarify if the results are causal or correlational. In addition to impeding scientific progress, non-transparent and incorrect practices can catch the public's eye and reduce trust in research.

Conclusions

Anthropogenic climate change poses a substantial threat to societal living conditions[1]. Here, we argue that neuroscience can substantially contribute to the fight against climate change, and provide a framework and a roadmap to organize and prioritize neuroscience research in this domain. We outline different key questions and pathways to which neuroscientists can contribute (Fig. 1). In path A, we propose that neuroscience can evaluate and quantify how the different consequences of climate change impact the brain, and we discuss possibilities for how neuroscience might be leveraged to better adapt to these negative consequences. In path B, we discuss existing and potential future research on the neural substates of decisions with pro-environmental and environmentally harmful outcomes, and explore how neuroscientific knowledge can inform communication and intervention strategies to promote climate action. We emphasize the need for purposeful and impactful research, international collaboration, and interdisciplinary integration to make notable progress in addressing climate change. Bridging levels of analysis, from neurons to societal actions, is crucial in solving these existential challenges.

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Competing interests

The authors declare no competing interests.

Additional information

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