Postdigital Science and Education
https://doi.org/10.1007/s42438-018-0008-5

ORIGINAL ARTICLES

Brain Data: Scanning, Scraping and Sculpting the Plastic Learning Brain Through Neurotechnology

Ben Williamson[1]

Abstract

Neurotechnology is an advancing field of research and development with significant implications for education. As 'postdigital' hybrids of biological and informational codes, novel neurotechnologies combine neuroscience insights into the human brain with advanced technical development in brain imaging, brain-computer interfaces, neurofeedback platforms, brain stimulation and other neuroenhancement applications. Merging neurobiological knowledge about human life with computational technologies, neurotechnology exemplifies how postdigital science will play a significant role in societies and education in decades to come. As neurotechnology developments are being extended to education, they present potential for businesses and governments to enact new techniques of 'neurogovernance' by 'scanning' the brain, 'scraping' it for data and then 'sculpting' the brain toward particular capacities. The aim of this article is to critically review neurotechnology developments and implications for education. It examines the purposes to which neurotechnology development is being put in education, interrogating the commercial and governmental objectives associated with it and the neuroscientific concepts and expertise that underpin it. Finally, the article raises significant ethical and governance issues related to neurotechnology development and postdigital science that require concerted attention from education researchers.

Keywords Biosocial · Brain · Data · Neuroscience · Neurotechnology · Postdigital science

The human brain has become the focus of concerted attention among policymakers, the media and the public as neuroscientific understandings have left the laboratory to shape how societies understand human life and social affairs (Rose and Abi-Rached 2013). Technical innovations in computing software and data analytics now appear to promise to make human neurology amenable to inspection without the need for complex clinical or medical apparatuses, making the generation of digital 'brain data' possible in 'real time'

✉ Ben Williamson
ben.williamson@stir.ac.uk

[1] University of Stirling, Stirling, UK

and in situ. ‘Neurotechnology’ is a broad field of brain-centred research and development dedicated to opening up the brain to computational analysis, modification, simulation and control. It includes advanced neural imaging systems for real-time brain monitoring; brain-inspired ‘neural networks’ and bio-mimetic ‘cognitive computing’; synthetic neurobiology; brain-computer interfaces and wearable neuroheadsets; brain simulation platforms; neurostimulator systems; personal neuroinformatics; and other forms of brain-machine integration (Nuffield Council on Bioethics 2013; Rose et al. 2016; Yuste et al. 2017). These rapid advances in human neuroscience and ‘pervasive neurotechnology’ are bringing about new ‘brain-society-computer entanglements’ and potentially ‘unprecedented opportunities for accessing, collecting, sharing and manipulating information from the human brain’ (Ienca and Andorno 2017: 1). Pervasive neurotechnology has also been valued by market researchers as a multi-billion dollar sector for investment and monetisation of patents, intellectual property and licensing (SharpBrains 2015), stimulating a significant rise in organisations and investors seeking ‘neurotechnology capital’ (Potomac Institute 2015).

As a result, neurotechnology has been accompanied by hyperbolic claims about ‘a new era of “augmentation,” “enhancement,” “optimization” or “upgrades” of various kinds, which promise to make us “better than well” or “better than humans,” if not “better than human”’ (Williams et al. 2011: 137). A vast range of techniques has been developed ‘aimed at cognitive modification and enhancement’, such as ‘brain-machine interfaces, … electric stimulators, and brain mapping technologies’, which ‘now target the brain for modification and rewiring’ (Pitts-Taylor 2016: 18). Therefore,

> if in the past decades neurotechnology has unlocked the human brain and made it readable under scientific lenses, the upcoming decades will see neurotechnology becoming pervasive and embedded in numerous aspects of our lives and increasingly effective in modulating the neural correlates of our psychology and behaviour (Ienca and Andorno 2017: 5).

Whilst caution is required about neurotechnology-determinist views, it appears to hold potential to ‘scan’ the structure and functions of the brain at high degrees of visual and statistical fidelity, ‘scrape’ electrical signals from the brain in order to produce analysable digital brain data and then to ‘sculpt’ and modulate the brain through electrical stimulation, feedback and neuroenhancement. In these ways, neurotechnology promises not only to make it possible to understand human neurology better and thereby target brain regions and functions to change individual behaviours, but to transform whole societies by intervening in the brain.

Merging neurobiological knowledge about human life with computational technologies, neurotechnology exemplifies how hybrid ‘postdigital’ technologies and sciences consisting of technological and non-technological, biological and informational elements combined in new ways will play a significant role in societies in decades to come (Jandric et al. 2018; Taffel 2016). As a postdigital composite of scientific expertise in computing and algorithms with embodied and embrained biology, neurotechnology raises significant questions about how the human brain may be examined, modelled, understood and made amenable to manipulation and modification in years and decades to come.

A wave of advocacy for neurotechnology development and implementation is now being experienced in the field of education. Rather than taking a determinist perspective, the aim of this article is to critically review neurotechnology research and development and examine the aspirations and purposes to which it is being put as it is emerging in education. As Rose (2016: 158) asks, even if it is 'premature to conclude that these neurotechnologies have rendered the mind transparent through their access to traces in the brain … let alone in using brain modulation directly for the government of conduct', why still do some dream that new neurotechnologies will make it possible to 'read' the brain or even 'read back' into it, what practical applications might such technologies lead to and what social, political and commercial aspirations catalyse them? This article sets out an agenda for research on postdigital neurotechnology, a conceptual framework and a series of emerging challenges to begin addressing such questions within the educational context. It contributes to burgeoning scholarship examining the increasing mobilisation of theory, research and practice from the life sciences and computing sciences to inform and influence educational policy and practice (Gulson and Webb 2018), in particular by developing concepts from 'biosocial' theory, 'sociotechnical' software studies and 'posthumanist' theory to conceptualise the postdigital interpenetration of the biological, the social and the technical, as well as the imaginary, in neurotechnology development and application.

The Neurotechnology Revolution

The human brain has become the focus of intense interest across scientific, technical, governmental, and commercial domains in recent years. Increasingly, critical social scientific studies of neuroscience have begun to highlight the social power imputed to neuroscience to solve major societal problems (Rose and Abi-Rached 2013), its explanatory force for popular culture, public policy, business and marketing (Broer and Pickersgill 2015; Pykett 2015) and its role in contemporary understandings of the human self and identity (Pitts-Taylor 2016). Crucially, the brain has been reconceived as 'plastic' and 'permeable' to external influence, reflecting 'a long history of attempts to govern deeply plastic bodies' (Meloni 2018: 5). Whitehead et al. (2018) describe a new era of 'neuroliberalism' in which neurological insights, combined with psychology and behavioural sciences, are used to deliberately shape and govern human conduct. Studies have also emerged of how neurotechnologies are being developed to augment, enhance brain function and optimise the neural correlates of behaviour and cognition, with the Morningside Group of neuroscientists, neurotechnologists and ethicists claiming,

> we are on a path to a world in which it will be possible to decode people's mental processes and directly manipulate the brain mechanisms underlying their intentions, emotions and decisions; where individuals could communicate with others simply by thinking; and where powerful computational systems linked directly to people's brains aid their interactions with the world such that their mental and physical abilities are greatly enhanced. (Yuste et al. 2017: 160)

In this context, neurotechnology development over the coming years and decades promises both to enhance the scientific understanding of the brain and to enhance the functioning of the brain too, raising significant risks and ethical challenges that are only just beginning to be addressed (Ienca and Andorno 2017).

Neuroscientific research into the brain itself has advanced significantly with the development and refinement of brain imaging neurotechnologies. Driven by massive research grants and private partnerships, huge teams of neuroscience experts associated with international projects have begun to visualise and build ‘wiring diagrams’ and computational models of the cells and neural circuits of the brain at a highly granular, neuromolecular level of detail and fidelity, all based on the collection and analysis of massive records of brain data (Rose et al. 2016). Therefore, brain imaging neurotechnologies ‘embody and enact the premise that the brain is the place where mental events are located and that there must, therefore, be material traces of such mental events in the brain itself. And if those traces exist, it must be possible—both in principle and now it seems in practice—to make them legible’ (Rose 2016: 5).

In a further advance on neuro-imaging, brain-computer interfaces (BCI) are designed to ‘decode’ mental states from ongoing brain signals (Blankertz et al. 2016; Ramadan and Vasilakos 2017). The goal of BCI R&D is to develop wearable ‘neuroheadset’ technologies that can record from very large numbers of neurons simultaneously in order to create ‘a seamless, high-throughput data link between the human brain and computers’ which ‘could make a “brain modem” really possible’ (Piore 2017). In other words, the intention behind BCIs is to scrape the brain for signals that might then be able to interact with devices, not just scan and visualise brains. Some medical grade-invasive BCI electrodes literally scrape the cortical surface to detect high-fidelity brain signals, but the creation of noninvasive, consumer-grade BCIs has become the focus of interest by many international organisations, technology entrepreneurs and investors (Metz 2017; Piore 2016; Regalado 2017a, b; SharpBrains 2015). They are ‘investing in the creation of devices that can both “read” human brain activity and “write” neural information into the brain’, with the potential for ‘direct linking of people’s brains to machine intelligence, and the bypassing of the normal sensorimotor functions of brains and bodies’ (Yuste et al. 2017: 160–61).

The perceived ‘plasticity’ of the brain has also become the focus for the growth of ‘neurostimulation’ products and practices (Wexler 2017). Brain stimulator devices ‘are not primarily used for recording or decoding brain activity but rather for stimulating or modulating brain activity electrically’ (Ienca and Andorno 2017: 5). Recent technical breakthroughs in electrode design suggest it is feasible to modulate neuronal activity and modify electrical signaling between neurons by synthetically catalyzing electrochemical reactions with silicon wires (Lerner 2018). Although clinical research exploring its efficacy remains far from conclusive, neurostimulation has been promoted as a cheap and effective tool to enhance cognitive and behavioural function (Horvath et al. 2014). As a result, a marketplace in Do-It-Yourself neurostimulation has grown since the early 2010s, with DIY ‘neurohackers’ attempting to optimise their brains to achieve enhanced performance using consumer kits (Wexler 2017). Whilst, then, neuroimaging is primarily concerned with scanning brain structure and function and BCI R&D with scraping electrical signals from the brain, neurostimulators are specifically engineered to sculpt the brain to perform in enhanced or optimised ways.

Neuroscience and neurotechnology development are not merely scientific and technical fields of innovation and discovery. Critical social science studies of neuroscience have engaged with the politics involved when social norms and power 'entangle with neurobiological processes' (Pitts-Taylor 2016: 5). The expert knowledge of neuroscience is assuming a significant role in contemporary techniques of governance and political objectives (Broer and Pickersgill 2015). The brain has become a 'biopolitical resource' for international competitiveness and the object of social control, such that 'the problems of governing living populations now seem to demand attention to the brains of citizens' (Rose and Abi-Rached 2014: 5). As a consequence, the brain has become the focus not just for medicalised forms of treatment, but also the political focus of efforts to improve the brain, and by doing so to shape positive outcomes for society at large. In this biopolitical context, a permeable and plastic subjectivity with qualities of malleability, modifiability and manipulability is the target of 'intensive regimes of regulation and surveillance' (Meloni 2018: 12).

The policy implications of neuroscientific and neurotechnological development have been articulated by (among others) the Potomac Institute for Policy Studies, a policy institute with its own Center for Neurotechnology Studies that informs US government departments and military agencies. Its report 'Enhancing the Brain and Reshaping Society' claims that neuroenhancements will become widespread, improve collective human performance and transform society in coming years (Potomac Institute 2014). As a result, it has called for collaborative efforts between policymakers, scientists and the private sector to develop novel neurotechnologies that can enhance individuals' cognitive abilities and behaviours in order to 'improve social order' (6) and thereby 'ensure neuroenhancement of the individual will result in enrichment of our society as a whole' (45).

As the Potomac Institute's aspirations indicate, neurotechnology is imprinted with powerful social and political visions of a future in which brain data can be used to know and monitor populations, and to enhance the mental states of individuals to meet certain aspirations for society at large. Neurotechnological applications register the emergence of imagined 'neurofutures' based on a 'neuro-realist' set of 'brain facts' which assume that 'mental life can be understood, mapped, visualized, maintained, managed, improved, enhanced or optimized today or in the near future in these neuro-related, brain-based ways' (Williams et al. 2011: 136). In the rest of this article, the concept of imagined neurofutures underpins the non-determinist perspective taken on neurotechnology, drawing attention to such technologies as framed by political and commercial aspirations which sometimes obscure the current state of technical development, especially in education.

Education and Neuroscience

Educational neurotechnologies are part of a fast-growing interest among academic researchers, policymakers, global charities, research funders and commercial companies in the application of neuroscience to education (Busso and Pollack 2015). As an emerging academic field, educational neuroscience (or 'Mind, Brain and Education' as known in north America) has its own postgraduate programs, dedicated journals, special issues, conferences, special interest groups, research centres, policy advocates and sources of funding (Commissar and Brookman-Byrne 2017), as well as debates and controversies (Howard-Jones et al. 2016). Practical applications of educational neuroscience (sometimes referred to as 'neuroeducation') have proliferated to include a variety of brain-targeted teaching resources and brain-training programs, as well as educational and social policies directed at children's brains for cognitive enhancement, emotional self-regulation and other forms of educational performance improvement (de Vos 2016). Increasingly, researchers of educational neuroscience and developers of neuroeducation applications are seeking technical methods for collecting 'real-time' brain data from authentic school contexts or educational environments, and are actively pursuing development of neuro-imaging, wearable enhanced learning technologies and related devices to achieve this aim (Charland and Dion 2018).

Although much educational neuroscience aims to develop scientific understanding of the neural correlates of learning, a strongly normative aspiration to improve future education and enhance learning also animates much of the interest in brain-based teaching and research (Pykett 2015). A recent editorial for a special issue on 'Brain science, education and learning' envisaged the use of neuroscientific knowledge and technologies to inform new educational policies and practices for fast-changing times:

> The breathtakingly rapid pace of change in the twenty-first century … is pressuring us to develop a wider range of multifaceted, multidisciplinary, complex, and integrated competencies, for which many education and learning systems are yet to be ready. … Building a scientific groundwork offers hope, by providing an expanded, updated, and potentially useful toolkit for improving education and learning. … Thus, understanding the 'learning brain' can provide an additional tool … to facilitate students' learning and development. (Marope 2016: 188)

For educational neuroscientists, because learning 'at a neurobiological level literally means changing the structure, functioning, and connectivity of young brains', in order to '"sculpt" the unique brain of an individual learner', concerted efforts are being made to explore 'how neuroscience can feed into educational thinking, policy, and practice' (Marope 2016: 188–89). Neuroscience insights have already been translated into new educational 'policy science' approaches, often through direct policy advocacy and lobbying (McGimpsey et al. 2016), as part of how new knowledges in the life sciences, powered by computational technologies, are influencing social and educational policy-making and analysis (Gulson and Webb 2018).

At the core of much educational neuroscience research—and of efforts to build practical neuroeducation applications especially—is the neuroscientific concept of 'plasticity' (Bishop 2013). Neuroplasticity describes how the brain is materially affected by learning, experience, or environmental stimuli and interaction, as synaptic connections between neurons are 'wired' together, trimmed, pruned and 'rewired' across the entire lifespan (Tovar-Moll and Lent 2016), and is part of a contemporary fascination with 'corporeal plasticity' that extends across the life sciences (Meloni 2018). Brain plasticity has been studied by neuroscientists at every level of nervous system organisation, from molecular activity through specific neuronal networks to brain-wide systems and behaviours, although it has recently become something of a buzzword and catalysed dubious claims about the capacity to 'rewire the brain' (Costandi 2016: 13). Nonetheless, within educational neuroscience, plasticity has become an important concept for studies seeking to trace learning in dynamic brain structure and functioning:

> The asymmetrical, reciprocal interaction between learner and teacher is basically an interaction between two brains…. Neuroplasticity may be defined as the ability of the brain to undergo temporary or permanent changes whenever it is influenced by other brains and by the environment. (Tovar-Moll and Lent 2016: 200)

For many neuroeducation advocates, the normative task is to design 'brain-targeted' pedagogic interventions and practices that are intended to activate plasticity processes in order to change the brain to achieve certain outcomes. Neuroscience-based technological developments therefore present opportunities for businesses and governments to enact new techniques of neuroenhancement through education by targeting the plastic learning brain toward particular cognitive and affective capacities. The development of new neurotechnologies appears to make the learning brain legible in real time, whilst its plasticity is inspiring technical innovations to modulate or influence the brain.

To make sense of the postdigital intersections of neuroscience, political imaginaries and technical development within education, the next section presents a conceptual framework combining insights from critical biosocial studies of neuroscience, science and technology studies of sociotechnical systems and posthumanist theorisations of human, biological and technical assemblages.

Bio-socio-technical Assemblages

The permeability of the body and the brain to their social, material and technical surroundings—as both nurtured and natured, biologically embodied and socioculturally embedded—is at the core of 'biosocial' studies (Meloni et al. 2016). Biosocial studies emphasise how social environments 'get under the skin' to influence the biological functions of the body, whilst also acknowledging how biology extends 'outside the skin' through human actions that impact upon the social environment (Fitzgerald and Callard 2015; Pickersgill 2013). Much biosocial research focuses on neuroplasticity and other biological processes by which the brain changes continuously throughout life in response to socioculturally embedded experience, embodied stimuli and environmental context (Bone 2016). Biosocial studies therefore acknowledge that 'the brain is a multiply connected device profoundly shaped by social influences' (Meloni et al. 2016: 9), both 'constituted by evolutionary biology' and also 'embedded in complex social networks' (Pitts-Taylor 2016: 2). As such, 'the body bears the inscriptions of its socially and materially situated milieu', being 'socially modulated' and 'influenced by power structures in society' (Meloni et al. 2016: 13). Biosocial studies of education have also begun to emerge that connect neuroscience and bioscience with sociology of education, seeking to understand learning processes as the dynamic outcomes of biological, genetic and neural factors combined with socially and culturally embedded interactions, and political and economic contexts (Youdell 2016).

Despite its emphasis on how power structures in society become etched in brains, biosocial theory has to date neglected the specific role of technical systems in the complex social networks within which brain plasticity may be activated. Social scientific studies of digital technologies in science and technology studies (STS) refer to 'sociotechnical systems' as the contingent product of particular interests, values and logics which are encoded in the systems and devices (Postigo and O'Donnell 2017). Software, specifically, is simultaneously a product of social, economic and political dynamics, and productive of social, economic and political effects in the world, since it is written 'within diverse social, political and economic contexts', and then 'augments, supplements, mediates and regulates our lives and opens up possibilities—but not in a deterministic way' (Kitchin and Dodge 2011: 43–44). Importantly, too, sociotechnical studies are concerned with the 'imaginaries' that animate technical development—those visions of social order that their originators believe should and could be attained through the application of technology in social, political and economic contexts, and which catalyse technical innovation in the present (Jasanoff 2015). Making sense of neurotechnology requires engagement with both biosocial accounts of brain plasticity and non-deterministic sociotechnical accounts of software, as well as the imagined neurofutures that underpin them, in order to understand the ways that coded environments, social networks and experiences might interact with material bodies and plastic brain processes.

Posthumanist analyses offer resources for conceptualizing how organic bodies and silicon technologies operate as single systems, and for 'rethinking the articulation of humans with intelligent machines' (Hayles 1999: 247). From this perspective, Hayles (2017) has conceptualised how technical devices embedded in sociocultural environments make a neurological difference by sculpting the plasticity of brain structure, function and connections. In particular, her posthumanist account of 'cognitive assemblages' of human biological and technical components builds on 'extended cognition' conceptualisations of humans as 'organic-technological hybrids' whereby cognition and intelligent action are the products of 'human-artefact coalitions' that encompass brain processing, bodily activity, sociocultural environment and material things such as computational media (Wheeler 2011). Moreover, because the brain is 'endowed with a high degree of neural plasticity' and digital media are becoming more pervasive and 'embedded in the environment', the 'integration of humans and intelligent machines' has 'significant neurological consequences' (Hayles 2013: 11), and 'the clear implication is that children who grow up in information-intensive environments will literally have brains wired differently' (100). Such posthumanist analyses help conceptualise the interpenetration of the biological and the technical, though it remains essential, as in software studies, to remain critically cautious about claims that technical innovation will alter human bodies and behaviours in any deterministic way, and to adopt scepticism about oversimplified, ahistorical explanations of plasticity (Meloni 2018).

The interpenetration of cognitive technologies and human neurobiology therefore demands forms of analysis that are attentive to human biological processes, social contexts and environments, and the smart technologies embedded in such environments, all of which are constantly assembling and mutating through situated and contingent biosocial and sociotechnical dynamics to create posthuman assemblages. These combinations of the social, environmental, technical and biological are the focus for emerging 'postdigital' studies that collapse the hard distinction between the digital and other materialities, drawing conceptual resources from software studies, new materialist theory and posthumanist philosophy (Berry 2014). Postdigitality, with its rejection of digital/analogue, material/immaterial, human/nonhuman, nature/culture and virtual/real binaries, implies that humans need to be understood as relational assemblages, 'convergences', or 'meshworks of biology and technology':

> The impacts of evolving technologies on the plastic structures of human neurobiological systems entail that this exterior technical milieu impacts the development of the individual organism as well as structuring its environment, blurring the lines between exterior and interior. (Taffel 2016: 325)

Drawing on this view of the relationality of technology, plastic neurobiology and social environments, the postdigital bio-socio-technical hybridity of educational neurotechnologies may then be understood as three sets of interpenetrating ‘codes’—biological codes, computer codes and social codes.

Biological codes consist of bodily materials, such as genetic codes and the chemicals, cells, neurons, synapses, nervous systems and neural networks that constitute the organ of the brain. These neurobiological codes are not entirely ‘natural’ categories, but themselves the codified knowledge of specific expert disciplinary practices, classifications and categories generated by scientists. Thus, whilst biological codes consist of embodied material, they are readable and intelligible only via scientific lenses and disciplinary vocabularies. *Computer codes* include digitally coded software, computer hardware, networked systems and algorithms. Again, the codes that enact these technologies, written in specific programming languages, are the product of technical specialists working in dedicated settings, with project plans, business objectives and research questions to address. Finally, *social codes*, or codes of conduct, consist of the governing norms, rules, regulations and power relations that pervade environments and structure human action, cognition and affects. These social codes of conduct are the product of experts and authorities that seek to guide, manage or govern human conduct for certain ends. They include but are not confined to official government policies in a context where governance has increasingly dispersed to a range of international organisations, think tanks, commercial companies and philanthropic institutions, particularly those offering or promoting technologies that can modify, shape or influence conduct in ways informed by scientific expertise. These social codes are also animated by imaginary neurofutures of the kinds of societies that could or ought to be attained through neurotechnology application across a range of domains. Indeed, as studies of both neuroscience and software insist, imagined futures infuse both scientific inquiry and technical innovation.

The bio-socio-technical codes of neurotechnology addressed in the rest of this article in particular consist of:

- *Neurobiological codes* of neuroplasticity, neurogenesis, synaptic plasticity, gene expression, epigenetics and chemical neuromodulation, as categorised, classified and codified through the disciplinary apparatus of neuroscience research.
- *Computer codes* that execute neurotechnology, brain imaging, brain-computer interfaces, neurostimulation and hardware, which are produced and practised by technical specialists such as neurocomputing researchers, device producers and manufacturers, software engineers, algorithm designers, data analysts and graphic visualisers.
- *Social codes*, or preferred forms of conduct, such as cognitive modification, behavioural and emotional optimisation, augmented cognition, neuroenhancement and other forms of augmentation as defined through the aims, aspirations and

> imaginary neurofutures of government departments and agencies, policies, philanthropic foundations and think tanks, commercial companies and entrepreneurs.

In other words, the enactment of neurotechnology depends on biological codes pertaining to the brain being made amenable to being read by, modeled on or written on to by, the computer codes of specific software, hardware and algorithms, in ways which reflect and reproduce the social codes of conduct promoted by various authorities according to the preferred imaginary of the future they believe should be attained. Sociotechnical processes of technical development, animated by certain social visions of how neurotechnology might also reshape society, underpin how the plastic brain may be scanned, scraped and sculpted. Biosocial dynamics may also be activated when such technologies are embedded in environments and interact with humans in ways that might interpenetrate human cognition and shape the plasticity of the brain to achieve those visions. The following sections further unpack the postdigital bio-socio-technical codes of neurotechnologies designed to scan, scrape and sculpt the plastic learning brain in education.

Scanning the Brain Through Neuro-imaging

Brain scanning has developed since the 1960s from computerised tomography (CT), through positron emission tomography (PET) and magnetic resonance imaging (MRI) in the 1980s, to today's electroencephalogram (EEG) recordings of brain activity, which detect electrical signals when brain cells activate, and functional magnetic resonance imaging (fMRI) of oxygenation in different parts of the brain. Brain scans are thus the 'most spectacular faces or fronts of contemporary neuroscience' (Williams et al. 2011: 138). Various brain imaging neurotechnologies have been used by educational neuroscience researchers to generate insights for educational policymakers and practitioners. These include wearable headbands to study students' 'brain-to-brain synchrony' within the classroom context (Dikker et al. 2017), neuro-imaging to visualise the brain 'lighting up' when students have adopted a 'growth mindset' (Moser et al. 2011) and EEG brain scanning to detect the neural correlates of students' emotions (Spreeuwenberg 2017).

Attempts have also been made to use brain imaging technologies to analyse the possible biological mechanisms by which socioeconomic status (SES) influences and affects brain and cognitive development in children (Thomas 2017). Specifically, such studies have used brain scanning techniques such as fMRI to measure the cortex, or outer surface of the brain, which is understood to be influenced by experience-related synaptic pruning and increased myelination—the process that enables signals to travel between the brain and other body parts—that expands the surface outward. The results show variety in the volume of certain parts of the brain related to language development, memory and attention, which correlate with SES. Neuroscientifically produced evidence of the 'neurocognitive profile' of SES indicates a causal link that 'growing up poor can keep a child's brain from developing' whilst 'the brains of those with higher family income and more parental education had larger surface areas than their poorer, less-educated peers' (Mariani 2017). According to such 'poverty brain' studies, socioeconomic status is traceable and quantifiable as percentile differences in grey matter based on analysis of brain images produced from fMRI and EEG data (Pitts-Taylor 2016).

Such studies and conclusions have begun to influence policymakers, who can interpret the results to specify remedial intervention for at-risk groups, such as early years education provision, child tax credits and other ‘income-enhancement policies’ (Mariani 2017). In these ways, neurotechnologies are becoming integral parts of new ‘policy science’ (McGimpsey et al. 2016) approaches, enabling policymakers to see policy problems visualised in the neurobiological detail provided by highly persuasive brain images, and to define intervention in response. Meloni (2014) has described the challenges associated with rising awareness of ‘local biologies’—the way that bodies embedded in social settings bear locally specific biological markers of their environment and experience—and the potentially deficit-based ways in which such environments and those inhabiting them may be treated and intervened upon.

Caution is required about the persuasive allure of neuroimagery in educational neuroscience. Despite the ‘neuro-realism’ they convey, their production and reception as objective or real ‘brain-facts’ is in fact a sociotechnical accomplishment involving multiple interpretations, translations and mediations:

> assumptions are not simply ‘designed into’ these scans, but ‘read out’ of them at every stage in the production process, from selecting subjects and the statistical techniques and mathematical models used …, to the decision over how to colour them and which images to publish. (Williams et al. 2011: 139)

The digitally produced neuro-realism of brain visualisation is a sociotechnical artefact of many expert practices, technical affordances and disciplinary assumptions, theories, experimental ‘set-ups’ and neuroscientific ‘styles of thinking’ (Rose and Abi-Rached 2013). Moreover, brain images themselves possess ‘persuasive power’ and are influential because they appeal ‘to people’s affinity for reductionistic explanations of cognitive phenomena’ whilst oversimplifying and misrepresenting conclusions from neuroscience studies (McCabe and Castel 2008: 343).

Approached as a bio-socio-technical assemblage, educational neuro-imaging consists of biological codes pertaining to cortical surface, synaptic pruning and myelination, as defined by neuroscientific expertise. It requires computer codes that enact brain scanning hardware, data analysis and visualisation software, and involves social codes of preferred form of conduct that specify certain ‘normal’ paths of child development and focus policy on intervening in the lives and families of lower SES children.

Scraping the Brain with BCIs

Beyond the uptake of neurotechnology in educational neuroscience research, advocates claim neurotechnology has potential use in classrooms. Some have argued that brain-computer interface (BCI) ‘neurosensing’ devices could be used to measure students’ cognitive activity and attention in real time (Meyers 2015). Although significant reservations exist about either the technical capacity or ethics of BCIs (Regalado 2017a, b), entrepreneurial interest has grown to support the idea that ‘invisible, frictionless and seamless interfaces’ between human brains and AI will have massive implications for education:

> The implications for learning are obvious. When we know what you think, we know whether you are learning, optimise that learning, provide relevant feedback and also reliably assess. To read the mind is to read the learning process…. We are augmenting the brain by making it part of a larger network … ready to interface directly with knowledge and skills, at first with deviceless natural interfaces using voice, gesture and looks, then frictionless brain communications and finally seamless brain links. Clumsy interfaces inhibit learning, clean smooth, deviceless, frictionless and seamless interfaces enhance and accelerate learning. This all plays to enhancing the weaknesses of the evolved biological brain … and [to] think at levels beyond the current limitations of our flawed brains. (Clark 2017)

The imaginary vision of using BCI headsets to take seamless real-time EEG readings of students' brainwaves has animated the company BrainCo, a spin-out from Harvard University's Center for Brain Science and Graduate School of Education (http://www.brainco.tech/#/). BrainCo has developed a headband that reports 'real-time' brainwave data to a teacher's dashboard to indicate levels of attention and engagement, and which might also be used to inform neurofeedback-based brain-training programs. Its promotional video claims it 'accurately translates brain signals into attention level' and BrainCo intends to compile the 'world's largest brainwave database' so that it can quantify the 'invisible metric' of student engagement as legible brain data (Johnson 2017a). The company is understood to be the first producer of a neuroheadset specifically marketed to schools and teachers, despite scientific scepticism about the technology and concerns around brain data privacy and ethics. Moreover, by compiling a database of brain activity from large numbers of users, its founding CEO has claimed, BrainCo intends to '"use artificial intelligence on what will be the world's largest database to improve our algorithms for things like attention and emotion detection"' (Johnson 2017a). Similarly, the company BrainGaze has developed technologies for 'cognitive development tracking' in infants and children, 'based on the discovery of the predictive power of small eye movements as a marker for cognitive visual processing', and has received philanthropic funding from the Bill and Melinda Gates Foundation (http://www.braingaze.com/).

Other sources have suggested that BCIs could be used to inform adaptive learning platforms (Royal Society 2011). It has been claimed that as 'adaptive educational computer programs are being developed in tandem with imaging studies of how such innovations drive changes in brain activity, new possibilities may emerge for educational and cognitive neuroscience research efforts to inform one another in increasingly rapid cycles' (McCandliss cited in Howard-Jones et al. 2015: 140). The assumption is that 'EEG can be processed in real time, supporting applications that require use of online measurement of neural response (e.g., as part of an adaptive system)' (Howard-Jones et al. 2015: 136). The World Economic Forum, as part of its 'Future of Neurotechnologies and Brain Science' program, has also begun to explore 'brain-wearable technology' and 'brain-computer interface' applications for 'optimizing education', notably by 'dynamically adjusting learning' according to real-time brain scanning of individual students (Hadzilacos 2017).

An example of a neuro-adaptive learning platform is Century, 'the tried-and-tested platform that learns how the brain learns and provides a personalised path to mastery for every one of your students' through 'personalised messaging grounded in cognitive neuroscience' (http://www.century.tech/). Staffed by a team of engineers and neuroscientists, Century claims to blend cognitive neuroscience insights into the learning brain with artificial intelligence and machine learning technology, multimedia content and real-time data dashboards of students' achievements and progress. Such neuro-adaptive learning technologies apply brain science insights to personalised learning, based on the assumption that since the brain remains plastic, it is open to shaping through the targeted use of adaptive software systems that can conduct real-time EEG brain imaging and then target learners with the most personally relevant or necessary content or approach. In other words, neuro-adaptive software based on EEG holds the potential to promote brain-personalised learning. The underlying assumption is that personalised learning technologies can better activate neuroplastic changes because they are individually targeted and dynamically adjusted according to each student's brain data.

Such examples of neuro-adaptive software and brain-personalised learning bring together neurobiological codes related to brain plasticity and cognitive development with computer codes that enact adaptive digital learning technologies, such as AI, machine learning algorithms and predictive analytics, all whilst pursuing an ambition to enhance 'brain power' through brain-personalised learning, and thereby instil in children new codes of skilled cognitive conduct. Of course, significant imaginary work infuses these efforts. The neurofuture of brain optimisation assumes that BCIs can accurately track neural signals and translate them into meaningful data for use in adaptive forms of education, though as yet evidence is lacking for their effects.

Sculpting the Brain with Neurofeedback and Neurostimulation

BCIs are primarily associated with real-time monitoring and inference from brain signals, but Ienca and Andorno (2017: 4) highlight how the 'possibility of *mining the mind* (or at least informationally rich structural aspects of the mind) can be potentially used not only to infer mental preferences, but also to prime, imprint or trigger those preferences'. The use of 'neurofeedback learning software' connected to BCIs is therefore a means of not just scraping brain data, but of potentially sculpting brain performance. Neurofeedback involves the use of brainwave monitoring devices to trace the brain activity of individuals. The person can then be trained to modify their brainwaves by visual and/or auditory feedback through computer programs such as videogames. The goal of neurofeedback is to modify the frequency spectrum of spontaneous neural oscillations, with some evidence that neurofeedback learning platforms may help children learn to control their attentional state (Bishop 2013). In particular, neurofeedback technologies have been trialled with children with ADHD (attention deficit hyperactivity disorder) and other disorders linked to abnormal functioning in brainwave oscillations.

One device has been used in studies to promote 'mindfulness' in schools through neuroheadsets, brain-data dashboards and neurofeedback algorithms, with the aim of reducing problematic classroom behaviours (Johnson 2017b). Muse, a 'personal meditation system', is a commercially available neuroheadset with EEG sensors and a neurofeedback app to alert users in real time to their personal brain activity (http://www.choosemuse.com/). The Muse headset has been used extensively in brain research to allow rapid EEG data collection. Its manufacturer, InteraXon, claims the device can captured the full range of brainwave activity, and that if its sensors pick up indicators of stress or anxiety (as fluctuations in brainwave activity), the app provides meditative training content to focus the user's attention. Its website references neuroscientific evidence that mindfulness meditation can positively influence brain growth; that EEG-neurofeedback can optimise cognitive performance; and that 'brainwave training' can result in neuroplastic changes. Researchers at Kansas State University used the Muse headset in a trial study with over 400 8th grade middle school students. The 20-week study concluded Muse improved the concentration of these students, as measured by office referrals for disciplinary action, through the application of mindfulness-based neurofeedback learning (Business Wire 2017). Similarly, researchers from the University of Cambridge have developed a wearable 'cognitive biometric' device that tracks 'diaphragmatic neuro-respiratory signals' as proxies for states of concentration and arousal. FOCI uses machine learning to analyse and visualise the results, and a 'focus-enhancing AI Mind Coach'—based on cognitive training, positive reinforcement and neurofeedback techniques—to provide 'real time advice to optimise focus' (https://fociai.com/). These devices indicates how ideas from popular brain science related to mindfulness and other therapeutic social-emotional interventions have been transposed into classroom practices (Gagen 2015).

Despite scientific reservations, political support for commercial educational neurofeedback technology has also emerged. Head of the US Department of Education, the private-education advocate Betsy DeVos, is a major investor and former board member of Neurocore, a brain-training treatment company specializing in neurofeedback technology development and application (Rogers 2017). The company uses EEG headsets to diagnose individuals' symptoms by comparing their brainwaves to a massive database of others' brainwaves. Its proprietorial neurofeedback software can then be applied to run a game that rewards the 'desired' brain activity. Over time, Neurocore claims, the brain starts to learn to produce activity that was rewarded by the increase in stimulation. One of Neurocore's targets is children with ADHD; its 'natural treatments' with drug-free neurofeedback 'work with a child's natural ability to learn, helping them reach their full potential', though its underlying neuroscience has been contested (Boser 2017).

Neurofeedback development is primarily driven by social concerns about behavioural and attentional disorders related to abnormal functioning in brainwave oscillation. Its goal is to train brains to function according to neuroscientifically defined 'normal' oscillations in brainwaves that are associated with aspects of learning, such as alertness, active thinking, attention and higher-order information consolidation. Emerging technologies of neurostimulation, however, extend beyond neurofeedback to direct electrical activation of brain regions that could boost learning and cognitive skills development.

Neurostimulation modifies neural membrane function and enhances synaptic plasticity to enable neuronal connectivity to take place (Bishop 2013). Noninvasive brain stimulation through electrodes attached to the skull can, it is argued, 'modulate cortical excitability and temporarily increase brain plasticity', with the consequent 'potential to boost learning and enhance performance on cognitive tasks' (Au et al. 2016: 1419). Neurostimulation techniques such as transcranial electrical stimulation (tES) have been explored for their potential as cognitive enhancers with young people. According to a review of neurostimulation research in relation to education, the use of tES techniques has been linked to improvements in several cognitive domains, including memory, attention, language, mathematics and decision-making, some of which have been found to be long-lasting (Schuijer et al. 2017). Although Schuijer et al. (2017: 6–7) note that 'tES is associated with a range of promising cognitive benefits, which could potentially boost children's educational performances', they also caution that 'no certainty exists yet with regard to the benefits of tES-based enhancement for cognitive wellbeing, and incorrect application settings could even result in impairment of cognitive function'. Nonetheless, it appears that neurostimulation technologies are becoming increasingly desirable in some parts of education as a way of enhancing cognition, with emerging reports of DIY use by students for boosting exam performance (Yuhas 2018).

From a more speculative perspective, the Center for Neurotechnology Studies at the Potomac Institute has issued a report on 'neurotechnology futures' with some key implications for education (Potomac Institute 2013). It describes how brain interface and neurostimulation technologies could become applications for 'augmented cognition', including 'non-invasive devices that complement or supplement human capabilities, such as tools for learning and training augmentation'. It has detailed how 'greater understanding of the neural mechanisms of learning and memory is needed to provide the appropriate theoretical basis for neurotechnologically enhancing learning' and enabling the educational system 'to significantly improve teaching techniques for iteratively more complex knowledge'.

The Potomac Institute shares staff and provides advice to the US military Defense Advanced Research Projects Agency (DARPA), which has itself begun exploring the potential to boost the acquisition of skills and learning through its Targeted Neuroplasticity Training (TNT) program. The program aims to develop safe, noninvasive neurostimulation methods for activating synaptic plasticity—the neural requirement for learning:

> Targeted Neuroplasticity Training (TNT) seeks to advance the pace and effectiveness of a specific kind of learning—cognitive skills training—through the precise activation of peripheral nerves that can in turn promote and strengthen neuronal connections in the brain. TNT will pursue development of a platform technology to enhance learning of a wide range of cognitive skills…. The TNT program seeks to use peripheral nerve stimulation to speed up learning processes in the brain by boosting release of brain chemicals, such as acetylcholine, dopamine, serotonin, and norepinephrine. These so-called neuromodulators play a role in regulating synaptic plasticity, the process by which connections between neurons change to improve brain function during learning. By combining peripheral neurostimulation with conventional training practices, the TNT program seeks to leverage endogenous neural circuitry to enhance learning by facilitating tuning of neural networks responsible for cognitive functions. (McClure-Begley 2016)

As is clear, TNT bears the inscriptions of its military backers, whose aim is to produce enhanced cognitive skills for military personnel through direct transcranial neurostimulation. The codified neuroscience knowledge behind such aspirations refers to peripheral nerve stimulation and the activation of brain chemicals and neuromodulators, as well as 'tuning' of neural networks, related to skills learning. Further, DARPA R&D has begun to explore possibilities of 'human-AI integration', seeking to mobilise 'neuroergonomics' design to create real-time interfaces between human and machine cognition (Axe 2018). Although TNT is primarily aimed at military training, it indicates how the scientific and technical possibilities of transcranial neurostimulation may be taken up in other educational efforts to modulate neuronal activity and thereby improve skills learning (Choe et al. 2016), paving the way for neurostimulation of children in order to likewise 'tune' or sculpt those parts of the brain associated with memory, attention, language, decision-making and other cognitive aspects of learning.

A strong social code infuses the design and development of neurostimulation, neurofeedback and related neurotechnologies for education and training. This emphasises enhanced cognitive skills required to deal with increasingly complex knowledge, and assumes that young people are to take on and embody certain forms of preferred cognitive conduct to deal with future demands, rather than rely on their 'weakly evolved' and 'flawed' biological brains (Clark 2017). The acceleration of learning proposed by neurotechnology advocates is informed by codified knowledge of neurobiological, chemical and neuromodulation processes and their role in regulating synaptic plasticity, and is then to be enacted via computer coded brain-machine interface devices, neurostimulators and neuroenhancement prostheses that can interact with mental processes seamlessly.

Ethics, Rights and Neurogovernance

Although the imaginaries associated with neurotechnology currently exceed technical capacity, their potential impact on the corporeal plasticity of individuals and wider societies over coming decades raises considerable challenges that bioethicists are beginning to address. The Nuffield Council on Bioethics (2013) has reported the need for ethical, regulatory and responsible research and innovation frameworks in relation to novel neurotechnologies, particularly those targeted at children:

> attention is warranted in respect of any unintended impacts on children's brains of devices that use neurostimulation, function by influencing brain plasticity, or encourage the repeated use of particular neural pathways, as the effects of these on the developing brain are still largely unknown. This concern is particularly acute given that children are likely to be a key target group both for cognitive enhancement for educational purposes. (Nuffield Council on Bioethics 2013: 174)

The report cautions about the coercive use of neurostimulation and neurofeedback with children, adding that 'the effects of these interventions on the developing brain are, as yet, unclear, and children and young people may be less well equipped to resist pressures from educators or parents who wish them to use neurotechnologies to enhance their capacities for learning and educational performance' (Nuffield Council on Bioethics 2013: 233). Schuijer et al. (2017) set out similar ethical concerns in relation to neuroenhancement technologies such as transcranial neurostimulation devices and their potential to be used as ‘child management tools’.

Neurologists themselves are concerned about serious privacy risks related to brain signal recordings from ‘personal neuroinformatics’ ‘floating around and being used and reused for various purposes’ and are building new privacy and ethics frameworks to mitigate against neural security risks (Stopczynski et al. 2014). The bioethicists Ienca and Andorno (2017) have further noted the potential for modification of emotions and cognition, direct manipulation of a person’s neural computation, technology-induced personality change and neuromodulation of behaviours, and propose the need for new human rights frameworks in response. Neurotechnologies also raise issues of new forms of discrimination arising from neural augmentation, as pressure to expand sensory, cognitive and motor capacities potentially generates new issues of equitable access and changes societal norms regarding perceptions of normalcy and difference, and the possibility that bias could be engineered into neurotechnologies as a result of ‘scientific or technological decisions … based on a narrow set of systemic, structural or social concepts and norms’ (Yuste et al. 2017: 162).

Ethical concerns over the uses of neurotechnologies reflect the potential for these developments to be used to exercise ‘neuropower’ over individuals. As Pitts-Taylor (2016) argues, neuroscience-based programs designed to mould and modulate behaviour through targeting the plastic brain for modification represent strategies of ‘preemptive neurogovernance’ that are intended to promote the economic and political optimisation of the population. Advances in neurotechnology clearly amplify the possibilities of preemptive neurogovernance, and the shaping of society and the social order through the modification of the mental states, affects and thoughts of individuals. The plasticity of the brain has become the basis for technoscientific ambitions to monitor, control and transform processes of life for political and commercial purposes (Pitts-Taylor 2016). Rose and Abi-Rached (2013: 13) have further argued that the plastic brain is now the focus for attempts to ‘govern the future through the brain’, as is especially the case with interventions into the developing brains and hence future lives of children. In this sense, the brain has become:

> both a potentially legible surface of thoughts and intentions, and the potentially modulatable locus of those thoughts and intentions. … [L]egibility in itself is only a first step: reading out the messages from the brain leads to the hope that one might read back messages into the brain to modulate those thoughts and intentions themselves. (Rose 2016: 157)

Explanations of the interplay of biological, technical and social dynamics, such as that of plasticity, have in this sense become resources with which to govern, since ‘plasticity is often seen as an enabling condition underlying the modernist fantasy of instrumental management of the body and … the making of an unprecedented figure of the human’ (Meloni 2018: 6–7). In rendering the brain legible through neuro-imaging and to being ‘read’ through brain signal recording, neurotechnology experts have sought to make it possible to stimulate or write signals back into the brain, to get under the scalp and inside the skull, and in so doing to rewire and manage its neuroplastic circuitry and functioning in order to achieve political and social objectives.

Conclusion

Educational neurotechnology at the present time is slowly taking shape through the varied imaginaries and practical efforts of neuroscientists, commercial companies, military agencies and promoters such as foundations, learned societies and think tanks. It represents a new postdigital science of education that merges brain biology, advanced data, software and algorithms with commercial and political imperatives. Understanding and analyzing neurotechnology from a postdigital perspective requires engagement with biosocial studies of neuroscience, sociotechnical studies of technology production and posthumanist theory on the assemblages produced by human-machine integration. Approaching neurotechnology as a postdigital bio-socio-technical assemblage of neurobiological codes, computer codes and social codes foregrounds how such technologies are the contingent result of specific efforts of scientists, disciplinary expertise, technologies and their engineers, and social, commercial and political aspirations to achieve certain ends through the biological modification of the brain and cognition. In these ways, neurotechnology supports the uptake of neuroscience in public policy and 'neuroliberal' efforts to govern through neurological insights (Whitehead et al. 2018), where techniques of 'targeting the brain' are mobilised to 'optimise' human capacities and 'neuroscience is used to support and construct particular understandings of society' (Broer and Pickersgill 2015: 54).

Specifically, the neurotechnologies surveyed in this article support strategies of educational neurogovernance that involve a reshaping of the neurobiological codes of the brain through the intervention of computer codes that in turn reflect and are designed to shape particular social codes pertaining to desired and preferable forms of conduct, behaviour, emotional comportment, cognition and thought. Although such imaginaries and aspirations may as yet exceed the technical capacity of existing neurotechnologies, these imagined neurofutures are catalyzing significant technical innovation. As neurotechnology promoters such as DARPA, WEF, Potomac Institute and Betsy DeVos indicate, there are military, political, commercial and social order imperatives behind aspirations to govern minds and plastic brains through neurotechnology-enhanced learning. As neurotechnologies produce new kinds of knowledge about the learning brain, they allow new kinds of experts and authorities to propose new ways of enhancing and optimizing brain performance through neurobiological intervention and augmentation. With a shift in education policy and practice to adopt theory, research and practice from both the life sciences and computational sciences, new kinds of 'bio-edu-policy-science actors' may be emerging as authorities in educational policy, 'not only experts on intervening on social bodies such as a school, but also in intervening in human bodies' (Gulson and Webb 2018: 287). A new plastic subjectivity is emerging from contemporary neuroscience and neurotechnology, one that is biologically malleable, modifiable and manipulable, and therefore the legitimate focus for scientific intervention.

The emerging developments and controversies over neurotechnology in education traced in this article raise significant social and ethical issues about ways 'brain data' may be used in a wide variety of sectors and for diverse purposes. The article has surveyed emerging technologies, practices and actors involved in neurotechnology development and advocacy in education, and proposed a conceptual framework to analyse the neurobiological codes, computer codes and social codes that constitute neurotechnologies. Further studies of the political, military, philanthropic, entrepreneurial and commercial interests involved in imagining and developing neurotechnology markets and interventions are required. So too are theoretically engaged studies of the postdigital sciences and sociotechnical processes involved in producing neurotechnologies, and of their uptake and biosocial effects across a range of domains. Deeply social and ethical questions also need addressing about using brain data to exercise neuropower over mental states, and about how to safeguard neural security amid coercive promises about neuroenhancement. The possibilities opened up by neurotechnologies suggest the need for novel forms of analysis drawing on postdigital, biosocial, sociotechnical and posthumanist theory and methods that can unpack how human life is being made amenable to being scanned, scraped and sculpted, how new forms of hybrid posthuman, postdigital and plastic subjectivity are being envisaged and to trace how the plastic brain has become the focus of efforts to govern and enhance societies.

References

Au, J., Katz, B., Buschkuehl, M., Bunarjo, K., Senger, T., Zabel, C., Jaeggi, S. M., & Jonides, J. (2016). Enhancing working memory training with transcranial direct current stimulation. *Journal of Cognitive Neuroscience, 28*(9), 1419–1432.

Axe, D. (2018). The Army is working on brain hacks to help soldiers deal with information overload. *Motherboard*, 3 May: https://motherboard.vice.com/en_us/article/59j7ja/the-army-is-working-on-brain-hacks-to-help-soldiers-deal-with-information-overload.

Berry, D. M. (2014). Post-digital humanities: Computation and cultural critique in the arts and humanities. *Educause, 49*(3), 22–26.

Bishop, D. V. M. (2013). Research review: Emanuel miller memorial lecture 2012 – neuroscientific studies of intervention for language impairment in children: interpretive and methodological problems. *Journal of Child Psychology and Psychiatry, 54*(3), 247–259.

Blankertz, B., Acqualagna, L., Dahne, S., Haufe, S., Schultze-Kraft, M., Sturm, I., Uscumlic, M., Wenzel, M.A., Curio, G. & Muller, K.-R. (2016). The Berlin brain-computer interface: progress beyond communication and control. *Frontiers in Neuroscience* 10(530): https://doi.org/10.3389/fnins.2016.00530

Bone, J. (2016). The nature of structure: a biosocial approach. Sociological Review Monograph Series, 64: Biosocial matters: rethinking sociology-biology relations in the twenty-first century*:* 238–255.

Boser, U. (2017). Betsy DeVos has invested millions in this 'brain training' company. So I checked it out. *The Washington Post*, 26 May: https://www.washingtonpost.com/posteverything/wp/2017/05/26/betsy-devos-neurocore/.

Broer, T., & Pickersgill, M. (2015). Targeting brains, producing responsibilities: the use of neuroscience within British social policy. *Social Science and Medicine, 132*, 54–61.

Business Wire (2017). KSU research finds muse meditation drastically reduces middle-school student office referrals. Business Wire, 8 November: http://www.businesswire.com/news/home/20171108005646/en/KSU-Research-Finds-Muse-Meditation-Drastically-Reduces.

Busso, D., & Pollack, C. (2015). No brain left behind: consequences of neuroscience discourse for education. *Learning, Media and Technology, 40*(2), 168–186.

Charland, P., & Dion, J.-S. (2018). The use of psychophysiological data to better understand real-time learning: the fragile balance between the validity of data and the authenticity of data collection contexts. *Neuroeducation, 5*(1), 1–3.

Choe, J., Coffman, B. A., Bergstedt, D. T., Ziegler, M. D., & Phillips, M. E. (2016). Transcranial direct current stimulation modulates neuronal activity and learning in pilot training. *Frontiers in Human Neuroscience, 10*(34). https://doi.org/10.3389/fnhum.2016.00034.

Clark, D. (2017). AI moving towards the invisible interface. *Donald Clark Plan B*, 3 May: http://donaldclarkplanb.blogspot.co.uk/2017/05/ai-moving-towards-invisible-interface.html.

Commissar, L., & Brookman-Byrne, A. (2017). IMBES pre-conference: using insight from research to improve education. *Mind, Brain, and Education*. https://doi.org/10.1111/mbe.12159/full.

Costandi, M. (2016). *Neuroplasticity*. London: MIT Press.

de Vos, J. (2016). The death and the resurrection of (psy)critique. The case of neuroeducation. *Foundations of Science, 21*(1), 129–145.

Dikker, S., Wan, L., Davidesco, I., Kaggen, L., Oostrik, M., McClintock, J., Rowland, J., Michaelareas, G., Van Bavel, J. J., Diong, M., & Poeppel, D. (2017). Brain-to-brain synchrony tracks real-world dynamic group interactions in the classroom. *Current Biology, 27*(9), 1375–1380. https://doi.org/10.1016/j.cub.2017.04.002.

Fitzgerald, D., & Callard, F. (2015). Social science and neuroscience beyond interdisciplinarity: experimental entanglements. *Theory, Culture and Society, 32*(1), 3–32.

Gagen, E. A. (2015). Governing emotions: citizenship, neuroscience and the education of youth. *Transactions of the Institute of British Geographers, 40*, 140–152.

Gulson, K. N., & Webb, P. T. (2018). 'Life' and education policy: intervention, augmentation and computation. *Discourse: Studies in The Cultural Politics of Education, 39*(2), 276–291.

Hadzilacos (2017). A podcast on the future of brain technology. World Economic Forum, 11 May: https://www.weforum.org/agenda/2017/05/a-glimpse-into-the-future-neurotechnology.

Hayles, N. K. (1999). *How we became posthuman: virtual bodies in cybernetics, literature, and informatics*. London: University of Chicago Press.

Hayles, N. K. (2013). *How we think: digital media and contemporary technogenesis*. London: University of Chicago Press.

Hayles, N. K. (2017). *Unthought: the power of the cognitive nonconscious*. London: University of Chicago Press.

Horvath, J. C., Carter, O., & Forte, J. D. (2014). Transcranial direct current stimulation: five important issues we aren't discussing (but probably should be). *Frontiers in Systems Neuroscience, 8*(2). https://doi.org/10.3389/fnsys.2014.00002.

Howard-Jones, P., Ott, M., van Leeuwen, T., & De Smedt, B. (2015). The potential relevance of cognitive neuroscience for the development and use of technology-enhanced learning. *Learning, Media and Technology, 40*(2), 131–151.

Howard-Jones, P. A., Varma, S., Ansari, D., Butterworth, B., De Smedt, B., Goswami, U., Laurillard, D., & Thomas, M. S. (2016). The principles and practices of educational neuroscience: comment on Bowers (2016). *Psychological Review, 123*, 620–627.

Ienca, M., & Andorno, R. (2017). Towards new human rights in the age of neuroscience and neurotechnology. *Life Sciences, Society and Policy, 13*(5), 1–27.

Jandric, P., Knox, J., Besley, T., Ryberg, T., Suoranta, J., & Hayes, S. (2018). Postdigital science and education. *Educational Philosophy and Theory, 50*, 893–899. https://doi.org/10.1080/00131857.2018.1454000.

Jasanoff, S. (2015). Future imperfect: science, technology, and the imaginations of modernity. In S. Jasanoff & S.-H. Kim (Eds.), *Dreamscapes of modernity: sociotechnical imaginaries and the fabrication of power* (pp. 1–33). Chicago: University of Chicago Press.

Johnson, S. (2017a). This company wants to gather student brainwave data to measure 'engagement'. *EdSurge*, 26 October: https://www.edsurge.com/news/2017-10-26-this-company-wants-to-gather-student-brainwave-data-to-measure-engagement.

Johnson, S. (2017b). Brainwave headsets are making their way into classrooms—for meditation and discipline. *EdSurge*, 14 November: https://www.edsurge.com/news/2017-11-14-brainwave-headsets-are-making-their-way-into-classrooms-for-meditation-and-discipline.

Kitchin, R., & Dodge, M. (2011). *Code/space: SOftware and everyday life*. London: MIT Press.

Lerner, L. (2018). Researchers invent tiny, light-powered wires to modulate brain's electrical signals. *UChicagoNews*, 19 February: https://news.uchicago.edu/article/2018/02/19/researchers-invent-tiny-light-powered-wires-modulate-brains-electrical-signals.

Mariani, M. (2017). The neuroscience of inequality: does poverty show up in children's brains? *The Guardian*, 13 July: https://www.theguardian.com/inequality/2017/jul/13/neuroscience-inequality-does-poverty-show-up-in-childrens-brains.

Marope, P. T. M. (2016). Brain science, education, and learning: making connections. *Prospects, 46*, 187–190.

McCabe, D. P., & Castel, A. D. (2008). Seeing is believing: the effect of brain images on judgments of scientific reasoning. *Cognition, 107*(1), 343–352.

McClure-Begley, T. (2016). *Targeted neuroplasticity training (TNT)*. DARPA: https://www.darpa.mil/program/targeted-neuroplasticity-training

McGimpsey, I., Bradbury, A., & Santori, D. (2016). Revisions to rationality: the translation of 'new knowledges' into policy under the Coalition Government. *British Journal of Sociology of Education*: https://doi.org/10.1080/01425692.2016.1202747*, 38*, 908–925.

Meloni, M. (2014). Remaking local biologies in an epigenetic time. *Somatosphere*, 8 August: http://somatosphere.net/2014/08/remaking-local-biologies-in-an-epigenetic-time.html.

Meloni, M. (2018). A postgenomic body: histories, genealogy, politics. *Body & Society, 24*(3), 3–38.

Meloni, M., Williams, S. & Martin, P. 2016. The biosocial: sociological themes and issues. Sociological Review Monograph Series 64, no. 1: *Biosocial Matters: Rethinking Sociology-Biology Relations in the Twenty-First Century*: 7–25.

Metz, R. (2017). Facebook's sci-fi plan for typing with your mind and hearing with your skin. *MIT Technology Review*, 19 April: https://www.technologyreview.com/s/604229/facebooks-sci-fi-plan-for-typing-with-your-mind-and-hearing-with-your-skin/.

Meyers, M. (2015). Connecting the classroom with the Internet of Things. *EdSurge*, 28 March: https://www.edsurge.com/news/2015-03-28-connecting-the-classroom-with-the-internet-of-things.

Moser, J. S., Schroder, H. S., Heeter, C., Moran, T. P., & Lee, Y.-H. (2011). Mind your errors: evidence for a neural mechanism linking growth mind-set to adaptive posterror adjustments. *Psychological Science, 22*(12), 1484–1489.

Nuffield Council on Bioethics. (2013). *Novel neurotechnologies: intervening in the brain*. London: Nuffield Council on Bioethics. http://nuffieldbioethics.org/wp-content/uploads/2013/06/Novel_neurotechnologies_report_PDF_web_0.pdf.

Pickersgill, M. (2013). The social life of the brain: neuroscience in society. *Current Sociology, 61*(3), 322–340.

Piore, A. (2016). Government seeks high-fidelity 'brain-computer' interface. *MIT Technology Review*, 2 February: https://www.technologyreview.com/s/600686/government-seeks-high-fidelity-brain-computer-interface/.

Piore, A. (2017). U.S. to fund advanced brain-computer interfaces, *MIT Technology Review* 10 July: https://www.technologyreview.com/s/608219/us-to-fund-advanced-brain-computer-interfaces/.

Pitts-Taylor, V. (2016). *The brain's body: neuroscience and corporeal politics*. London: Duke University Press.

Postigo, H., & O'Donnell, C. (2017). The sociotechnical architecture of information networks. In U. Felt, R. Fouche, C. A. Miller, & L. Smith-Doerr (Eds.), *The Handbook of Science and Technology Studies* (4th ed., pp. 583–608). London: MIT Press.

Potomac Institute. (2013). *Neurotechnology futures study*. Arlington: Potomac Institute for Policy Studies http://www.potomacinstitute.org/images/studies/NTFSReport-FINAL.pdf.

Potomac Institute. (2014). *Neurotechnology: enhancing the human brain and reshaping society*. Arlington: Potomac Institute Press http://www.potomacinstitute.org/images/stories/publications/22JanNeurotechEnhancementReport.pdf.

Potomac Institute. (2015). *Trends in neurotechnology*. Arlington: Potomac Institute Press http://www.potomacinstitute.org/images/stories/publications/NeuroTrendsAug2015.pdf.

Pykett, J. (2015). *Brain culture: shaping policy through neuroscience*. Bristol: Policy Press.

Ramadan, R. A., & Vasilakos, A. V. (2017). Brain computer interface: control signals review. *Neurocomputing, 223*, 26–44. https://doi.org/10.1016/j.neucom.2016.10.024.

Regalado, A. (2017a). The entrepreneur with the $100 million plan to link brains to computers. *MIT Technology Review*, 16 March: https://www.technologyreview.com/s/603771/the-entrepreneur-with-the-100-million-plan-to-link-brains-to-computers/.

Regalado, A. (2017b). With Neuralink, Elon Musk promises human-to-human telepathy. Don't believe it. *MIT Technology Review*, 22 April: https://www.technologyreview.com/s/604254/with-neuralink-elon-musk-promises-human-to-human-telepathy-dont-believe-it/.

Rogers, K. (2017). What the heck is neurofeedback technology, Betsy DeVos's pet project? *Motherboard*, 25 January: https://motherboard.vice.com/en_us/article/betsy-devos-is-invested-in-a-company-trying-to-treat-adhd-with-brain-training.

Rose, N. (2016). Reading the human brain: how the mind became legible. *Body & Society, 22*(2), 140–177.

Rose, N., & Abi-Rached, J. (2013). *Neuro: the new brain sciences and the management of the mind*. Oxford: Princeton University Press.

Rose, N., & Abi-Rached, J. (2014). Governing through the brain: neuropolitics, neuroscience and subjectivity. *Cambridge Anthropology, 32*(1), 3–23.

Rose, N., Aicardi, C., & Reinsborough, M. (2016). *Foresight report on future computing and robotics: a report from the HBP foresight lab*. London: King's College London.

Royal Society. (2011). *Brain waves II: neuroscience implications for education and lifelong learning*. London: The Royal Society.

Schuijer, J. W., de Jong, I. M., Kupper, F., & van Atteveldt, N. M. (2017). Transcranial electrical stimulation to enhance cognitive performance of healthy minors: a complex governance challenge. *Frontiers in Human Neuroscience, 11*, 1–15. https://doi.org/10.3389/fnhum.2017.00142.

SharpBrains. (2015). Market report on pervasive neurotechnology: a groundbreaking analysis of 10,000+ patent filings transforming medicine, health, entertainment and business. SharpBrains.com: https://sharpbrains.com/pervasive-neurotechnology/.

Spreeuwenberg, R. (2017). Does emotive computing belong in the classroom? *EdSurge*, 4 January: https://www.edsurge.com/news/2017-01-04-does-emotive-computing-belong-in-the-classroom.

Stopczynski, A., Greenwood, D., Hansen, L.K. & Pentland, A. (2014). Privacy for personal neuroinformatics. Available at SSRN: https://doi.org/10.2139/ssrn.2427564

Taffel, S. (2016). Perspectives on the postdigital: beyond rhetorics of progress and novelty. *Convergence: The International Journal of Research into New Media Technologies, 22*(3), 324–338.

Thomas, M. S. C. (2017). A scientific strategy for life chances. *The Psychologist, 30*, 22–26 https://thepsychologist.bps.org.uk/volume-30/may-2017/scientific-strategy-life-chances.

Tovar-Moll, F., & Lent, R. (2016). The various forms of neuroplasticity: biological bases of learning and teaching. *Prospects, 46*, 199–213.

Wexler, A. (2017). The social context of 'do-it-yourself' brain stimulation: neurohackers, biohackers, and lifehackers. *Frontiers in Human Neuroscience, 11*, 1–6. https://doi.org/10.3389/fnhum.2017.00224.

Wheeler, M. (2011). Thinking beyond the brain: educating and building from the standpoint of extended cognition. *Computational Culture* 1: http://computationalculture.net/article/beyond-the-brain.

Whitehead, M., Jones, R., Lilley, R., Pykett, J., & Howell, R. (2018). *Neuroliberalism: behavioural government in the twenty-first century*. London: Routledge.

Williams, S., Katz, S., & Martin, P. (2011). The neuro-complex: some comments and convergences. *Media Tropes, 3*(1), 135–146.

Youdell, D. (2016). A biosocial education future? *Research in Education, 96*(1), 52–61.

Yuhas, D. (2018). Students are zapping their brains to get ahead in school—but evidence for the practice is limited. *The Hechinger Report*, 21 February: http://hechingerreport.org/students-zapping-brains-get-ahead-school-evidence-practice-limited/.

Yuste, R., Goering, S., Arcas, A., et al. (2017). Four ethical priorities for neurotechnologies and AI. *Nature, 551*(7679), 159–163 Available at: http://www.nature.com/news/four-ethical-priorities-for-neurotechnologies-and-ai-1.22960.