Brain-computer interfaces and education: the state of technology and imperatives for the future

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Abstract: Progress in the field of brain-computer interfaces (BCIs) has accelerated in recent years. While the majority of research has focused on alleviating the burden of physical and psychological disabilities, use of BCI devices has expanded to a variety of applications. New educational platforms and assistive technologies have been developed to improve learning strategies and increase cognitive capabilities for both healthy and disabled individuals. This paper first reviews the BCI landscape by providing a general outline of current technology then discusses research relevant to education. The literature on educational technology is used to describe common patterns in implementation of innovations, which highlights the need for understanding complexities of educational settings and broader social contexts. In anticipation of emerging BCI technology, recommendations are made for researchers and policymakers to promote implementation strategies associated with positive academic outcomes and reduction of achievement gaps.

Keywords: BCI; brain-computer interface; assistive technology; neurotutoring; achievement gap.

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1 Introduction

Brain-computer interfaces (BCIs)[1] have advanced far beyond the first simple electrodes surgically inserted into a human skull in the 1970s (Vidal, 1973; Guger et al., 2015); now, a wide array of neural prostheses and communication devices not only correct disabilities, but also alter and enhance capabilities of healthy individuals (Brunner et al., 2015). With hundreds of millions of dollars from Silicon Valley heavyweights, companies like *Neuralink* and *Kernel* aim to transform language and literacy within the next decade through brain-to-machine and brain-to-brain communication systems.

Over the past century, many technological innovations have been applied to learning environments (Reiser, 2001). While educational technology can have positive impacts on academic achievement, a lack of attention to the complexities of educational settings and broader social contexts often causes initiatives to perform poorly and exacerbate existing inequities across lines of race, class, and gender (Warschauer, 2011). In order to avoid repeating mistakes of the past, researchers and policymakers must begin to consider educational BCI technology in anticipation of forthcoming changes.

Speculations about potentially profound social implications of BCIs run wild in the imaginations of Hollywood producers, intellectual futurists, and YouTube conspiracy theorists. This conceptual paper does not indulge fantasies about possible futures, but remains grounded in present scientific research to accomplish five goals:

1 describe the state of BCI technology

2 present current learning science research that utilises BCIs

3 discuss the potential of BCI technology for educational applications

4 summarise the historical relationship between educational technology and academic outcomes

5 draw relevant parallels to offer suggestions for researchers and policymakers.

A quasi-systematic literature review was conducted (‘systematised review’, see Grant and Booth, 2009). To investigate recent advances in BCI technology, lists of search terms were generated around key topics in the field and pursued through Google Scholar. Articles from 2000 to 2018 (inclusive) were used for the technological review (Sections 2 to 4). Purposive selection of articles was used to construct a narrative that represents key trends in BCI development. Results of this review were used as a basis for a discussion of implementation and policy (Sections 5 and 6). This process aimed to synthesise the latest findings in a way that encourages new discussions about BCI-based educational technology.

2 The state of brain-computer interface technology

BCIs are digital systems that allow direct communication between a brain and an external device. This requires technology capable of either accurately reading and interpreting neural signals in a way that preserves human meaning or stimulating appropriate neural pathways (and/or facilitating connections between neurons) to reliably and consistently transfer information.

These can be accomplished using devices that are invasive (directly inserted into the brain) or non-invasive.[2] Nearly all current BCI systems are based on unidirectional information flow between the brain and the device, while other biological systems may be used as feedback mechanisms (for instance, a person using a BCI to type on a computer transfers information to the computer through a direct neural connection, but then uses their eyes to read the output on the screen as feedback to adjust their typing). Bidirectional brain-computer communication systems must have the ability to both read neural signals and stimulate the brain. Depending on the application, this may require multiple devices working in tandem. Regardless of whether information exchange is unidirectional or bidirectional, a real-time network must be established to allow dynamic machine-brain interfacing. Technological advances and illustrative examples in neural sensing, stimulation, and bidirectional networks are briefly discussed below.

2.1 Reading neural signals

Several devices have been used to read neural signals as part of BCI systems; each has particular strengths and constraints (Nicolas-Alonso and Gomez-Gil, 2012; Lebedev and Nicolelis, 2006). Electrodes surgically inserted into the brain provide the most reliable and accurate information transfer, but are limited by the number of neurons they can contact and are susceptible to declining function over time (Polikov et al., 2005; Cogan, 2008). The most commonly used non-invasive device is electroencephalography (EEG), which involves placing a set of electrodes on the scalp to read brain activity. Its low price and versatility comes at the cost of noisy signals and low bandwidth (Frey et al., 2013). Other non-invasive devices, such as functional Magnetic Resonance Imaging (fMRI) and magnetoencephalography (MEG), use magnetic fields to comprehensively assess brain activity with a high degree of accuracy, but are expensive and require patients to be stationary within a large machine (Reichert et al., 2017; Ruiz et al., 2014). BCIs employ complex decoding methods regardless of which device is used and substantial training is often required for subjects to be able to use the interfaces effectively (He et al., 2015; Hiremath et al., 2015).

Neuroprosthetics[3] aimed at restoring functions of disabled individuals have been a common application of neural sensing devices. Implanted electrodes (notably the BrainGate array) have allowed tetraplegics to control a range of electronic and prosthetic devices (Hochberg et al., 2006). Progress has been made in developing non-invasive systems to control real and artificial limbs (Müller-Putz et al., 2017), including restoration of the ability to walk in parapalegics (Do et al., 2013). Both invasive and non-invasive BCIs have been used to reestablish communication with individuals who suffer from ‘locked-in syndrome’ and would otherwise be unable to interact with the world (Chaudhary et al., 2015; Fedele et al., 2016).

Significant advances in the accuracy and speed of reading neural signals, as well as types of information that can be measured have expanded the uses of BCI technology. Variations of EEG devices have been incorporated into mass-marketed products; several companies (such as *NeuroSky*, *Emotiv*, and *intendiX*) sell devices, apps, and software based on thought-controlled user input. Functional MRI has also been employed for a variety of purposes; fMRI has been used to recognise and reconstruct actual pictures of imagined images and movies (Naselaris et al., 2009, 2015; Nishimoto et al., 2011; Miyawaki et al., 2008) and to determine consumer preferences for brand products (Venkatraman et al., 2011).

2.2 Stimulating neurons

Both invasive and non-invasive methods are widely used to stimulate neurons. Arrays of electrodes inserted into the nervous system (in the brain or elsewhere) can be used to excite neurons in ways that send meaningful signals to the individual (Cogan, 2008).

Non-invasive brain stimulation technology includes an alphabet soup of acronyms for different devices and techniques (Kadosh, 2014). Most important are transcranial magnetic stimulation (TMS) and transcranial electric stimulation (tES). TMS uses large coils of wire to generate strong magnetic potentials that directly activates specific areas of the brain. tES is used to increase or decrease excitability of neurons and can involve direct current (tDCS) or alternating current (tACS, also referred to as cranial electrotherapy stimulation, CES).

Neuroprosthetics have consistently been at the forefront of neuron stimulation technology. Cochlear implants can restore a sense of hearing by using electrodes to directly stimulate auditory nerves with signals from an external microphone. The first cochlear implants were approved by the FDA in the 1980's, and since then, hundreds of thousands of patients have received the devices (NIDCD, 2017). More recently, a variety of invasive devices have been successful in partially restoring sight (Chuang et al, 2014; Dobelle, 2000).

Several advancements of invasive neuron stimulation have garnered high-profile attention in recent years. False memories have been successfully created in mice to predictably change behaviour (Ramirez et al., 2013). Implanted electrodes have been used to control the movements of animals (Graham-Rowe, 2002) and the technology has become so accessible that a cheap educational kit can allow kids to implant wireless BCIs in cockroaches to control movement via smartphone (Dickerson, 2013).

Non-invasive devices require operation by trained medical professionals and the technology does not have the same degree of precision as inserted electrodes. As a result, the current medical and practical applications are more limited than invasive BCI devices. Nevertheless, the technology has been used to achieve several milestones in human experiments. TMS has been used to change moral decision-making in subjects (Young et al., 2010), guide participants through a virtual maze (Losey et al., 2016), and produce predictable movements in limbs and extremities (Arca et al., 2015). Both TMS and tES have been used to treat pain, depression, and schizophrenia (Lefaucheur et al., 2014; Brunoni et al., 2016).

2.3 Bidirectional systems

Real-time machine-brain networks have been successfully established using neural reading and stimulation technologies (both invasive and non-invasive). Recently, substantial research has been devoted to bidirectional neuroprosthetic systems. Artificial limbs can restore sensation (Navarro et al., 2005) and new devices aim to restore motor function through bidirectional information transfer (Fetz, 2015; Mendrela et al., 2016), which has been successful in monkeys (O'Doherty et al., 2011).

Bidirectional BCIs have been developed to create new forms of communication. Electrodes implanted in separate individuals have been linked together to create direct brain-to-brain sensory networks as a first step towards direct 'thought communication' (Warwick et al., 2004, 2005). The first non-invasive human-to-human brain interface combined brain scanning and stimulation technologies to allow one researcher to control the movement of another researcher's finger remotely using thoughts alone (Rao et al., 2014). In a demonstration of seamless integration of BCI technology, Goebel et al. (2004) created a system that allowed two participants in separate fMRI machines to play a thought-controlled version of the classic arcade game 'pong' in real time. Direct brain-to-brain connections have enabled mice to share information that allowed them to collaborate on tasks remotely (Pais-Vieira et al., 2013). In 2014, two people successfully exchanged messages via a non-invasive brain-to-brain connection (Grau et al., 2014).

Table 1 Typology of common unidirectional BCI devices

	Invasive	*Non-invasive*
Reading	Inserted electrodes	EEG, fMRI, MEG
	e.g., BrainGate prosthesis control	e.g., Emotiv EPOC headset (EEG)
Stimulating	Inserted electrodes	tDCS, TMS
	e.g., Cochlear implants	e.g., treatment for clinical depression

3 Learning science and brain-computer interfaces

Current BCI research is largely focused on the development of assistive devices for physical disabilities and treatments for neurological disorders (Brunner et al., 2015; Müller and Carmena, 2017). Recent findings have relevance for the learning sciences; BCI devices have been used to directly enhance cognitive capabilities and improve communication methods in ways that facilitate learning for individuals suffering from various medical conditions. Research has also demonstrated potential applications for healthy subjects.

3.1 Enhancing learning and cognition

Stroke victims have been at the forefront new BCI research. Beyond neuroprosthetics for patients (Buch et al, 2008), BCI devices that involve stimulation of the brain encourage neuroplasticity that may restore endogenous motor function (Mrachacz-Kersting et al., 2016; Shindo et al., 2011). Randomised controlled trials have shown the benefit of BCI technology for motor skill acquisition and cognitive rehabilitation (Pichiorri et al, 2017). BCIs have also been used for brain mapping to probe the extent of brain damage resulting from strokes in order to tailor appropriate treatments (Kim and Winstein, 2017).

Successful application of tDCS to improve language and speech recovery in stroke patients has spurred research in many directions (Sebastian et al., 2017; Au et al., 2017; Coffman et al., 2014; Parasuraman and McKinley, 2014; Holland et al., 2011; Utz et al., 2010). Use of tDCS has been shown to enhance language skills not only for individuals with other language deficits (Turkeltaub, 2016; Hsu et al., 2015), but also for healthy subjects (Monti et al., 2013; Sparing et al., 2008). Neural stimulation techniques have been experimentally demonstrated to improve other cognitive processes (Shah-Basak and Hamilton, 2017; Luber and Lisanby, 2014; Nelson et al., 2014; Clark et al., 2012), such as working memory (Brunoni and Vanderhasselt, 2014; Zaehle et al., 2011) and self-control (Wessel et al., 2013), although some results have been mixed (Horvath et al., 2015). Notably, TMS and tDCS have been shown to be potential treatments for adults and children with ADHD (Sotnikova et al., 2017; Rubio et al., 2016; Munz et al., 2015).

3.2 Assisting learning

For patients with severe physical disabilities, BCI devices that facilitate communication can improve functionality in many areas of life, including learning. A number of invasive and non-invasive systems allow patients to control the movement of a computer cursor using thoughts. Current technology is limited in the speed with which users can type messages, but new non-invasive systems currently being developed in the private sector may allow users to communicate up to 100 words per minute by directly translating imagined thoughts to text (Richardson, 2017). Little is known about the products that companies are developing due to the obvious value of such innovations, but these advancements are feasible with available technology (Sereshkeh et al., 2017; Basak, 2017; Mohanchandra and Saha, 2016). These devices could change learning strategies for all individuals, not just those suffering from disabilities.

4 Brain-computer interfaces in educational contexts

Until the turn of the century, the gap between neuroscience and educational applications was considered ‘a bridge too far’ (Bruer, 1997), but with advances in technology, methodology, and practice, this gap has slowly been closing. Driving this trend is an understanding that academic progress is best facilitated when educational methods fit each student’s needs and learning is appropriately scaffold (Kirschner et al., 2006; NRC, 2000; Vygotsky, 1980). Digital learning environments are uniquely suited for this degree of personalisation (Kirschner and Gerjets, 2006). Intelligent tutoring systems (ITSs) are “computer programs that model learners’ psychological states to provide individualised instruction” (Ma et al., 2014). There are a wide variety of ITSs, but they generally share common features: an interface that allows the user to interact with interlinked models of student knowledge, information to be learned, and instructional strategies (Sottilare et al., 2013). These computer systems have been found to be as effective as human tutors (Ma et al., 2014; VanLehn, 2011).

ITSs use data collected about a student to create an experience that may involve conducting assessments or assigning tasks, giving feedback or hints, answering questions, offering prompts, or presenting new information (Ma et al., 2014). The most basic form of ITS is an error-adaptive learning environment, where models of student knowledge are created based on incorrect responses to questions (Corbett, 2001). More advanced ITSs use artificial intelligence (Wenger, 2014) and physiological measurements, such as heart rate or pupil dilation (Mcquiggan et al., 2008). BCIs present a new possibility for ITSs, allowing direct assessment of cognitive and emotional states rather than indirect approaches.

Although BCI technology is still in its early stages, applications for education are already being explored. Researchers have created a digital learning environment that adjusts content based on students’ cognitive workload measured by an EEG device (Spüler et al., 2017). Similarly, commercially-available educational software released by NeuroSky pairs digital educational activities with measurements of attention through an inexpensive EEG headset (NeuroSky, 2017). Studies have demonstrated how executive functioning could be measured and in ways that are suitable for complex learning environments (Spüler et al., 2017). Systems are currently being developed that are responsive to the emotional states of students (Galway et al., 2015). BCI-based educational games have been used to reduce math anxiety (Verkijika and De Wet, 2015). Computer adaptive testing has been combined with real-time measurements of attention via EEG (Marchesi and Riccò, 2013).

Beyond ITSs, integration of multiple BCI systems may eventually yield the most dramatic advances in educational technology. Researchers have recently succeeded in combining different BCI systems to measure and stimulate brain activity simultaneously (Schestatsky et al., 2013; Miniussi and Thut, 2010; Ruff et al., 2009; Antal et al., 2011). In a hypothetical scenario using current technology, students may input information into a computer using their thoughts while their brain is scanned to determine appropriate regions for administering neural stimulation that will optimise learning. Such speculation only serves to illustrate the wide variety of configurations and functions of educational BCIs that may be possible.

Although progress has been made, major limitations and challenges remain. Current BCI educational systems are only proof-of-concepts and have not demonstrated more efficacy than other error-adaptive ITSs, due to a combination of technological and pedagogical factors (Spüler et al., 2017). Usability is also a significant issue for mainstream application of EEG devices; systems often face tradeoffs between setup time, comfort, signal quality, and cost (Hairston et al., 2014). Perhaps the most significant challenges are in the social and cultural domains, which often go unrecognised in technical literature. The impact and effectiveness of educational technology ultimately depend on the social and cultural contexts of implementation, as discussed below.

5 Effective implementation of educational technology

The trajectories of past innovations provide insight into educational challenges that await the BCI-based learning interventions. The study of educational technology has generated a wealth of knowledge concerning development and dissemination of new devices; scholarly literature provides evidence of several consistent patterns and themes. The present discussion focuses on two key ideas particularly salient to emerging technology:

1 positive academic outcomes depend on implementation that appropriately considers social context

2 reducing achievement gaps requires understanding differences in the use of devices across social groups.

5.1 Academic effectiveness

Development of new educational technology is often accompanied by exaggerated claims of potential impacts and tremendous financial investment (Reiser and Dempsey, 2012; Reiser, 2001; Mishra et al., 2009; Romiszowski, 2004). In 1913, advancements in audiovisual technology led Thomas Edison to claim "[b]ooks will soon be obsolete in schools" (Reiser, 2001). One hundred years later, Nicholas Negroponte (founder of One Laptop Per Child) made a strikingly similar prediction that laptops would replace physical books within five years (Combs, 2010). History has repeatedly provided examples of educational technologies that failed to live up to expectations. Over the last century, hundreds of millions of dollars have been invested (and lost) in several waves of hype surrounding new innovations, such as educational radio and television (Reiser, 2001; Tiffin, 1980) and e-learning (Romiszowski, 2004). Technologies that do end up becoming widely used often have mixed educational impacts because expectations were not grounded in the complexities of learning (Reiser and Dempsey, 2012; Mishra et al., 2009; Kulik, 2003; Wenglinsky, 1998).

Implementation of educational technology typically follows a ‘standard model’ of top-down imposition that neglects social dynamics and is out of touch with the needs of students and teachers (Kling, 2000); technology is mistakenly treated as a panacea for educational challenges. As a leading researcher of educational technology describes: “Just as music does not reside in the piano, teaching, learning, and knowledge does not reside in the computer” (Warschauer, 2011). The tremendous enthusiasm surrounding new innovations, combined with a belief that technology has inherent properties that will confer knowledge to all youth regardless of social status, often leads to misinformed policies and interventions that produce poor academic outcomes and perpetuate inequities in learning.

A failed laptop distribution program in Birmingham provides a poignant example (Warschauer et al., 2011). Without the input of the local school district, the mayor and city council president decided to buy and distribute 15,000 laptops to elementary school children. The implementation did not include essential affordances, such as training, curriculum development, or technical support structures. Analyses involving the schools, teachers, and students before and after distribution showed dismal results. These ‘one-to-one’ programs which provide laptops to students have been found to generate radically different educational outcomes depending on how the interventions are conducted (Zheng et al., 2016; Warschauer, 2005; Penuel, 2006).

5.2 Educational equity

Dissemination of educational technology typically follows a standard progression, consistent with theories about diffusion of innovations (Rogers, 2010; Romiszowski, 2004). First, cutting-edge technology designed for specialised purposes is applied to the educational domain. Next, educational technology is made accessible to students with exceptional privilege, and then gradually (and unevenly) to marginalise groups, if at all. Sutton (1991) provides an illustrative example of this process. Early computers were designed for highly technical applications. The first computer for consumers was developed in 1975 and was rapidly repurposed for educational use. By the end of the following decade, nearly 90% of public schools had at least one computer. Wealthier schools were able to purchase more devices than poorer schools, which divided technology use along lines of race and class. Gradually, access across all social groups increased over time, although inequities in types of use persisted.[4]

Social status and culture mediate the educational effects of technology, even when physical access is equal (Warschauer and Matuchniak, 2010; Warschauer, 2011). For instance, patterns of computer use differed between high and low SES students who had comparable access (Warschauer et al., 2004). Usage patterns of high SES students have been associated with greater academic benefits than the usage patterns of low SES students; similarly, white students have been found to benefit more than black students (Battle, 1999). Wenglinsky (2005) found that low SES schools predominately used computers for drill and practice, which were negatively associated with academic achievement, whereas high SES schools relied on other activities that were positively associated with academic achievement, such as word processing, simulations, and data analysis.

Generally, educational technology initiatives tend to exacerbate inequities (Vigdor et al., 2014; Battle, 1999; Sutton, 1991). This is due to several factors, notably because high-achieving students are most likely to benefit from technology. There are various dimensions of equity (e.g., race, class, gender, ability, etc.) and many types of resources and capital (e.g., material resources, human capital, social networks, etc.) that shape how technology is used (Warschauer and Newhart, 2016). Differential use of technology across race, class, and gender is apparent for nearly all media and devices (Warschauer and Matuchniak, 2010), including the internet (Jones et al., 2009), gaming (Kinzie and Joseph, 2008), and smartphones (Smith and Page, 2015). Researchers have hypothesised that this may be a result of differences in resources and support associated with the students' culture and social context (Giacquinta et al., 1993).

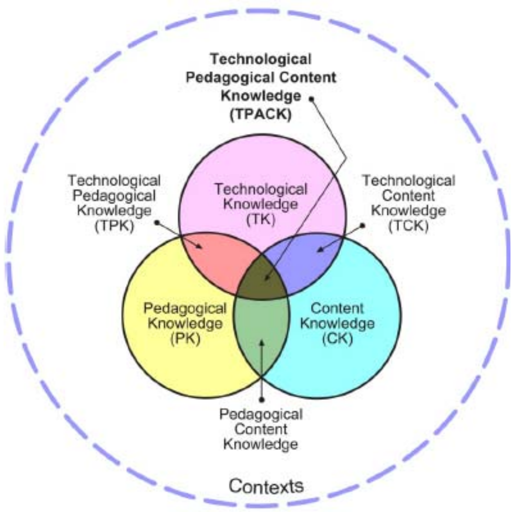
5.3 Successful implementation

It is possible for technological interventions to improve learning outcomes; positive exemplars have been well-documented. One such example is the Student Writing Achievement Through Technology Enhanced Collaboration (SWATTEC) program in the Saugus Union School District in California (Warschauer, 2011). This one-to-one laptop program was scaled up between 2008 and 2010. Faculty, students, and administration were all involved in the implementation process. Teachers participated in extensive professional development over a two-year period prior to the intervention. Software, curriculum, and social media were integrated across classes in ways that produced authentic learning experiences for students. The laptops used open-source applications available to all students. SWATTEC's plan recognised that technology is a collaborative tool embedded in a complex social context; interventions take time, school politics are relevant, and social effects are often unpredictable. Despite a high proportion of low-income English learners, schools in the district saw dramatic increases in test scores, which garnered national acclaim for the program. SWATTEC exemplifies Warschauer's (2011) 'Four C's' of effective use of educational technology:

1. Content that is differentiated, rich, and interactive.
2. Community that is supportive and collaborative.
3. Construction of meaningful, public digital entities and identities by students.
4. Composition of different types of educational deliverables (such as writing papers or creating media).

Mishra and Koehler (2006) created a robust framework for conceptualising effective education as "the interplay between pedagogical knowledge, content knowledge, and technology knowledge." In this 'TPACK' framework, the intersections of each of the three types of knowledge are considered separately. (For instance, the intersection of pedagogical and content knowledge includes understanding the most important representations for making a certain subject comprehensible to others while being aware of the audience's preconceptions and misconceptions of the topic.) Ultimately, the intersection of all three types of knowledge, technological pedagogical content knowledge, has emergent properties beyond the individual components and provides a foundation for effective teaching with technology. Evaluations have been created to assess effective education using technology (Koehler et al., 2012). This framework complements other literature that finds successful technological interventions in educational settings require a thorough understanding of complex social contexts (Harper and Milman, 2016; Warschauer et al., 2014; Reiser and Dempsey, 2012; Wenglinsky, 2005; Keller, 2005).

Figure 1 Diagram of the TPACK framework (see online version for colours)



Source: from Koehler and Mishra (2009)

6 Imperatives for the future

BCIs may become the next educational fad; whether or not the devices will be capable of promoting positive academic outcomes and reducing achievement gaps depends on decisions of researchers and policymakers. In recent years, BCI devices have followed the same trajectory of development and dissemination as past innovations. A deliberate effort must be made to diverge from the status quo; policymakers and researchers have an opportunity to anticipate developments in BCI technology and avoid mistakes that befell other promising educational initiatives.

6.1 Recommendations for policymakers

In the US, a number of existing national programs aim to encourage technological literacy and ‘21st century’ competencies: as Preparing Tomorrow’s Teachers to Use Technology (PT3), Enhancing Education Through Technology (ED Tech), Partnership for 21st Century Skills, and National Educational Technology Plan. Such programs need to be adapted to adequately encourage and support evidence-based implementation of educational technologies to ensure that all students will benefit from educational technology, especially in light of the potentially transformative nature of BCIs (Voithofer and Foley, 2007; Foley and Voithofer, 2003).

At the state and national level, policymakers need to adopt a forward-looking perspective and consider emerging technologies when designing new initiatives. For instance, educational standards, teacher training programs, and systems of evaluation and accountability should be compatible with BCI devices. In the past, lack of proper policies regarding new technologies has led to poor academic outcomes (Barbour, 2017) and fostered educational inequities (Newhart et al., 2017). Guidelines for proper implementation of educational technology should be provided for school administrators, consistent with research discussed above (Warschauer, 2011; Culp et al., 2005).

BCI technology has not yet advanced to a stage where specific district-level policies would be appropriate. Local officials should evaluate and reflect on their past and current educational technology initiatives. Implementation strategies that provide necessary affordances to equitably increase academic achievement should be institutionalised (Warschauer, 2011). Such strategies should include the input of all stakeholders.

Policymakers must avoid the pitfalls of the past. First, public officials need to maintain evidence-based decision-making against the allure of technological hype. Second, to use an illustrative metaphor, policymakers should not endorse the myth that technology inherently gives knowledge in the same way a fire gives heat (Dede, 1995). Third, public officials need to be cautious of the influence of educational technology companies, which may use economic and political means to prevent the development of necessary policies. (For example, online learning has shown very poor educational results, yet has been given favourable regulatory treatment due to the influence of companies which promote it; see Barbour, 2017.) Involving non-industry experts in interventions may be part of an effective strategy to avoid conflicts of interest and accomplish each of these three.

All public programs and policies should be grounded in research, but this cannot be accomplished unless research is adequately supported by policymakers. First, research on the applications of BCIs needs to be prioritised. There is already a precedent for the creation of government initiatives to investigate the social impact of paradigm-shifting emerging technologies (e.g., nanotechnology and society; Roco, 2011). Over $100 million has already been spent on BCI research over the past few decades by the US government; research should be expanded to study potential applications of BCIs and their implications (Miranda et al., 2015). Second, there has been a persistent lack of research in educational technology, at least partially because researchers have not had the resources to keep up with the rapid pace of technological progress (Roblyer and Knezek, 2003; Roblyer, 2005). Policymakers need to robustly support research of educational innovations and related academic outcomes.

6.2 Recommendations for researchers

It is the responsibility of educational researchers to use scientific studies to inform policies. A variety of BCI devices will be applied to educational settings in coming years; the certainty of this trend presents an opportunity for researchers to proactively anticipate changes instead of creating frameworks for understanding innovations after large-scale implementations have occurred and advocating for policy changes reactively. There are six areas of research that can be pursued now to lay the foundation for future interventions.

First, and perhaps most importantly, technological challenges must be resolved; the full transformational potential of BCI educational systems cannot be realised without more innovation. Some necessary advancement is entirely technical. For instance, advances in EEG signal processing through PCA-based covariate shift adaptation or classifier adaptation could be important contributions (Spüler et al., 2017) and integrating physiological and neurological measurements may yield more accurate predictive models (Mcquiggan et al., 2008). Other technological challenges require expertise in educational and social domains. Specifically, improving the quality and complexity of intelligent scaffolding may increase efficacy of intelligent tutoring systems (VanLehn, 2011). Ensuring usability of devices in practical settings and accessibility for all types of learners is necessary (Hairston et al., 2014). Ultimately, BCI systems will need to be designed with socio-technical features suitable for complex learning environments.

Second, educational researchers should begin developing partnerships with BCI scientists to explore realistic possibilities of applications and build a research network capable of comprehensively addressing all aspects of the new technology. New international BCI research organisations have been formed in recent years and the involvement of social scientists is essential; leading BCI scientists acknowledge that the lack of interdisciplinary perspectives "leads to false beliefs and unrealistic views on what a BCI is and which problems BCIs can solve" (Brunner et al., 2015).

Third, a detailed historical analysis is needed to assess the potential impact of BCIs by identifying ways that the technology could be fundamentally different than past innovations. A sociohistorical perspective is crucially important for considering implementation of future devices (Bellamy, 1996; Wilburg, 2003) and educational technologies should be situated within broad social theories (Saettler, 2004). Currently, BCI technology lacks this theoretical frame.

Fourth, and more generally, research is needed to understand educational technology more deeply, and in particular, its implications for equity (Roblyer, 2005; Selwyn, 2012). For instance, work must be done to explain how state and federal policies may influence digital equity, both within educational settings and more broadly (Becker, 2007).

Fifth, an economic analysis of the BCI landscape must be undertaken using a critical social lens with attention to educational goals. This will involve several features. Ongoing evaluations of education-related BCI developments should keep track of costs, realistic academic benefits, and returns on investments to avoid creating financial "bubbles" and ensure that public funds are spent wisely. BCI business models should be compared to those used with other educational technologies to determine the most effective strategies for providing high quality, equitable learning experiences. The link between new technology companies and schools should be monitored, especially considering Silicon Valley's keen interest in educational philanthropy (Reckhow and Snyder, 2014; Bacon, 2014). Research can help ensure that businesses are appropriately regulated, which has not been the case with other educational technologies (Barbour, 2017).

Sixth, researchers should begin to conceptualise how BCI devices could be implemented and tested in learning environments. The study of past educational technologies can be used to design studies and make hypotheses to explore possible complexities and contentions of BCIs. Research will be needed to establish appropriate criteria for making initial judgements, create quality measures that constitute good use, find strategies for curricular integration, train teachers and administrators to apply new technologies, and understand potential implications for academic outcomes and equity.

7 Concluding remarks

It is uncertain how BCI-based educational technology will differ from past innovations (Reiser, 2001; Mishra et al., 2009). If BCI devices become as influential as their designers intend, the implications for learning will be proportionally profound. Just as educational research has provided insight into possible threats to positive academic outcomes, the field also gives recommendations. Crucially, technology cannot be treated as a tool that will inherently and instantly bring positive change, but instead must be recognised as part of a complex 'sociotechnical network' (Kling, 2000). Implementation needs to be driven by thoughtful and intentional policies informed by social science (Warschauer, 2011). Engineers are rapidly advancing BCI communication systems, and with equal fervour, educational researchers should anticipate new technologies in order to support future academic success.

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Notes

1 A number of other terms and acronyms have been used interchangeably with 'BCI', including brain-machine interface (BMI), mind-machine interface (MMI), or direct neural interface (DNI); see Brunner et al. (2015).

2 Typically, a third category of BCIs are distinguished as 'partially invasive' these devices are not discussed in detail in this paper, see Hassanien and Azar (2015) for more information.

3 The term 'neuroprosthetics' has sometimes been used interchangeably with BCIs. BCIs are a subclass of neuroprosthetics; the latter encompasses any devices that can be integrated with any part of the nervous system, whereas the term BCI specifically refers to devices applied to the brain.

4 Equity depends on more than simply access, as discussed below, and the 'digital divide' is not the most appropriate framework, see Warschauer (2002) and Compaine (2001).