Introduction

Popular understandings of the human brain in the twenty-first century are characterised through a computer metaphor. In this review, I situate the computer metaphor within its historical context, positioning it as the most recent incarnation of metaphors of the brain which draw upon technology. I argue that communication technology metaphors produced for the brain appear to capture its essential characteristics, due to these technologies being designed to emulate human labour.

The review undertaken here is part of a broader project which examines how popular news media utilises scientific knowledge to promote the sexual division of labour. Print news articles are a prime site for reliance upon metaphors as journalists are allocated limited space by newspaper editors, and write to be understood by a large and varied audience. I noticed that many of the news articles collected for the project were sprinkled with metaphors for the brain, mostly referring to electronic circuitry. References to 'wiring' and 'programming' permeate

news reporting of sex differences in brain and behaviour, imparting the notion that these differences are fixed and pre-determined. The terminology of computers is used to describe the brain and its workings to the extent that it is not made clear that a metaphor is being used.

I begin this review article with a historical understanding of metaphors of the brain, noting aspects of the current computer metaphor of the brain which echo components of the earlier metaphors. This historical perspective is taken to demonstrate that the contemporary computing metaphor is not as self-evident as it may seem but is rather a reflection of the current most influential technology. I trace brain metaphors from the earliest which relied upon engineering advances, to those from the late 1800s which particularly focused on communication technologies, culminating (for now) in today's computing metaphor. Finally, I explain how the computing metaphor reinforces understandings of sex differences in the human brain and therefore in behaviour.

Placing understandings of the brain on a timeline allows us to consider that the computer metaphor is not so much a description of how the brain functions as it is a description of current technology. I concur with communications scholar Brian Winston's argument that since the late eighteenth century, human capacities have been likened to whichever machine dominates at the time, a tendency which he calls "mechanemorphism" (2002, p. 155). In this article, I demonstrate that such "mechanemorphism" has an even longer history, over thousands of years. A corollary of this argument is that metaphors of the brain will change to accommodate the prominence of new technologies (Brooks 2015, p. 296). Therefore, it is anticipated that prominent technologies in the future will be adapted into metaphors for the brain.

No other part of the body is as riddled with metaphors as the brain. This is because the role of the brain is privileged in the mind/body split. Being regarded as the seat of personhood, the brain is accorded more significance and attention than any other part of the human body. One

could argue that the panoply of metaphors is not due to cultural projections but rather is reflective of the attributes of the brain (Borck 2012). However, this is an unsatisfying explanation, itself reflective of the cultural beliefs which give rise to so many metaphors. There are many other parts of the body which are also quite complicated or poorly understood, but are not given as much thought. For example, medical historian Cornelius Borck (2012, p. 118) points to the liver as an incredibly complex organ which has lost its cultural significance, and is therefore not understood through metaphor.

In addition to the brain being singled out for understanding through metaphors, it also experiences an instability in the metaphors projected upon it, as the metaphors track technological developments. The computing analogy, which now dominates both expert and lay-understandings of the brain, is only the most recent in a long history of metaphors to describe the brain and its functions. The next section constructs a narrative of changing metaphors of the brain throughout history.

Past metaphors of the brain

A hydraulic metaphor of the body, which included the brain, characterised understandings from Hippocrates (460 – 370 BC) until medieval times. This has been the most enduring metaphor of the brain to date. Hippocrates taught that different ratios of the four humours (blood, phlegm, black bile, yellow bile) were responsible for people's differences of gender and temperament (combinations of the qualities hot, cold, moist, and dry). The movement of the four humours within the body was seen as analogous to the mechanism of ancient water clocks, with which time measurements could be accurately inferred from a known rate of steady water flow into a container with volume markings. According to artificial intelligence scholar George Zarkadakis (2015), the hydraulic metaphor was so compelling because Hippocrates' ideas of the body emerged simultaneously with the invention of hydraulic engineering in Ancient

Greece. Due to this confluence, the concept of the body as being defined by the flow of humours appeared to be self-evident. There is little that can be traced from the hydraulic metaphor to more recent communications metaphors of the brain. Current understandings of the brain no longer reflect the underlying principles of the hydraulic metaphor, though the concept of the four humours survives in some of the expressions we use to describe emotions. Another point of difference is that for all prominent metaphors of the brain which came after the hydraulic metaphor, the output of the technology bore a similarity to human activities. The hydraulic metaphor can only be used to explain the workings, but not the results, of human thought.

The next major development in understandings of the body and brain came from Graeco-Roman physician Galen (130 – 210 AD), who believed there to be no distinction between mind and brain, and theorised that people are hydraulic automata (robots) (Zarkadakis 2015). Hydraulic automata which repetitively imitated the movements of living creatures were then constructed as proof of Galen's idea (Zarkadakis 2015). A commonality between the automaton and computer metaphors of the brain is that both demonstrate fixed patterns of action ('programming', in the computer metaphor). Hydraulic automata, being simple water-powered robots, represent an intermediate step between the hydraulic and computing metaphors of the brain. The automaton metaphor was later adapted into a machine metaphor by René Descartes in the 1600s, who argued that the human body is a machine with the organs serving the role of components such as gears and pistons (Zarkadakis 2015). Like computing metaphors for the brain, the machine metaphor captures the notion of modularity. More recent metaphors for the brain have not supplanted the machine metaphor for the rest of the body, for example, the bodies of athletes are spoken about as finely-tuned machines. Both the automaton and machine metaphors represent a simplification of the brain's function, being focused not just on process but also on predictable outputs.

No newer metaphor for the brain has enjoyed the longevity of these early metaphors, as understandings of the brain have kept up with key developments in information and communication technologies since the late nineteenth century.

Information and communication technology metaphors of the brain

The previous 150 years of metaphorical descriptions of the brain borrow chiefly from information and communication technologies. While this is a relatively recent development when considering thousands of years of technological metaphors for the brain, hints of communication technology metaphors can be found much earlier in philosophical understandings of the mind. Aristotle's (384 – 322 BC) likened the mind to a blank writing tablet (Hamlyn 1968 [2002], p. 59), in what is the first example of comparing information and communication technologies to human thought. However, it was not until the nineteenth century that information and communication technologies were utilised to explain the physical operations of the brain.

The industrial revolution accelerated technological development and thus increased the number of available metaphors for the brain. Prior to the computer metaphor, electrical telegraphy, and later telephone switchboards, became metaphors for the brain's workings (Borck 2012, p. 120). Both the telegraph and telephone metaphors emphasise communication within the nervous system and emphasise the brain as superior to the rest of the body as its 'central office' or 'control room' (Draaisma 2000, p. 139). The electrical telegraph was the first method of electronic communication for long distances, becoming a key part of infrastructure in the West in the mid-nineteenth century. The concept of the telegraph network was projected onto the nervous system, with the brain instantaneously transmitting messages throughout the body (Otis 2001, p. 73). The telegraph metaphor was used to explain mental breakdowns, which under this model were believed to occur when the transmission of messages failed (Morus

2000). This metaphor was also applied in the opposite direction, with the telegraph network billed as the nervous system of the state (Borck 2012; Otis 2001).

Telephony later revolutionised telecommunications in the late nineteenth century, bringing with it the opportunity for a new metaphor of the brain. According to the telephone switchboard metaphor, memories were stored in the brain, with associations made between them (Eichenbaum & Cohen 2004, p. 6). These associations were believed to mimic the physical wires of a telephone exchange switchboard, at which a human operator would connect callers with one another.

Both the telegraph and telephone metaphors attempt to capture how the brain processes information, with little to say about how this information was created (Malabou 2009, p. 34). The telegraph metaphor provides a more integrated picture of the brain with the rest of the nervous system, a quality which has been lost in the computer metaphor. The telegraph and telephone metaphors of the brain bear only superficial similarities to the current computer metaphor, which is much more detailed, providing analogues to many different aspects of the brain and mind.

The computer metaphor of the brain

Most recently, computing metaphors have characterised how the brain is understood, arising in the mid-twentieth century alongside the building of the first electronic computers (Gigerenzer & Goldstein 1996, p. 134). The computer metaphor entirely superseded the telephone switchboard metaphor, despite the coexistence of the two technologies.

The computer metaphor is now pervasive in understandings of the brain. It represents a short-hand way of describing the functions of the brain which are now attributed the most importance. Psychologist Robert Epstein (2016) argues that human intelligence can no longer be discussed without utilising the computing metaphor. He compares this to how in the past, discussions of

human intelligence could not occur without making statements about a deity. The computer metaphor of the brain has become a definition of the brain, and it is inconceivable to describe one without the other.

The computer metaphor encapsulates neuroscientific understandings of the modular brain; that is, cognitive functions are localised to particular regions of the brain. Different faculties can be directly compared to the components of a computer, for example, the hard drive for working memory and peripherals for sensory organs. The implication is that different functions can be located in parts of the brain. Behaviour can be conceptualised as the brain following pre-set programs. Neural circuits are an example where the terminology overlaps; with the word 'circuit' being borrowed from electronics. 'Hard-wiring' is a defining feature of brain metaphors, including the computer metaphor, which rely upon electronics. In a literal sense, hard-wiring refers to the fixed physical connections between components of an electronic circuit. When applied to the brain, 'hard-wiring' indicates that there are immutable structures underlying the brain's workings to produce predictable outcomes.

The computer metaphor simplifies understandings of the brain by casting off elements which do not have a computer hardware analogue. Adapting to one's environment (i.e. learning) is impossible within the computer metaphor (as noted earlier, artificial neural networks which 'learn' are modelled on the brain, rather than the other way around). Similarly, evolution is not accounted for in the computer metaphor. Differences between generations of computers are in no way analogous to evolution as it is undergone by organisms (including their brains) over a long timescale. Most notably, consciousness cannot be accommodated by the computer metaphor. Consciousness has been likened to software running on the 'hardware' of the brain structures (Cisek 1999), but this is a weak point of the metaphor as it is inherently dualistic and defies the picture of emergent consciousness arising from the brain's structures. As consciousness is poorly understood by current models of the brain, it is unsurprising that it is

inadequately explained within the computer metaphor. There is no room in the computer metaphor for conceptions of free will, as behaviour and driving principles are dictated by the brain's 'programming'.

There is a two-way relation between technology and concepts of the brain. Computing metaphors (to explain the brain) and brain metaphors (to explain digital computing) feed into one another. Knowledge of the brain's workings can fuel advances in computation. Key examples of this include image-analysis algorithms which are inspired by edge-sensitive neurons found in the brains of cats and in primates (Bell & Sejnowski 1997); and artificial neural networks, which are problem-solving entities modelled on the brain (e.g. McCulloch & Pitts 1943). McCulloch and Pitts' influential article, which laid the groundwork for development of artificial neural networks, pre-dated the computing metaphor of the brain. Their article may have been the inspiration for the first suggestion (by John von Neumann, one of the inventors of electronic computing) that the brain functions like a computer (Gigerenzer & Goldstein 1996, p. 134). Indeed, von Neumann believed that drawing parallels between the brain and computers would lead to a richer understanding of the functioning of both (Gigerenzer & Goldstein 1996). Some of the parallels between brains and computers are outgrowths of the circularity between descriptions the two. Examples of the brain being used as a metaphor for the computer are seen in the naming of a computer's data storage as 'memory' and its coding as 'language', both borrowed from human faculties (Winston 2002, p. 155). This circularity also occurred in earlier brain metaphors, in particular, with the building of hydraulic automata to demonstrate similarities between human and robot behaviour.

Mixing of metaphor and reality

All of the brain metaphors canvassed here illustrate the interplay between metaphor and what is regarded as the true nature of things. Galen did not conceptualise people as "like" automata,

rather, he thought people essentially are automata, albeit more complicated than human-made versions. The same mixing of reality and metaphor is evident in recent metaphors of the brain. As the brain relies on small electrical signals, it can be considered as made up of (neural) circuits. The brain is then analogous to the circuit boards of a computer, with neurons in place of metal wiring. The computer metaphor was utilised quite literally by computer scientist Eric Jonas and neuroscientist Konrad Kording to lampoon the neuroscientific research program of mapping the structure of the brain (connectome) to yield insight about its workings (Jonas & Kording 2017). The pair applied this paradigm to a microprocessor, subjecting it to a series of experiments mimicking those performed by neuroscientists. They found that the experiments could not derive a meaningful understanding of the processor, and therefore conclude by anology that current neuroscientific methods provide only a rudimentary understanding of cognition. The foundation of their argument is that the brain and the computer processor can be probed and understood in the same ways (alternatively, they could have presented their evidence as an argument against the computer metaphor).

The hydraulic and computer metaphors of the brain appear to capture the nature of the brain in that there are similarities between outputs of the human brain, and outputs of the technologies implicated in the metaphor. However, these outputs are similar precisely because we have invented technologies to make our activities easier, more efficient, and more accurate. This is the case for the predecessor to the modern computer, with Charles Babbage planning the analytical engine because he sought to save scientists from the drudgery of performing calculations so they could focus on tasks for which a mind is required (Otis 2001, p. 32). The brain and the technology it is compared to can only be considered equivalent if one takes a 'black box' approach. Analogies are less applicable to components of the black box. One can write a program which a computer follows to produce an output identical to that created by a human (as Babbage proposed). However, the program is one of many possible pathways to

reach that output, and cannot be used to infer properties of other pathways including a human approach (Carello, Turvey, Kugler & Shaw 1984 p. 231). Humans are capable of remembering information and performing calculations, for example, but these are achieved using entirely different strategies to those employed by computers. This difference is obscured when the language of computers is projected onto understandings of the brain. In the computer metaphor, thinking, calculating, and programming are collapsed into one concept (Malabou 2009, p. 35).

This is not to disparage the use of metaphors for laypeople's understandings of the brain. Metaphors assist us to learn new concepts quickly, and can help with the deduction of further information about the concept (Haken 1993, p. 135). However, applying the computer metaphor too literally becomes an issue when it shapes entire research programs (Brooks 2015; Cisek 1999; Haken 1993), as in the case of Galen's engineer's automata (Zarkadakis 2015), or in the case of some neuroscientific investigations today (Jonas & Kording 2017). The computer metaphor can also be misleading when it is used to create and emphasise group-level differences between people. In popular sources, the metaphor can be applied too literally to explain different types of brains as having characteristic wiring or programming.

Metaphors of the sexed brain

The entrenchment of metaphors in how the brain is understood results in an unnecessarily rigid understanding of the sexed brain. Understandings of female and male brains and behaviour has a long history, with the earliest known scientific attempts to delineate this difference coming from the teachings of Hippocrates and Aristotle. The sexed brain as studied separately from the body has been an area of particular interest since the 1800s with the rise of phrenology and craniology. The idea of distinct male and female brains was not invented by the computer metaphor; however, the metaphor is utilised to support and naturalise ideas of innate difference.

The computing metaphor of the brain is not explicitly gendered, though, the disembodied, algorithmic, rational nature of the computing brain may be understood as inherently masculine. The implied masculinity of the brain and of the computer feed into one another. Ellen Van Oost (2000) argues that computers came to be masculine in the 1950s and 1960s through comparisons to the brain, as well as through re-characterisation of computer programmers as creative (male) rather than diligent (female). This masculinisation of the computer occurred simultaneously with the development of the computing metaphor of the brain. A conception of the brain-computer nexus as masculine serves to present the male brain as the default. However, the gender work performed by the computer metaphor lies not in othering the female brain, but by establishing the male and female brain as two distinct objects which are structured differently and therefore foster different patterns of behaviour.

Importantly, the computer metaphor argues that there are aspects of the brain which are unchangeable and set at birth ('hard-wiring'). It is through the notion of hard-wiring that the metaphor is conscripted into promoting gender roles, as it can be claimed that there are essential and immutable female and male brain structures which are presumed to generate gendered behaviours. Hard-wiring affirms the gendered architecture of the brain, and emphasises that it is a fixed attribute. The current sex differences paradigm in neuroscientific research, in which exposure to hormones in the womb is regarded as setting the sexed brain structure, is known as the 'hard-wiring' model (Jordan-Young & Rumiati 2011). Additionally, the 'programming' aspect of the metaphor can be an analogy for the influence of sex hormones. The brain is regarded as following a pre-determined sequence of events, which is triggered by the release of hormones at different times. As noted earlier, the computer metaphor has no provisions for learning or plasticity of the brain. Therefore, the metaphor excludes the ideas of feminist neuroscientists and others who contend that observed differences in the brain result from interactions between the brain and the culture it inhabits (e.g. Fine 2013). Under the computer

metaphor, male and female brains are designed and optimised for different behavioural outputs. The rigidity of the brain metaphor suggests that gendered behaviours, as produced by the brain's 'circuitry' or 'programming', cannot be changed any more than a computer can decide to disobey its design.

Conclusion

Metaphor is a tool commonly used in popular accounts to efficiently communicate essential aspects of the brain, and the gendered brain in particular. In this article, I drew upon a range of literature to situate the computer metaphor of the brain as the most recent in a long line of metaphors of the brain which draw upon technology. I discussed the relationship between metaphor and reality, probing the extent to which the computer metaphor constructs and reflects attributes of the brain. Finally, I explicated how the computer metaphor functions to create the notion of distinctly gendered brains.

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