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Chapter Two

Integrating Neuroprostheses into Human Sensory, Cognitive, and Motor Processes:

A Biocybernetic Ontology of the Host-Device System

Abstract. In this text, we develop an ontology that envisions, captures, and describes the full range of ways in which a neuroprosthesis may participate in the sensory, cognitive, and motor processes of its human host. By considering anticipated future developments in neuroprosthetics and adopting a generic biocybernetic approach, the ontology is able to account for therapeutic neuroprostheses already in use as well as future types of neuroprostheses expected to be deployed for purposes of human enhancement.

The ontology encompasses three areas. First, a neuroprosthesis may participate in its host's processes of *sensation* by (a) detecting stimuli such as photons, sound waves, or chemicals; (b) fabricating sense data, as in the case of virtual reality systems; (c) storing sense data; (d) transmitting sense data within a neural pathway; (e) enabling its host to experience sense data through a sensory modality such as vision, hearing, taste, smell, touch, balance, heat, or pain; or (f) creating mappings of sensory routes – e.g., in order to allow sensory substitution. Second, a neuroprosthesis may participate in processes of *cognition* by (a) creating a basic interface between the device and the host's conscious awareness or affecting the host's (b) perception, (c) creativity, (d) memory and identity, or (e) reasoning and decision-making. Third, a neuroprosthesis may participate in processes of *motion* by (a) detecting motor instructions generated by the host's brain; (b) fabricating motor instructions, as in the case of a medical device controlled by software algorithms rather than its host's volitions; (c) storing motor instructions; (d) transmitting motor instructions, as within a neural pathway; (e) effectuating physical action within effectors such as natural biological muscles and glands, synthetic muscles, robotic actuators, video screens, audio speakers, or wireless transmitters; (f) allowing the expression of volitions through motor modalities such as language, paralanguage, and locomotion; or (g) creating mappings of motor routes. The use of such an ontology allows easier, more systematic, and more robust analysis of the biocybernetic role of a neuroprosthesis within its host-device system.

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Introduction

Having formulated in the previous chapter an ontology of the neuroprosthesis as a computing device, in this chapter we develop an ontology of the neuroprosthesis as a biocybernetic instrument that becomes integrated into the neural circuitry of a human organism in order to participate in processes of sensation, cognition, and motor action. This investigation of the nature of neurocybernetic technologies will then be carried further in the next chapter by developing an ontology of the neuroprosthesis as a means for the 'cyborgization' of human beings that shapes how such individuals experience posthumanized digital-physical ecosystems.

Fundamental Characteristics of Neuroprostheses

A neuroprosthesis can be defined as *an artificial device that is integrated into the neural circuitry of a human being* to create a neurocybernetic host-device system with both human and computerized elements.[1] In principle, neuroprostheses may be either 'invasive' (i.e., surgically implanted in the brain of a human host) or 'non-invasive' (e.g., consisting of an external device worn by a human host); however, at present it is difficult to develop non-invasive technologies that can become truly integrated into the neural circuitry of a human being.[2] According to the definition used in this text, contemporary neuroprostheses are thus typically identified with 'neural implants'; devices utilizing non-invasive technologies such as EEG or fMRI are likely to be classified more generally as brain-computer interfaces (BCIs) or brain-machine interfaces (BMIs) rather than neuroprostheses.

Contemporary neuroprosthetic devices are typically classified as either sensory, motor, bidirectional sensorimotor, or cognitive neuroprostheses.[3] As shall be explored within this text, however, the distinctions between these different categories of neuroprostheses are not clear-cut; for example, an artificial eye that is primarily considered to be a 'sensory neuroprosthesis' because it restores or enhances the sight of its human host might also possess strong cognitive or motor aspects.

Neuroprostheses are currently used primarily for therapeutic purposes, as a means of restoring some capacity that is absent as a result of injury or ill-

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[1] See Lebedev, "Brain-Machine Interfaces: An Overview," *Translational Neuroscience* 5, no. 1 (2014), and Gladden, "Enterprise Architecture for Neurocybernetically Augmented Organizational Systems" (2016).

[2] See Gasson, "Human ICT Implants: From Restorative Application to Human Enhancement" (2012), p. 14, and Panoulas et al., "Brain-Computer Interface (BCI): Types, Processing Perspectives and Applications" (2010).

[3] See Lebedev (2014).

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ness: thus cochlear implants and retinal prostheses are used to restore sensory functionality to those who are deaf or blind, robotic prosthetic limbs are used to replace natural biological limbs that have been amputated, and deep brain stimulation (DBS) devices are used to treat tremors in those suffering from Parkinson's disease.[4] However, efforts are underway to develop and deploy neuroprostheses whose purpose is not to restore some capacity that is found in typical human beings but to grant their human hosts sensory, cognitive, and motor capacities that far exceed those that are possible for natural biological human beings.[5]

Developing an Ontology of the Neuroprosthesis as Participant in Human Sensory, Cognitive, and Motor Processes

In the following sections, we develop an ontology of the neuroprosthesis as a participant in human processes of sensation, cognition, and motor action. The ontology is biocybernetic in nature, insofar as it focuses primarily on patterns of communication and control within the host-device system.[6] Unlike some contemporary schemas for classifying neuroprostheses, this ontology is intended not only to allow the description, categorization, and analysis of those therapeutic neuroprostheses that are already in use; by taking into account anticipated future developments in the field of neuroprosthetics and envisioning as broadly as possible the potential biocybernetic capacities of neuroprosthetic devices, this ontology is designed to be generic enough to account for the characteristics of the full spectrum of future neuroprostheses that may be developed for purposes of human enhancement.

As illustrated in Figure 1, our ontology is organized into three areas, which allow neuroprostheses to be understood according to their participation in human processes of sensation, cognition, and motion. These aspects of the ontology are developed in detail in the following sections.

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[4] See, e.g., Gasson et al., "Human ICT Implants: From Invasive to Pervasive" (2012); Ochsner et al., "Human, non-human, and beyond: cochlear implants in socio-technological environments" (2015); Weiland et al., "Retinal Prosthesis" (2005); Viola & Patrinos, "A Neuroprosthesis for Restoring Sight" (2007); and *Deep Brain Stimulation for Parkinson's Disease*, edited by Baltuch & Stern (2007).

[5] See, e.g., McGee, "Bioelectronics and Implanted Devices" (2008); Warwick & Gasson, "Implantable Computing" (2008); Gasson (2012); Gladden, "Neural Implants as Gateways to Digital-Physical Ecosystems and Posthuman Socioeconomic Interaction" (2016); and Gladden, "Enterprise Architecture for Neurocybernetically Augmented Organizational Systems" (2016).

[6] The field of cybernetics offers a transdisciplinary theoretical framework and vocabulary that allows insights to be shared and translated between the diverse range of disciplines that study patterns of communication and control in machines, living organisms, or social systems. For this classic definition of cybernetics, see Wiener, *Cybernetics: Or Control and Communication in the Animal and the Machine* (1961).

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Fig. 1: An Ontology of the Neuroprosthesis as Participant in Sensory, Cognitive, and Motor Processes

I. Sensation

- **A. Detection of stimuli and transduction into cellular action potentials**
  - 1. Electromagnetic reception
    - a. Photons
    - b. Electric current or charge
    - c. Magnetic fields
  - 2. Mechanoreception
    - a. Sound waves
    - b. Particle kinetic energy
    - c. Gravity
    - d. External bodily pressure
    - e. Internal bodily pressure
    - f. Excessive pressure
  - 3. Chemoreception
    - a. Solutes and other substances in liquid mixtures
    - b. Atmospheric particulates
    - c. Internal body chemistry
  - 4. Activity cycles
  - 5. Xenostimuli
- **B. Fabrication of electrochemical signals in a sensory neural pathway**
- **C. Storage of sense data**
  - 1. Memory type
    - a. Volatile memory
    - b. Non-volatile memory
  - 2. Information format
    - a. Digital data files
    - b. Neural network activation patterns
- **D. Transmission of action potentials in a sensory neural pathway**
- **E. Modalization of sensory experience**
  - 1. Vision
  - 2. Hearing
  - 3. Taste
  - 4. Smell
  - 5. Touch
  - 6. Posture and bodily extension (proprioception)
  - 7. Balance
  - 8. Heat and cold
  - 9. Energy level (interoception)
  - 10. Pain
  - 11. Passage of time
  - 12. Acoustic contextualization
  - 13. Magnetoreception
  - 14. Electroreception
- **F. Mapping of sensory routes**
  - 1. Routing biologically receivable sense data to its biologically normal modality
  - 2. Routing fabricated sense data to an arbitrary modality
  - 3. Remapping biologically receivable sense data to an atypical but natural modality
  - 4. Employing a non-human xenosensory mapping
    - a. Mapping sense data from xenostimuli to an arbitrary modality
    - b. Mapping arbitrary sense data to a xenesthetic modality

II. Cognition

- **A. Basic interface with the mind**
  - 1. With the host's conscious awareness
  - 2. Without the host's conscious awareness
- **B. Perception**
  - 1. Percepts
  - 2. Consciousness and self-awareness
  - 3. Sleep
  - 4. Emotion
  - 5. Autonomous mental reactions
- **C. Creativity**
  - 1. Ideation and imagination
  - 2. Dreaming
- **D. Memory and identity**
  - 1. Memory
    - a. Sensory memory (SM)
    - b. Short-term memory (STM)
    - c. Long-term memory (LTM)
  - 2. Personality
  - 3. Habit
  - 4. Belief
- **E. Reasoning and decision-making**
  - 1. Working memory (WM)
  - 2. Attention control
  - 3. Volition
  - 4. Metavolition and conscience
  - 5. Internal monologue
  - 6. Savant skills

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III. Motion

A. Detection of action potentials or other motor instructions in a motor neural pathway

B. Fabrication of cellular action potentials in a motor neural pathway

C. Storage of instructions for (repeated) motor execution
- **1.** Memory type
  - **a.** Volatile memory
  - **b.** Non-volatile memory
- **2.** Information format
  - **a.** Digital data files
  - **b.** Neural network activation patterns

D. Transmission of cellular action potentials in a motor neural pathway

E. Effectuation of physical action
- **1.** Stimulation of natural biological effectors
  - **a.** Contraction and relaxation of muscles
    - *i.* Voluntary functions
    - *ii.* Autonomic functions
  - **b.** Regulation of gland cells' production and release of chemicals
- **2.** Control of artificial effectors
  - **a.** Electromagnetic emissions
    - *i.* Photons
    - *ii.* Electric current or charge
    - *iii.* Magnetic fields
  - **b.** Mechanical effectors
    - *i.* Sound waves
    - *ii.* Particle kinetic energy
    - *iii.* Motion of an actuator
  - **c.** Chemical production and release
    - *i.* Release of airborne chemicals into atmosphere
    - *ii.* Release of chemicals into a liquid mixture
  - **d.** Xenoactive phenomena

F. Modalization of motor action
- **1.** Symbolic action
  - **a.** Language classified by its mechanism of production
    - *i.* Oral language
    - *ii.* Written language
    - *iii.* Sign language
  - **b.** Language classified by its historical origin
    - *i.* Natural human language
    - *ii.* Synthetic language
    - *iii.* Language of thought
- **2.** Nonsymbolic action
  - **a.** Paralanguage
  - **b.** Oculesics
  - **c.** Kinesics
  - **d.** Haptic communication
  - **e.** Proxemics
  - **f.** Internal organ activity

G. Mapping of motor routes
- **1.** Routing natural motor instructions to their biologically normal effector
- **2.** Routing fabricated motor instructions to an arbitrary effector
- **3.** Remapping natural motor instructions to a biologically atypical but natural effector
- **4.** Employing a non-human xenoexpressive mapping
  - **a.** Mapping motor instructions to a xenergetic effector
  - **b.** Mapping motor instructions to manifest a xenopractic motor modality

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I. Sensation

Many neuroprosthetic devices perform or participate in behaviors designed to sense details about their host's body[7] or the surrounding external environment. For some of these devices, the act of sensing may be incidental to their primary function; for example, a cognitive or motor neuroprosthesis might employ sensors to aid with device calibration or troubleshooting, or it might receive software updates through the use of radio receivers.

Other devices are **sensory neuroprostheses** whose primary function is to fill some role in the sensory processes of their human host.[8] Many sensory neuroprostheses present sense data to the conscious awareness of their host's mind, where it is perceived and consciously experienced. Other neuroprostheses may provide sense data to a host's spinal cord or brain in a way that triggers some autonomous reflex response in a manner that is not perceived by the host's conscious awareness.

A sensory neuroprosthesis performs tasks like acquiring sense data from distal stimuli such as physical objects and sources of energy and transducing it into cellular action potentials; fabricating cellular action potentials within a sensory neural pathway; storing sense data; transmitting proximal stimuli toward the brain of the device's human host in the form of cellular action potentials within a sensory neural pathway; modalizing sensory experience by presenting it to the mind in a form that it can perceive;[9] or mapping the sensory routes that connect sense data, sense organs, and sensory modalities. Below we consider in more detail these ways in which a neuroprosthesis can participate in its host's processes of sensation.[10]

A. Detection of Stimuli and Transduction into Cellular Action Potentials

Some neuroprosthetic devices serve as receptor organs that acquire sense data from distal stimuli such as physical objects and sources of energy and utilize a process of transduction to translate that input into the form of cellular action potentials that can be transmitted to postsynaptic neurons in the

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[7] Theoretical and practical issues relating to such devices are discussed in *Implantable Sensor Systems for Medical Applications*, edited by Inmann & Hodgins (2013).

[8] For an overview of sensory neuroprostheses, see, e.g., Troyk & Cogan, "Sensory Neural Prostheses" (2005); Merkel et al., "Central Neural Prostheses" (2007); and Lebedev (2014).

[9] Neuroprostheses that generate or alter perceptions primarily by manipulating interneurons within the brain (rather than sensory organs or nerves) and which relate to mental phenomena such as memory and imagination are classified as cognitive rather than sensory neuroprostheses and are discussed in a later section.

[10] A comprehensive investigation of the natural biological systems that perform sensory roles within the human organism can be found, e.g., in Smith, *Biology of Sensory Systems* (2008), and Møller, *Sensory Systems: Anatomy and Physiology* (2014).

body of a device's human host.[11] Below we consider a range of stimuli found within a host's body or the external environment which neuroprostheses may be capable of detecting through various receptor mechanisms.

1. Electromagnetic Reception

A neuroprosthetic device may be capable of registering the presence of electromagnetic radiation, a magnetic field, or electric charge.

a. Photons

A photoreceptive neuroprosthesis registers electromagnetic radiation – most commonly from the environment external to the host's body – by detecting photons. In a natural biological human being, such sensors include at least three types of photoreceptor cells embedded in the retina. Rods do not distinguish colors and provide poor spatial resolution, but they are highly sensitive and can be activated by a single photon, offering a degree of monochromatic vision in very low-light conditions. Cones detect specific wavelengths of light (i.e., colors) and are only activated upon absorbing a large number of photons, which means that colors are not naturally distinguishable in extremely low-light conditions. Finally, photosensitive ganglion cells are also activated by absorbing photons; however, the information that they generate is not consciously experienced by the mind through the modality of vision. Instead they are believed to play a role in the generation of reflex responses and the regulation of circadian rhythms.[12]

A retinal prosthesis may attempt to mimic the natural functioning of the human eye by registering light that falls within the spectrum normally visible to human beings – or it may register electromagnetic radiation of a frequency higher than that of visible light (e.g., ultraviolet light, X-rays, or gamma rays) or lower than that of visible light (e.g., infrared light or radio waves). Such devices could potentially be employed, for example, to allow a human host to 'see' in infrared[13] or to visually detect the presence of Wi-Fi hubs or mobile devices that emit radio waves. Photoreceptive neuroprostheses may also take forms other than that of an artificial eye. For example, an implantable smartphone that has been surgically implanted within a host's abdomen, is integrated into the host's nervous system, and contains a radio receiver would also technically be a photoreceptive neuroprosthesis. Types of photoreceptive

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[11] Natural biological processes of transduction are discussed in Smith (2008), pp. 1-30, and Møller (2014), pp. 29-62.

[12] The structure and functioning of biological photoreceptors is discussed in Smith (2008), pp. 315-49, and Møller (2014), pp. 42-43, 269-71.

[13] Regarding neuroprosthetically enabled infrared vision, see Merkel et al. (2007).

neuroprosthetic devices already in existence include experimental retinal prostheses.[14]

b. Electric current or charge

An electroreceptive neuroprosthesis registers the presence of an electric charge in the form of static electricity or an electric current. In a natural biological human being, sensory and motor neurons can be indiscriminately stimulated by electricity from the external environment (as in the case of an electric shock), and the ability of neurons to be stimulated electrically (e.g., through the use of artificial electrode) makes possible the functioning of many types of neuroprosthetic devices. However, human beings are not known to possess specialized electroreceptors of the sort that are found, for example, in some aquatic or amphibious animals.[15]

c. Magnetic fields

A magnetoreceptive neuroprosthesis registers the presence of a magnetic field. It is not clear whether natural biological human beings possess any such specialized cells; the supposed existence of magnetosensitive bones or brain cells is a matter of ongoing debate.[16]

2. Mechanoreception

A neuroprosthetic device may incorporate a mechanoreceptive component that allows it to register physical motion or pressure. Such neuroprostheses can detect a range of phenomena.

a. Sound waves

Some neuroprosthetic devices contain a specialized form of mechanoreceptor that registers sound waves produced in the external environment or within a host's body. In a natural biological human being, such a sensory system includes hair cells in the ear.[17] An audioreceptive neuroprosthesis may

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[14] See Linsenmeier, "Retinal Bioengineering" (2005); Weiland et al. (2005); and Viola & Patrinos (2007).

[15] Electroreceptors in animals are discussed in Smith (2008), pp. 428-33. Note that not all electroreceptors possessed by neuroprostheses are designed to detect naturally occurring electric current or electric fields present in an environment: a neuroprosthetic device could also be said to possess 'electroreceptors' of a specialized sort if it includes a mini-stereo audio input jack or a power supply input port into which an AC or DC power cable can be inserted to charge the device's internal battery.

[16] For magnetic sensitivity in animals, see Smith (2008), pp. 434-35. In the case of neuroprosthetic devices, the detection of magnetic fields might be used, e.g., in a specialized way to detect the presence of an external hardware token that provides emergency access to a device. Such token-based access schemes for neuroprostheses are discussed in Gladden, *The Handbook of Information Security for Advanced Neuroprosthetics* (2015).

[17] Such biological mechanisms are discussed in Smith (2008), pp. 123-46, and Møller (2014), pp.

attempt to mimic the natural hearing process by registering only those sound frequencies and volumes that are detectable by the human ear, or it might provide augmented sensory capacities by registering sound waves possessing higher or lower frequencies or a lower volume than the ear can naturally detect. Existing types of such neuroprosthetic devices include cochlear implants and auditory brainstem implants.[18]

b. Particle kinetic energy

A thermoreceptive neuroprosthesis contains a specialized form of mechanoreceptor that registers the particle kinetic energy of matter adjoining it, which is transferred in the form of heat. (Note that this would not include a device utilizing the remote thermometric technique of pyrometry.) In a natural biological human being, there are different thermoreceptors specialized to detect heat and cold.[19]

c. Gravity

A neuroprosthesis may contain a specialized form of mechanoreceptor that registers the orientation of gravitational force exerted on the device (and thus – in a terrestrial environment – the direction toward the ground). In a natural biological human being, this system includes hair cells in the ears and vestibular nuclei in the brainstem that assist in maintaining balance and an upright posture.[20]

d. External bodily pressure

A tactioceptive neuroprosthesis contains a specialized form of mechanoreceptor that registers pressure from objects or phenomena external to the host's body that are touching the receptor. Such a neuroprosthesis may attempt to mimic the natural human sense of touch by registering only levels of force that fall within the range of what is typically perceptible by the fingers, skin, or other body organs; alternatively, it may possess a finer degree of sensitivity which allows it to register force too small to be detected by the unaided human body, or it may be capable of safely and accurately measuring very great physical forces which would result in incapacitating pain or the destruction of tissue if applied to an unmodified human body.

In a natural biological human being, this system includes mechanoreceptors in the somatosensory system, such as those in the skin, muscles, and

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191-260.

[18] See Cervera-Paz et al., "Auditory Brainstem Implants: Past, Present and Future Prospects" (2007); Merkel et al. (2007); and Bostrom & Sandberg, "Cognitive Enhancement: Methods, Ethics, Regulatory Challenges" (2009), p. 321.

[19] Thermosensitivity in biological organisms is discussed in Smith (2008), pp. 415-22.

[20] The role of hair cells in detecting bodily orientation is discussed in Smith (2008), pp. 123-31.

body organs.[21] Existing neuroprosthetic devices possessing such functionality include experimental bidirectional prosthetic hands that utilize such mechanisms to detect pressure applied to or by a hand's robotic fingers.[22]

e. Internal bodily pressure

A neuroprosthetic device may contain a similar sort of specialized mechanoreceptor that registers the degree of pressure that muscles and other internal body components exert on one another depending on their relative position. In a natural biological human being, this system includes mechanoreceptors in the skeletal striated muscles and joints that allow the brain to detect the body's posture and spatial orientation.

f. Excessive pressure

A neuroprosthetic device may possess specialized mechanoreceptors that detect levels of pressure which are so great that they are likely to damage or destroy the device or other natural or artificial components of the host's body. In this case, the primary purpose of a mechanoreceptor is not to detect excess pressure as a quantity that must be precisely measured for abstract data-gathering reasons but as an immediate physical danger that must be eliminated. While such a mechanoreceptor may be capable of measuring the current pressure with extreme sensitivity, it might instead only be activated once a certain threshold pressure has been detected and may thus only be capable of registering the binary states of 'non-excessive pressure' and 'excessive pressure.'

Rather than utilizing mechanoreceptors to directly detect excess pressure applied to it, a neuroprosthetic device could potentially detect excessive pressure (or other harmful forces) indirectly – for example, by utilizing chemoreceptors that detect chemical substances within the bloodstream whose presence indicates that some of the body's biological cells are being damaged or destroyed. In a natural biological human being, such excessive pressure is perceived through the sensory modality of pain, employing a mechanism involves nociceptors in the somatosensory system, including those in the skin, muscles, and body organs.[23]

3. Chemoreception

A neuroprosthetic device may possess chemoreceptors that detect the presence of particular kinds of chemical substances, typically on the basis of

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[21] Such biological systems are described in Smith (2008), pp. 99-122, and Møller (2014), pp. 159-90.

[22] For example, see Hoffmann & Micera, "Introduction to Neuroprosthetics" (2011), pp. 792-93.

[23] Biological mechanisms relating to pain are discussed in Smith (2008), pp. 437-62, and Møller (2014), pp. 337-65.

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their molecular structure. Chemical substances might reach such receptors in a variety of forms.

a. Solutes and other substances in liquid mixtures

A neuroprosthesis might incorporate a specialized form of chemoreceptor that registers the presence of particular chemical substances dissolved, suspended, or otherwise present in a liquid medium adjoining the receptor.[24] In a natural biological human being, such sensors include chemoreceptors found on the tongue's taste buds.[25]

b. Atmospheric particulates

Alternatively, a neuroprosthesis might include a specialized form of chemoreceptor that detects the presence of particular types of solid particulates, liquid droplets, or other substances present in an aerosol, suspended in the atmosphere, or otherwise contained in a gaseous mixture adjoining the receptor.[26] In a natural biological human being, such sensors include olfactory receptor neurons found in the nose.[27]

c. Internal body chemistry

A neuroprosthetic device may contain a specialized form of chemoreceptor that detects within the body in solid, liquid, or gaseous form particular chemical substances whose presence or absence provides information regarding the health or functionality of specific biological systems or the status of biological processes.

In a natural biological human being, such chemoreceptors (and mechanoreceptors) located in various body organs detect stimuli that are conveyed to the mind through the sensory modality of interoception and are experienced as feelings such as hunger, thirst, or drowsiness.[28]

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[24] For challenges with the development of chemoreceptive neuroprostheses to restore the sense of taste, see Merkel et al. (2007).

[25] Such chemoreceptors are described in Smith (2008), pp. 187-218, and Møller (2014), pp. 303-22.

[26] The difficulty of designing chemoreceptive neuroprostheses for restoring the sense of smell are noted in Merkel et al. (2007).

[27] Chemoreceptors of this sort are discussed in Smith (2008), pp. 219-44, and Møller (2014), pp. 303-22.

[28] Regarding the nature of interoception in the human organism, see Cameron, *Visceral Sensory Neuroscience: Interoception* (2001). For the possibility of neuroprosthetic devices that relate, e.g., to their host's need for or experience of sleep, see Claussen & Hofmann, "Sleep, Neuroengineering and Dynamics" (2012), and Kourany, "Human enhancement: Making the debate more Productive" (2013), pp. 992-93.

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4. Activity Cycles

A neuroprosthetic device may measure the passage of time by counting instances of some regular phenomenon such as electron transitions (in the case of atomic clocks), the oscillation of an electrically charged silicon dioxide tuning fork (in the case of quartz clocks), or diurnal cycles of light and darkness (in the case of some circadian oscillators found within natural biological organisms). In a natural biological human being, time is measured at a number of different scales by a complex array of systems including the cerebral cortex, cerebellum, and basal ganglia.[29]

5. Xenostimuli

A neuroprosthetic device might incorporate sensors that register the presence of some physical object, source of energy, activity, or other phenomenon that is not normally detectable in a meaningful way by the sense organs of a natural biological human being.[30] Examples might include a photoreceptive device that can receive radio transmissions from a Wi-Fi router or a chemoreceptive device that can detect the presence of radon gas. In comparison to the limited sensory capacities of a natural biological human being, such a neuroprosthetic device can be said to detect 'xenostimuli' through the use of 'xenoreceptors.'[31]

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[29] For a discussion of biological timekeeping mechanisms that are employed by living organisms at the intracellular and intercellular level to maintain both relatively short ultradian rhythms (which primarily regulate an organism's internal intracellular processes) and longer circadian rhythms (which primarily regulate an organism's interaction with its external environment), see Lloyd, "Biological Time Is Fractal: Early Events Reverberate over a Life Time" (2008).

[30] From one perspective, the body of a natural biological human being might be said to possess sensors that are capable of 'detecting' the presence of, e.g., X-rays or odorless airborne carcinogenic chemicals – insofar as cells within the body that are exposed to such phenomena may eventually manifest in response some recognizable behavior (such as cell death or the production of tumors) that indicate to the human being the presence of the phenomena. However, the structures contained within the body that react to the presence of such stimuli are not normally described as 'sensory receptors' (and the processes by which they register the presence of such phenomena are not described as the reception of 'sense data'), insofar as the structures do not constitute mechanisms that are specialized to serve that purpose and do not transmit information about the phenomena's presence to the spinal cord or brain through typical sensory pathways.

A liminal case is that of ultraviolet radiation: in itself, such radiation is invisible and cannot be directly detected by the human eye; however, its presence in sufficient quantities is 'detected' by melanocytes in the epidermis, which visibly signal the presence of UV radiation when the melanin contained within the cells undergoes a process of oxidation that darkens the pigment. An individual's (retrospective) realization that he or she has been exposed to an excessive quantity of UV radiation by means of the appearance of a sunburn is a not uncommon occurrence.

[31] The use of neuroprostheses to grant human hosts the ability to detect new kinds of stimuli not detectable to natural human beings is discussed in Warwick, "The Cyborg Revolution" (2014); Gasson et al. (2012); and Merkel et al. (2007).

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B. Fabrication of Electrochemical Signals within a Sensory Neural Pathway

One possible behavior for a sensory neuroprosthesis is for the device to accurately detect the presence of environmental or bodily stimuli using specialized receptors, transduce those stimuli into a pattern of electrochemical signals whose nature faithfully reflects the contents of the stimuli, and then transmit those signals to adjoining postsynaptic neurons so that they can be conveyed to the spinal cord or brain. That is the approach normally employed with contemporary sensory neuroprostheses, whose purpose is generally to restore as authentically as possible forms of biologically typical sense perception that are absent in a device's human host due to injury, illness, or some other medical condition.

However, rather than accurately detecting environmental or bodily stimuli that exist objectively as part of the primary physical world[32] and transducing them into electrochemical signals, another possible behavior is for a sensory neuroprosthesis to fabricate electrochemical signals that correspond to a particular set of distal stimuli (and which will be interpreted by the host's brain as such), despite the fact that those distal stimuli do not actually exist at that moment within the primary physical world. For example, a cochlear implant containing a sufficiently sophisticated computer could provide its human host with a real-time stream of auditory sense data that accurately reflects all of the sounds that the device is detecting in the surrounding environment: nearby conversations, the sound of traffic in the street outside, the whir of the fan in the host's desktop computer, the sound of the host's own breathing. However, by drawing on data stored within itself or accessed through the Internet, the implant could alternatively supply its host with the sounds of a Mozart symphony (to enhance the host's focus and productivity while immersed in some critical work-related task), soothing white noise (to help the host fall asleep in a distracting auditory environment), a 'replay' of a conversation that the host had engaged in an hour earlier and which the device had recorded (to refresh the host's memory regarding forgotten details of the conversation), or turn-by-turn navigation directions to a destination

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[32] Here, the term 'primary physical world' is used to refer to what is commonly described as the 'real' physical world, whose contents possess an objective, independent existence; that world can be contrasted with 'secondary physical worlds,' or virtual worlds whose contents are determined by the computational processes of a computerized virtual reality system. The contents of such virtual worlds are arbitrary, insofar as they are not constrained by the organization of the primary physical world and can be dramatically altered at will by a virtual world's human designer or world-management algorithms. Even secondary physical worlds are still 'real' and 'physical,' though, insofar as the structure of their contents is maintained within real physical objects (e.g., the hard drives or ROM chips of a VR computer system) and are experienced by their inhabitants through the mediation of real physical stimuli (such as electrons or chemical neurotransmitters used to stimulate neurons in a host's sensory system or brain).

while the host is driving an automobile (to avoid disturbing passengers with such continual interruptions or to avoid revealing to the passengers that the host does not already know the way to the destination).

In such cases, the neuroprosthetic device is not simply a passive receiver that attempts to detect environmental stimuli in the form of sound waves and convey them accurately and instantaneously to the mind of its host: instead, the device employs various specialized algorithms or processes to determine the auditory percepts that the host should experience; accesses audio files or other data stored within the device or acquired from a remote location (e.g., through the Internet) that contain the information needed to correctly assemble the stream of auditory sense data; computes the correct pattern of electrochemical signals that the cochlear nerve should receive in order for the host to ultimately experience the intended auditory percepts; and physically generates the correct electrochemical stimuli and transmits them to the cochlear nerve. From a biocybernetic perspective, a neuroprosthetic device that possesses such an ability to fabricate sense data is of a qualitatively different sort than one that is only capable of transducing and transmitting stimuli that currently exist within the real physical environment.[33]

C. Storage of Sense Data

A sensory neuroprosthesis may store sense data within itself either temporarily or indefinitely; the data stored may be either 'real' sense data that corresponds to actual sets of stimuli that were detected in the host's primary physical environment, sense data that was detected in some remote environment, or 'fabricated' sense data that was procedurally generated by the device. Such storage can employ different memory types and information formats.

1. Memory Type

a. Volatile memory

A sensory neuroprosthesis such as a cochlear implant will typically need to store newly received sense data within itself at least briefly in order to process the data and compute the pattern of electrical stimulation that will be applied to its host's neurons in order to transmit the data. Such data may be

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[33] The potential for sensory neuroprostheses to provide their hosts with sensory experiences that do not correspond to physical stimuli existing in the external primary physical world is discussed in Koops & Leenes, "Cheating with Implants: Implications of the Hidden Information Advantage of Bionic Ears and Eyes" (2012), and McGee (2008), p. 221.

stored using random-access memory (e.g., a DRAM or SRAM chip) that requires a continuous supply of electrical power in order to preserve the data. A loss of power to the device would result in the loss of such data.[34]

In principle, RAM can be used by a neuroprosthetic device to store sense data for a lengthy and indefinite period of time, as long as the device does not power down. However, in practice, RAM is used in mobile devices to store data that is being actively utilized for a brief period of time. This means that an implantable sensory neuroprosthetic device's use of electronic volatile memory technologies to store sense data would be functionally comparable to the mechanisms of iconic memory, echoic memory, haptic memory, and other forms of sensory memory (SM) that are employed by the human brain to store sense data for a brief period (e.g., a few hundred milliseconds) before it is processed by short-term memory (STM) and working memory (WM).[35]

b. Non-volatile memory

A sensory neuroprosthesis may also store sense data using non-volatile mechanisms that allow the data to be preserved even if the device is powered down. For example, a cochlear implant that is designed to allow its user to replay noteworthy conversations days or weeks after they occurred may store a copy of raw auditory sense data using flash memory that will maintain the data even if the device is restarted or its battery fails. From a functional perspective, such artificial memory technologies are comparable to the biological mechanisms for long-term memory (LTM) found in the human brain, which are able to store sense data in a relatively stable and permanent (if compressed and incomplete) form.[36]

2. Information Format

a. Digital data files

A neuroprosthetic device may store sense data in the form of binary digital files of the sort that can easily be exchanged with desktop computers or other external conventional computing systems. Data may be stored either in a raw format that preserves all available information but requires large file sizes or a processed and compressed format that preserves only selected information.

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[34] Regarding different memory mechanisms for computerized devices, see Dumas, *Computer Architecture: Fundamentals and Principles of Computer Design* (2006).

[35] Such memory mechanisms utilized by the human brain are discussed, e.g., in Baars, *In the Theater of Consciousness* (1997), and Baddeley, "The episodic buffer: a new component of working memory?" (2000).

[36] The human brain's mechanisms for long-term memory are discussed in Dudai, "The Neurobiology of Consolidations, Or, How Stable Is the Engram?" (2004). Efforts to develop artificially intelligent systems that can mimic such memory processes are described in Friedenberg, *Artificial Psychology: The Quest for What It Means to Be Human* (2008).

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A neuroprosthetic device's use of artificial technologies for the storage of digital data can be seen as roughly equivalent to the natural biological mechanisms by which the human body stores genetic information in the form of DNA.[37]

b. Neural network activation patterns

A neuroprosthetic device may store sense data within the components and processes of a physical artificial neural network that mimics to a greater or lesser degree the functioning of the human brain's biological neural network and which may directly interface with, complement, or partially replace neurons and neural structures within the brain.[38] Such a neural network stores information within its topology and activation patterns in a form that may be difficult or impossible for external computing systems to detect and decode and which may only be interpretable to the neural network in which the information is stored[39] – in effect, potentially creating a form of encryption that possesses the trait of information-theoretic security.

D. Transmission of Cellular Action Potentials within a Sensory Neural Pathway

It is possible for a neuroprosthetic device to serve as a 'bridge' that receives electrochemical signals that were generated by a natural biological sense organ and retransmits them along their path toward the brain of the device's host. For example, in a case where a secondary sensory neuron within the spinal cord has been damaged or destroyed (e.g., as a result of illness or injury), a neuroprosthesis might detect electrochemical signals produced by the related primary sensory neuron that correspond to sense data from mechanoreceptors in the skin and then retransmit that sense data to the tertiary neuron that carries it to the primary sensory cortex.[40] In healthy individuals,

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[37] And, indeed, the use of DNA by artificial devices as a mechanism for data storage and computation is a technology whose development is being actively pursued. See Church et al., "Next-generation digital information storage in DNA" (2012).

[38] The development of memristors represents one approach to fashioning such a neural network. See e.g., Snider, "Cortical Computing with Memristive Nanodevices" (2008); Versace & Chandler, "The Brain of a New Machine" (2010); *Advances in Neuromorphic Memristor Science and Applications*, edited by Kozma et al. (2012); and Lohn et al., "Memristors as Synapses in Artificial Neural Networks: Biomimicry Beyond Weight Change" (2014).

[39] Regarding the difficulty of analyzing and interpreting the current state of information contained within an artificially intelligent system, especially that of a distributed artificial intelligence (DAI) displaying emergent behavior, see Friedenberg (2008), pp. 31-32.

[40] For a discussion of such sensory pathways, see Smith (2008), pp. 19-30, and Møller (2014), pp. 63-158. While they relate to processes of memory rather than sensation, the 'memory prostheses' described in Soussou & Berger, "Cognitive and Emotional Neuroprostheses" (2008), operate on a similar principle by serving as a bridge between neurons that spans a damaged area within the

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such neuroprosthetic bridges could potentially be employed to allow sense data to reach the spinal cord or brain faster than would naturally be possible – but without altering the contents of the sense data.

E. Modalization of Sensory Experience

Some neuroprosthetic devices may sense details of their environment for internal purposes (e.g., to enable device calibration or the wireless downloading of routine software updates) without the results of those sensing processes being shared directly with the conscious awareness of their human hosts. Those sensory neuroprostheses that detect stimuli in order to present them to their hosts' conscious awareness must do so using a specific **sensory modality**, a means by which the human mind perceives, consciously experiences, and interprets sense data.[41]

For natural biological human beings, each of the body's sensory organs normally presents sense data to the mind using a particular fixed sensory modality: for example, the arrival of photons stimulating the retina is revealed to the mind through the modality of vision, while pressure applied to mechanoreceptors in the skin is presented through the modality of touch. However, atypical connections between a particular form of sense data and a particular sense modality are sometimes found in nature: for example, an individual suffering from projective chromesthesia[42] might see a particular color whenever his or her ears detect the presence of a particular frequency of sound waves; in such a case, auditory sense data detected by the ears is presented to the mind through the modality of vision.

A neuroprosthetic device may present authentic or fabricated sense data to the mind of its human host using any of a number of sensory modalities. For example, a neuroprosthesis that is capable of continually monitoring its host's blood glucose level could alert the host to the fact that his or her blood glucose has fallen to a dangerously low level by stimulating the cochlear nerve to present the host's conscious awareness with an audible tone (i.e., using the modality of hearing), by stimulating the optic nerve to present a flashing light in the host's field of vision (i.e., using the modality of vision), or by stimulating nociceptors in a designated part of the host's body to create a piercing

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hippocampus.

[41] Sensory modalities and related phenomena are discussed in Smith (2008), pp. 31-40.

[42] For an overview of such phenomena, see Cytowic, *Synesthesia: A Union of the Senses* (1989), and *Synaesthesia: Theoretical, artistic and scientific foundations*, edited by De Córdoba Serrano et al. (2014).

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sensation (i.e., using the modality of pain).[43] Key sensory modalities are discussed below.

1. Vision

A neuroprosthetic device may present sense data to the conscious awareness of its human host using the naturally existing sensory modality of vision. The sense data thus presented might correspond to visible light detected in the host's primary physical environment, visual patterns that represent the appearance of some fabricated object within a virtual world in which the host is immersed, or another form of sense data that has been mapped to the modality of vision.[44] In a natural biological human being, the perception of sense data through the modality of vision involves the optic nerve and regions of the brain such as the visual cortex.[45]

It should be noted that while the rods and cones present in a natural biological retina might be loosely understood as forming a field of vision with a 'resolution' comprising a certain number of 'pixels' with regard to the retina's ability to detect the arrival photons, the manner in which visual data is transmitted to the brain and perceived by the mind is vastly more complex. While a human eye contains far more than one million sensors (i.e., individual rods and cones), there are only about one million output neurons (in the form of ganglion cells) that transmit data from the eye to the brain, with roughly half of the visual data coming from the tiny fovea, or focal point at the center of the field of vision.[46] Moreover, different neurons within areas V1 and V2 of the visual cortex are responsible for detecting edges, corners, spatial orientation, colors, and motion, while other neurons may detect patterns corresponding to the face of a particular person or a certain type of object. This allows the mind to experience the visual environment not as an array of pixels that

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[43] It may also be possible for a neuroprosthetic device to present sense data to the conscious awareness of its human host in a manner that bypasses the body's sensory systems altogether: e.g., a neuroprosthesis that is capable of manipulating the processes of short-term or long-term memory may be able to provide its host with the (likely hazy and imperfect) *recollection* of having seen or heard something, despite the fact that the host had never originally experienced the sight or sound as incoming sense data. Such possibilities are considered in this text's later sections regarding memory as a form of cognition.

[44] Regarding the possibility of such sensory substitution, see Wiener (1961), loc. 2784ff; Lebedev (2014), p. 106; and Warwick (2014). For existing types of visual neuroprostheses, see See Linsenmeier (2005); Weiland et al. (2005); and Viola & Patrinos (2007). For the possibility of visual cortical implants, see Thanos et al., "Implantable Visual Prostheses" (2007).

[45] Vision in human beings is discussed in Smith (2008), pp. 281-378, and Møller (2014), pp. 261-302.

[46] See Linsenmeier (2005) for a discussion of some such issues.

changes from moment to moment but as a collection of recognizable objects and phenomena displaying various behaviors.

Simulations suggest that a retinal prosthesis would need to possess a visual resolution of 600-1,000 pixels in order to provide a level of vision that would allow its human host to perform functions such as reading ordinary text or recognizing faces.[47] It has been estimated that in order to fully replicate the visual acuity of a natural biological human eye, the photoreceptors of a retinal prosthesis would need to receive roughly 200 Gbps of raw sense data from the external environment and would transmit roughly 200 Mbps of processed sense data to the brain of the device's human host.[48]

2. Hearing

A neuroprosthesis may present sense data to the conscious awareness of its human host that is experienced through the naturally occurring sensory modality of hearing. The sense data experienced in this way might correspond to audible sound waves detected in the host's primary physical environment, sounds emanating from some fabricated object within a virtual world, or another type of sense data that has been mapped to the modality of hearing.[49] It has been estimated that in order to replicate the auditory sensitivity of a natural biological human ear, the mechanoreceptors of an auditory prosthesis would need to receive roughly 4 Mbps of raw sense data from the external environment and transmit 2 Mbps of processed sense data to the brain of the device's host.[50] In a natural biological human being, sensory experiences employing the modality of hearing are created by systems including the cochlear nerve and auditory cortex.[51]

3. Taste

A neuroprosthetic device may present sense data to the mind of its human host using the natural sensory modality of taste. Sense data presented in this way might correspond to the chemical properties of some object existing in the host's primary physical environment, to the 'taste' of some fabricated object existing within a virtual environment within which the host is immersed, or other sense data that has been mapped to the modality of taste. It has been

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[47] Weiland et al. (2005).

[48] See Berner, *Management in 20XX: What Will Be Important in the Future – A Holistic View* (2004), pp. 45-46.

[49] Existing types of auditory neuroprostheses include cochlear implants and auditory brainstem implants. See Bostrom & Sandberg (2009), p. 321, and Cervera-Paz et al. (2007).

[50] See Berner (2004), pp. 45-46.

[51] Hearing in human beings is discussed in Smith (2008), pp. 123-186, and Møller (2014), pp. 191-261.

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estimated that fully replicating the sensitivity of the human gustatory system would require the chemoreceptors of a gustatory neuroprosthesis to receive roughly 150 Mbps of raw sense data from the substance being tasted and would require the device to transmit 11 Mbps of processed sense data to the brain of its host.[52] In a natural biological human being, experiences of the modality of taste involve certain cranial nerves and the gustatory cortex.[53]

4. Smell

A neuroprosthesis may provide sense data to the conscious awareness of its human host in such a way that it is experienced through the naturally occurring sensory modality of smell. The sense data thus experienced might correspond to the chemical properties of airborne substances found in the host's primary physical environment, the 'smell' of substances within a virtual environment occupied by the host, or another type of sense data that has been mapped to the modality of smell. It has been estimated that in order to replicate the sensitivity of the human gustatory system, the chemoreceptors of an olfactory neuroprosthesis would need to receive roughly 20 Gbps of raw sense data from the gaseous mixture being smelled and transmit 30 Mbps of processed sense data to the brain of the device's host.[54] In a natural biological human being, components involved in the experience of smell include the olfactory bulb and olfactory cortex.[55]

5. Touch

A neuroprosthetic device may present sense data to the mind of its human host through the natural sensory modality of touch. Sense data presented in this manner might correspond to the shape, texture, and pressure of some object existing the host's primary physical environment, to the 'touch' of some fabricated object existing in a virtual environment within which the host is immersed, or to other sense data that has been mapped to the modality of touch. It has been estimated that in order to fully replicate the acuity of the human sense of touch, the mechanoreceptors of a neuroprosthetic 'skin' would need to receive roughly 1.5 Gbps of raw sense data and transmit 10 Mbps of processed sense data to the brain of the device's host.[56] In a natural

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[52] See Berner (2004), pp. 45-46.

[53] Sensations of taste in human beings are discussed in Smith (2008), pp. 208-18, and Møller (2014), pp. 303-22.

[54] See Berner (2004), pp. 45-46.

[55] The sense of smell in human beings is described in Smith (2008), pp. 225-24, and Møller (2014), pp. 303-22.

[56] See Berner (2004), pp. 45-46.

biological human being, the experience of touch involves systems such as the primary somatosensory area in the parietal lobe.[57]

6. Posture and Bodily Extension (Proprioception)

A neuroprosthetic device may present sense data to the mind of its human host using the natural sensory modality of proprioception, which provides an individual with an awareness of the position of his or her limbs in relation to his or her head and torso.[58] In a natural biological human being, components contributing to the experience of proprioception include sensory neurons in the inner ear and ligaments as well as the cerebrum and cerebellum. The capacity for proprioception allows one to sense whether one's arms are extended to the sides, raised overhead, or pointed forward even when one is standing in a darkened room and unable to see one's arms. Proprioceptive sense data presented by means of a neuroprosthesis might correspond to the current posture and extension of the host's primary physical body (including biological and artificial components), the posture and extension of the virtual (and potentially radically nonhuman[59]) body possessed by the host in some virtual environment, or another type of sense data that has been mapped to the modality of proprioception.

The use of a neuroprosthetic device to create the proprioceptive sensation of a virtual body part that does not exist as a real physical object is in some ways comparable to the phantom limb sensation that causes amputees to feel the presence of a limb that no longer physically exists.[60]

7. Balance

A neuroprosthesis may provide sense data to the conscious awareness of its human host that is experienced through the sensory modality of balance, which reveals the orientation and motion of the host's body relative to the ground. This modality allows an individual to know whether he or she is standing upright and motionless, spinning, or falling even when located in a darkened room in which it is impossible to see one's body or the surrounding environment. In a natural biological human being, the experience of balance is produced through joint action of components such as the vestibular system

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[57] Human beings' sense of touch is discussed in Smith (2008), pp. 112-22, and Møller (2014), pp. 159-90.

[58] See Siegel & Sapru, *Essential Neuroscience* (2006), pp. 259-60.

[59] For such possibilities, see Gladden, "Cybershells, Shapeshifting, and Neuroprosthetics: Video Games as Tools for Posthuman 'Body Schema (Re)Engineering'" (2015).

[60] See *Amputation, Prosthetic Use, and Phantom Limb Pain: An Interdisciplinary Perspective*, edited by Murray (2010).

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(including the inner ear, cerebellum, and thalamus), visual system, and proprioceptive system.[61]

If a neuroprosthetic device is employed, the sense data experienced through this modality might correspond to the orientation of the host's real physical body relative to the primary physical environment, the orientation of the host's virtual body relative to the infrastructure of a virtual world in which the host's conscious awareness is immersed, or another type of sense data that has been mapped to the modality of balance. The employment of a neuroprosthesis to create a sense of balance, motion, or motionlessness that does not correspond to the actual state of a host's real physical body is in some ways comparable to the phenomenon of subjective vertigo that causes an individual to feel as though his or her body is spinning when in fact that is not the case.[62]

8. Heat and Cold

A neuroprosthetic device may present sense data to the mind of its human host through the natural sensory modalities of heat and cold. Sense data presented in this fashion might reflect the temperature of the host's real physical body or the primary external physical environment, of the host's virtual body or the fabricated environment of a virtual world in which the host is immersed, or other sense data that has been mapped to the modalities of heat and cold. In a natural biological human being, the experience of heat and cold is regulated by systems including portions of the thalamus.[63]

9. Energy Level (Interoception)

A neuroprosthetic device may provide sense data to the conscious awareness of its human host that is experienced through the sensory modalities of interoception, which (among other things) allows the host to feel his or her internal energy level and the degree to which he or she needs to replenish his or her operating ability by inhaling or ingesting physical resources (such as oxygen, water, and food) or obtaining a sufficient amount of sleep. Such modalities may take the form of feelings such as hunger, thirst, drowsiness, or suffocation. In a natural biological human being, the modalities of interoception are regulated by various internal organs and regions of the brain.[64] If an interoceptive neuroprosthesis is employed, the sense data experienced through the modalities of interoception might correspond to the energy or

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[61] The sense of balance is discussed in Smith (2008), pp. 129-31.

[62] See Brandt, *Vertigo: Its Multisensory Syndromes* (2003).

[63] Thermosensitivity is discussed in Smith (2008), pp. 415-22.

[64] Regarding the nature of interoception in the human organism, see Cameron (2001). For the possibility of neuroprosthetic devices that relate, e.g., to their host's need for or experience of sleep, see Claussen & Hofmann (2012) and Kourany (2013), pp. 992-93.

resource level of the host's real physical body, the energy or resource level of the host's virtual body within an immersive virtual environment, or another type of sense data that has been mapped to one of the modalities of interoception.

10. Pain

A neuroprosthesis may present sense data to its host's mind using the naturally existing sensory modality of pain. In a natural biological human being, the experience of pain often results from the presence of an excess of skin pressure, kinetic energy, light, sound waves, or chemical substances that are causing damage or destruction to biological tissue and which at lower quantities would be experienced through a different modality (such as that of touch, heat, vision, hearing, or hunger). In a natural biological human being, the experience of pain may involve portions of the brainstem, among other systems.[65]

If a neuroprosthetic device participates in these processes, the sense data presented through the modality of pain might reflect excessive stimulation of or damage to biological or artificial components of its host's real physical body, the host's virtual body within an immersive virtual environment, or some other type of sense data that has been mapped to the modality of pain.[66]

11. Passage of Time

A neuroprosthetic device may present sense data to the mind of its human host in such a way that creates the experience of the passage of time. In a natural biological human being, such perception of the passage of time is regulated by a complex array of systems including the cerebral cortex, cerebellum, and basal ganglia.[67] If a neuroprosthetic device is involved, the sense data presented in this fashion might reflect the passage of time as measured within the primary physical environment in which the host's real physical body is located, the passage of time within some virtual environment in which the host is mentally immersed, or potentially some other form of sense data (e.g., the presence of high temperatures or a particular airborne chemical) which causes the neuroprosthetic device to present stimuli to the host's mind at an accelerated or decelerated rate.

If a neuroprosthetic device creates a fully immersive virtual reality environment in which visual, auditory, and other sense data are provided to its

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[65] The experience of pain by human beings is discussed in Smith (2008), pp. 437-62, and Møller (2014), pp. 337-65.

[66] For different kinds of neuroprosthetic devices that have an analgesic effect of reducing the experience of pain or producing a feeling of euphoria for their human host, see Denning et al., "Neurosecurity: Security and Privacy for Neural Devices" (2009).

[67] See *The Nature of Time: Geometry, Physics and Perception*, edited by Buccheri et al. (2003).

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host's conscious awareness by the device, it may be possible for the device to cause time to pass more slowly or quickly in the virtual world than in the real physical world in which the host's body is located. (For example, the host might be presented with the experience of sitting in an auditorium and listening to a lecture that lasts 50 minutes – while in real life the lecture had lasted 55 minutes but was recorded and played back to the host's conscious awareness at an accelerated rate.) Depending on the senses involved and the difference in speed between the real and experienced worlds, a host might feel as though: 1) the world's activities were continuing to occur at their regular speed but the host's cognitive and physical activities had been 'slowed down' or 'speeded up'; 2) the host's cognitive and physical activities were continuing to occur at their normal rate but the activity of the external world had been 'slowed down' or 'speeded up'; or 3) there was no detectable difference in the host's experience of the passage of time.

12. Acoustic Contextualization

A neuroprosthetic device may provide sense data to the conscious awareness of its human host that is experienced through the auditory sensory modality that allows one to 'feel' the size, shape, and contents of the environment in which one's body is located, even when the environment is completely dark and it is not possible to judge its extent and contents through vision or touch. When an individual intentionally produces a sound in order to judge the size and features of the environment based on the sound's echo, this modality takes the form of echolocation. When it relies on the characteristics of ambient sounds already present in the environment, it takes the more general form of acoustic wayfaring or contextualization. To some extent, all human beings possess a limited ability to exploit the information conveyed through this sensory modality: for example, a person might instinctively navigate his or her unlit home at night without bumping into walls by relying on subtle auditory clues provided by the hum of a refrigerator or water heater or the echoes produced by the sound of his or her footsteps on a hardwood floor. The skill of recognizing the information conveyed through this modality might be more explicitly trained and developed by, for example, one who is blind or who regularly works in a lightless environment.[68]

Some bat species possess specialized inner ears organs that are structured to be especially sensitive and accurate in detecting the particular frequency

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[68] For a discussion of echolocation and acoustic wayfaring, see Goldstein, *Sensation and Perception* (2014), pp. 312-13; Teng & Whitney, "The acuity of echolocation: spatial resolution in the sighted compared to expert performance" (2011); and Fiehler et al., "Neural correlates of human echolocation of path direction during walking" (2015).

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of sound wave generated by the bat's echolocation process.[69] In human beings, there do not appear to be specialized sensory structures dedicated for use in echolocation and acoustic contextualization. Instead, hair cells within the cochlea are continuously receiving a wide range of generalized auditory sense data and transmitting it to the brain – where most of it is experienced through the modality of hearing but where some of it may (consciously or subconsciously) be interpreted to provide information about the size, shape, and contents of the surrounding environment.

If an auditory neuroprosthetic device is employed to participate in such processes, the sense data experienced through the modalities of echolocation or acoustic contextualization might reflect the features of the primary physical environment in which its host's real physical body is located, the fabricated features of a virtual reality environment in which the host is immersed,[70] or perhaps another type of sense data that has been mapped to these modalities.

13. Magnetoreception

A number of invertebrates, mammals, and birds (e.g., the homing pigeon) show an ability to detect the presence and orientation of magnetic fields, which they may use as an aid in navigation or for other purposes.[71] The hypothesis that human beings may possess some natural mechanism for magnetoreception that allows the brain to perceive (even if subconsciously) the existence of magnetic fields is highly controversial,[72] although research has found, for example, that transcranial magnetic stimulation of the brain can have significant effects on emotions and other cognitive behavior.[73]

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[69] See Neuweiler, "Evolutionary aspects of bat echolocation" (2003).

[70] Robust and correct handling of the phenomenon of acoustic contextualization is necessary in order to create an immersive VR environment of the highest possible sensory fidelity. When fabricating the contents of a VR environment, it is not sufficient to accurately calculate and present the frequency, volume, and point-source direction of obvious environmental sounds (such as the voice of a conversation partner or the engine of a passing automobile); it is also necessary to determine, for example, the particular way in which these sounds are partially absorbed and reflected by a desk near which the listener is standing, depending on whether the desk is made of metal, wood, or some other substance. The fact that echolocation data can be successfully interpreted by human subjects in recorded (rather than live) audio sources is demonstrated, e.g., in Fiehler et al. (2015).

Efforts to develop artificial technologies to enhance or expand human beings' capacities for echolocation and acoustic wayfaring are described, e.g., in Sohl-Dickstein et al., "A device for human ultrasonic echolocation" (2015), and Davies, *Audification of Ultrasound for Human Echolocation* (2008).

[71] See Smith (2008), pp. 434-35, and Rozhok, *Orientation and Navigation in Vertebrates* (2008).

[72] See Hand, "Maverick scientist thinks he has discovered magnetic sixth sense in humans" (2016).

[73] See *A Clinical Guide to Transcranial Magnetic Stimulation*, edited by Holtzheimer & McDonald

Given these scientific uncertainties, it may or may not be possible for a neuroprosthesis to present sense data to its host's mind using a sense modality that involves the perception of magnetic fields. If it is possible, sense data presented through such a modality might reflect the characteristics of the magnetic fields (typically dominated by the earth's natural magnetic field) of the primary physical environment in which the host's physical body is located or an artificial magnetic field that has been created specifically to override the naturally occurring ambient magnetic fields and create the perception that the host's body is oriented in a different direction than it actually is; the latter arrangement might be used, for example, to make the magnetic fields experienced by a host who is immersed in a virtual reality environment consistent with the visual or auditory clues that the host is receiving regarding the direction of his virtual body's orientation. Note that if, for example, an individual possessed an artificial eye that displayed a computer-generated compass within the host's field of vision in order to indicate the direction of magnetic north, such a presentation would constitute a use of the natural modality of vision – not the use of a hypothesized perception of magnetic fields.

14. Electroreception

Some animals (including sharks, electric eels, and the platypus) possess a dedicated sensory system for electroreception that allows them to detect the presence of electric fields – often in order to locate prey.[74] In a natural biological human being, the perception of electrical charge as such is not known to exist as a separate sensory modality. While specialized electroreceptors of the sort found in fish are absent in human beings, a sufficiently large electric charge present in the environment can indiscriminately stimulate sensory and motor neurons in a way that produces the sensation of an electric shock; however, this is typically experienced through existing sensory modalities such as those of touch, vision, hearing, heat, and pain. Nevertheless, the ability to detect an electrical charge is a critical component of neurons' capacities for communication and control, and the basic functioning of many types of sensory and cognitive neuroprostheses is premised on the fact that that the application of an electric charge can generate desired responses in individual neurons or the brain as a whole. While the potential for a neuroprosthetic device to present sense data using a hypothesized sensory modality involving

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(2014); *Transcranial Magnetic Stimulation in Clinical Psychiatry*, edited by George & Belmaker (2007); and *Magnetic Stimulation in Clinical Neurophysiology*, edited by Hallett & Chokroverty (2005).

[74] See Smith (2008), pp. 428-33; *Electroreception*, edited by Bullock et al. (2005); and *Sensory Evolution on the Threshold: Adaptations in Secondarily Aquatic Vertebrates*, edited by Thewissen & Nummela (2008), pp. 425-432.

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the perception or experience of electric charge as such is thus unclear, it may merit further future research.

F. Mapping of Sensory Routes

A sensory neuroprosthetic device creates a 'mapping' by which a particular type of sensory stimulus is detected by a particular sense organ and experienced by the mind of the device's host through a particular sensory modality. Within the organism of a natural biological human being, many such sensory routes or mappings already exist: for example, photons present in the environment excite photoreceptors in the retina, which produce electrochemical signals that are transmitted to the visual cortex and experienced by the mind as particular sights. In that way, the stimulus of visible light is detected by the sense organ of the eye and experienced through the sensory modality of vision. It is possible for a neuroprosthetic device to participate in such a straightforward mapping that attempts to replicate or complete a mapping found naturally in the human body – such as when a cochlear implant detects sound waves that fall within the normal audible range of roughly 20 to 20,000 Hz and converts that stimulus into a pattern of electrical impulses that are transmitted to the cochlear nerve and the cochlear nucleus in the brainstem and perceived through the modality of hearing.

On the other hand, it is possible for a neuroprosthetic device to participate in a 'non-standard' sensory mapping. As noted earlier, the possibility of such mappings is suggested by the existence of the rare but naturally occurring neurological condition of synesthesia, in which sense data typically experienced through one sensory modality are instead (or also) experienced through a different modality – as is the case for individuals who see a color or taste a flavor upon hearing a particular sound.[75] Discussion of the potential use of neurocybernetic technologies to artificially 'remap' the processes of human sensation dates back at least as far as the 1940s, when Wiener considered the possibilities, for example, of rerouting sense data received by the eyes so that it would be experienced by the mind through the modality of hearing – or rerouting sense data received by the ears so that it would be perceived through the modality of vision.[76] Such neuroprosthetically aided sensory remapping could potentially have therapeutic uses: for example, a

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[75] Such phenomena occur, e.g., in cases of chromesthesia and lexical-gustatory synesthesia. Some research (e.g., into the phenomenon of ideasthesia) suggests that while in some cases of synesthesia it superficially appears as though one kind of sensory experience has directly triggered the other, it may in fact be the mind's internal semantic representation of elements contained in the first sensory experience (and not the sense data itself) which has triggered the second. See Cytowic (1989); *Synaesthesia: Theoretical, artistic and scientific foundations* (2014); and Jürgens & Nikolić, "Ideaesthesia: conceptual processes assign similar colours to similar shapes" (2012).

[76] See Wiener (1961), loc. 2784ff. For more recent discussions, see Lebedev (2014), p. 106, and Warwick (2014).

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neuroprosthetic device that includes a microphone and which stimulates the optic nerve or visual cortex could provide someone who is deaf with visual cues when certain kinds of environmental stimuli (e.g., the sound of a ringing doorbell or approaching siren) are detected. Such non-standard mappings will always be the case with neuroprosthetic devices that detect xenostimuli which the human body's natural biological sensory organs are incapable of detecting, as – by definition – such stimuli have no default modality through which the mind normally experiences them.

Below we consider different ways in which a sensory neuroprosthetic device can tie together sense data with a sense organ and sensory modality to create a unified process of sensing for its human host.

1. Routing Biologically Receivable Sense Data to its Biologically Normal Sensory Modality

A neuroprosthetic device may detect stimuli that are typically detected by a natural biological sense organ and present them to its host's mind using the modality that is naturally associated with that form of sense data. An example would be a robotic prosthetic hand that detects the pressure of external objects against its fingers and conveys that sense data to its host's mind through the modality of touch.[77]

2. Routing Fabricated Sense Data to an Arbitrary Sensory Modality

Instead of detecting stimuli that exist within its host's body or the external environment and conveying them through the electrochemical stimulation of neurons, a neuroprosthetic device might instead transmit electrochemical signals that do not correspond to any physical stimuli existing in the environment and detected by the device. A neuroprosthesis might fabricate such sense data, for example, in order to provide its host with an immersive sensory experience of a virtual world (or 'secondary physical world') that does not objectively exist as such in the primary physical environment.[78]

Such a mapping differs from human beings' natural biological sensory mappings, because the origin of the sense data lies not in some natural physical phenomena that occur independently of a neuroprosthetic device and are then detected by it but in digital constructs or objects that are purposefully fabricated by the device by means of its own internal computational processes and for some particular ends.

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[77] See Hoffmann & Micera (2011), pp. 792-93.

[78] Regarding the distinction between the primary physical world (or 'real world') and secondary physical worlds (or 'virtual worlds'), see the footnote in the earlier section on neuroprostheses that fabricate electrochemical signals within a sensory neural pathway.

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3. Remapping Biologically Receivable Sense Data to a Biologically Atypical but Natural Sensory Modality

Another possibility is for a neuroprosthetic device to detect stimuli that are normally detectable by the human body's natural biological sensory organs but to present them by means of a sensory modality which – while naturally occurring in human beings – is not the modality through which such sense data is normally experienced. Examples might include an artificial eye that can detect the current air temperature and uses augmented reality to display this as a set of numbers in its host's field of vision.[79]

One variation of such a routing is for a neuroprosthesis is to present sense data that relate to the external environment using a sensory modality that is normally a means of experiencing phenomena originating within the host's body. An example would be a neuroprosthesis whose external photoreceptor measures the amount of visible light present in the external environment and – when the level drops below a certain threshold (e.g., after the sun has set) – stimulates the relevant neurons to cause the device's host to experience that change through the modality of interoception as a growing sense of drowsiness. A complementary variation is for a neuroprosthetic device to present sense data relating to its host's internal bodily processes by means of a sensory modality that normally conveys sense data relating to the external environment. An example would be a neuroprosthesis that detects pressure within the body's muscles and joints in order to construct a representation of the body's current posture and displays an image of the body in the host's field of vision by stimulating the optic nerve.[80]

4. Routing Sense Data Using a Non-human Xenosensory Mapping

It is possible for a neuroprosthetic device to incorporate into its sensory mapping some non-natural 'xenosensory' element that is not found in the sensory mappings of natural biological human beings. The use of such technologies provides a human host with superhuman sensory capacities that are

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[79] The hypothesized technologies for sensory substitution discussed by Wiener would constitute such neuroprosthetic devices; see Wiener (1961), loc. 2784ff.

[80] In some ways, such a mapping is functionally comparable to forms of exteroception seen in animals such as the octopus, whose brain does not possess a mechanism for determining the precise current location and shape of each of its tentacles through its sense of proprioception (which would be an intensive and complex information-processing task, given the large number of limbs and infinite degrees of freedom possessed by each of them); instead, the brain gathers such information by visually observing its limbs. See Wells, M.J., *Octopus: Physiology and Behaviour of an Advanced Invertebrate* (1978); Zullo et al., "Nonsomatotopic organization of the higher motor centers in octopus" (2009); Niven "Invertebrate neurobiology: Visual direction of arm movements in an octopus" (2011); and Gutnick et al., "Octopus vulgaris uses visual information to determine the location of its arm" (2011).

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'extrasensory' in the sense of exceeding the natural limits of the human organism (although not in the sense of being paranormal).

a. Mapping sense data from non-human xenostimuli to an arbitrary sensory modality

One type of xenosensory mapping involves a neuroprosthetic device that is capable of detecting 'xenostimuli' (either in the external environment or within the host's body) that are not normally detectable by the human body's sense organs.[81] By definition, the augmented or wholly artificial sense organs used to register such sense data differ from those of natural biological human beings, and the mind does not have a natural default sense modality through which it consciously perceives such data; the designer of the device must decide which sensory modality will be used for that purpose.

b. Mapping arbitrary sense data to a non-human xenesthetic sensory modality

Another type of xenosensory mapping would involve a neuroprosthesis that presents sense data to the mind of its host using a sensory modality that is not normally experienced by a natural biological human being. It is not clear whether such a mapping is possible: the scientific knowledge and technological capacities needed to map xenostimuli to an existing natural sensory modality are relatively straightforward (and, indeed, such neuroprosthetic mappings have already been implemented on an experimental basis[82]); however, it is much more difficult to imagine how one might effect the creation of a new sensory modality within the mind – or the 'unlocking' of a natural biological modality that is typically latent. While practical avenues for the development or exploitation of such experiences of 'xenesthesia' are not immediately obvious, such a possibility should be acknowledged at a conceptual level as a subject meriting further research. Possible directions for research might involve studying atypical but natural phenomena such as synesthesia, hallucinations, or *déjà vu*, to explore whether they might provide a basis for the creation of new sensory modalities.

II. Cognition

A cognitive neuroprosthesis restores, augments, or otherwise participates in processes that are internal to the mind or brain of its host and which do not directly involve sensory organs or motor organs. In comparison to that of

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[81] Examples would include neuroprostheses that provide their host with infrared vision or the ability to hear ultrasonic phenomena. See, e.g., Warwick (2014); Gasson et al. (2012); and Merkel et al. (2007).

[82] For example, Warwick (2014) describes a successful experiment in which a surgically implanted microelectrode array was used to grant its human host 'extrasensory' perception in the form of the ability to detect ultrasonic phenomena.

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sensory and motor neuroprostheses, the development of cognitive neuroprostheses that can affect phenomena such as memory, emotion, and personality is still in its early experimental stages – although rapid advances are being made.[83]

A cognitive neuroprosthesis can be analyzed according to the extent to which it establishes a basic interface with the conscious awareness of its host, its impact on the contents of autonomous cognitive processes, and its impact on the execution of processes that involve conscious decisions by its host. Below we discuss these aspects of cognitive neuroprostheses in more detail.

A. Basic Interface with the Mind

Cognitive neuroprostheses can be classified according to whether a device interfaces with its host's cognitive processes at a conscious or subconscious level. A single device may act on both levels simultaneously.

1. With the Host's Conscious Awareness

It is possible for the action of a cognitive neuroprosthesis to directly inform, affect, be experienced by, or be controlled by its host's conscious awareness. An example would be a mnemoprosthetic device that stores long-term memories as engrams and which allows its host to recall and consciously experience a particular memory through an act of will.[84]

2. Without the Host's Conscious Awareness

Alternatively, a cognitive neuroprosthesis may be integrated with the neural circuitry of its human host in such a way that the host cannot consciously control the device and does not have a direct conscious experience of the device's operation. An example would be a sensor implanted in the brain that wirelessly transmits real-time data regarding the host's neural activity to an external computer, which is able to decode some aspects of what the host is consciously experiencing in that moment (e.g., whether he or she is imagining an oceanfront vista, is attempting to mentally solve a math problem, or is mentally rehearsing the melody of a favorite song), without the host knowing whether or not the device is in operation at any given moment.

Note that in the case of some neuroprosthetic technologies – such as deep brain stimulation (DBS) implants – a host may not possess direct and certain

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[83] For an overview of such technologies, see Soussou & Berger, "Cognitive and Emotional Neuroprostheses" (2008), and Gladden, "Enterprise Architecture for Neurocybernetically Augmented Organizational Systems" (2016).

[84] For discussion of future neuroprosthetic devices that could allow 'playback' of recorded or previously experienced information, see Merkel et al. (2007); Robinett, "The consequences of fully understanding the brain" (2002); and McGee (2008), p. 217.

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knowledge of the fact that that the device has been activated but may be able to infer as much from the conscious experience of the device's impacts, such as certain muscle behaviors or emotional effects.[85]

B. Perception

A neuroprosthetic device may access or affect those cognitive processes that enable or shape an individual's perception and experience of his or her own mind and body and the external environment that he or she inhabits. Such a device might relate to its host's mental percepts, degree of consciousness and self-awareness, periodic transition into and out of sleep and other states of unconsciousness, experience of emotions, and autonomous processes that induce experiences such as that of surprise.

1. Percepts

A percept is not sense data as received by the brain but as experienced and interpreted by the mind. Two people viewing the same inkblot or optical illusion may receive identical visual sense data from their eyes but perceive the data to present very different objects. Similarly, two people who listen to identical recordings of a work of classical music may experience the same auditory sense data in very different ways, if one person has a rich knowledge of music theory and the work's history and the other person does not. A percept frequently constitutes an integrated mental experience that combines several different types of sense data and cognitive processes; for example, the experience of conversing with another human being and one's interpretation of that experience may draw on auditory sense data (e.g., the sound of identifiable words being spoken as well as paralinguistic features such as tone of voice), visual sense data (e.g., the sight of the other person's gestures and facial expressions), emotion (e.g., one's attitude of fondness or dislike for the person who is speaking), and long-term memory (e.g., one's recollection of the meaning of the words being heard and the historical context and significance of the information being conveyed by one's conversation partner).[86]

A neuroprosthetic device that can affect the brain at the level of percepts – for example, causing its host to interpret an optical illusion in one way rather than another – would participate in the final stages of perception rather

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[85] For a discussion of the effects of DBS, see Kraemer, "Me, Myself and My Brain Implant: Deep Brain Stimulation Raises Questions of Personal Authenticity and Alienation" (2011), and Van den Berg, "Pieces of Me: On Identity and Information and Communications Technology Implants" (2012).

[86] For an overview of human perception, see Goldstein (2014); Rookes & Willson, *Perception: Theory, Development and Organisation* (2000); and *The Oxford Handbook of Philosophy of Perception*, edited by Matthen (2015).

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than the early stages of receiving raw sense data, and it may thus be understood primarily as a cognitive rather than sensory neuroprosthesis.[87]

2. Consciousness and Self-awareness

A neuroprosthesis may directly affect its host's experience of consciousness, sapience, and self-awareness. For example, it is conceivable that a neuroprosthetic device could impair or even destroy its host's ability to experience conscious self-awareness – such as by temporarily suppressing the activity of or destroying particular regions of the cerebral cortex or the brainstem's reticular activating system (RAS) to induce a coma-like state.[88] It can be speculated that a sufficiently sophisticated (and highly futuristic) neuroprosthetic system possessing adequate sensory, cognitive, and motor interfaces with its host might even suppress its host's conscious awareness without this being immediately obvious to outside observers, if the neuroprosthesis were able to cause its host's body to produce appropriate motor actions (such as speech or gestures) in response to sensory stimuli from the external environment.

3. Sleep

A neuroprosthesis may affect its host's processes of sleep – either by creating a sense of drowsiness and desire for sleep, directly inducing a state of unconsciousness (as is done by a general anesthetic), or artificially reducing an existing state of drowsiness and keeping an individual awake (as is done by some stimulants).[89] Efforts to develop neurotechnologies that can extend an individual's period of wakefulness are being undertaken by military research agencies; such technologies could be employed, for example, to allow soldiers to operate for extended periods of time without sleep when in hostile territory.[90]

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[87] Many kinds of neuroprosthetic devices relating to sensory perception already exist; see Lebedev (2014); Merkel et al. (2007); and Gladden, "Enterprise Architecture for Neurocybernetically Augmented Organizational Systems" (2016).

[88] Regarding the nature of comas in human beings, see *Coma Science: Clinical and Ethical Implications*, edited by Laureys et al. (2009), and *Comas and Disorders of Consciousness*, edited by Schnakers & Laureys (2012). Techniques such as transcranial magnetic stimulation have been used by researchers to temporarily take particular regions of the brain 'offline,' making it possible to study how the brain's performance of certain tasks is impacted by the impairment or disabling of those regions; see Ariely and Berns, "Neuromarketing: The Hope and Hype of Neuroimaging in Business" (2010).

[89] For the possibility of neuroprosthetic devices relating to sleep, see Claussen & Hofmann (2012) and Kourany (2013), pp. 992-93.

[90] Regarding efforts by the DARPA military research agency and other researchers to develop neurotechnologies for increasing soldiers' alertness and reducing their need for sleep, see, e.g., Falconer, "Defense Research Agency Seeks to Create Supersoldiers" (2003); Moreno, "DARPA On

4. Emotion

A neuroprosthesis may alter its host's immediate emotional state or influence the host's long-term patterns of emotional behavior.[91] Such a device could be used to treat emotional disorders or to optimize emotional behaviors for individuals (such as actors, politicians, teachers, counselors, police officers, or spies) whose work requires them to engage in highly effective social interactions.

5. Autonomous Mental Reactions

A neuroprosthesis may participate in cognitive processes that are autonomous, insofar as they are involuntary and take place beyond the conscious control of the mind of the device's host. Such processes might include the generation of feelings of surprise or dread in response to particular stimuli or a spontaneous irrational presumption or drawing of conclusions that results from a naturally occurring human cognitive bias.[92] Such autonomous cognitive processes are distinct, for example, from those processes of the autonomic nervous system (ANS) whose actions are often regulated by the brainstem and result in motor activity rather than internal cognitive effects as well as from those flexor withdrawal reflexes regulated by neurons in the spinal cord.[93]

C. Creativity

A neuroprosthetic device may access or affect cognitive processes that manifest mental creativity, including those relating to ideation and imagination and those that generate dreams while a device's host is asleep.

Your Mind" (2004); Clancy, "At Military's Behest, Darpa Uses Neuroscience to Harness Brain Power" (2006); and Wolf-Meyer, "Fantasies of extremes: Sports, war and the science of sleep" (2009).

[91] For the possibility of developing emotional neuroprosthetics, see Soussou & Berger (2008); Hatfield et al., "Brain Processes and Neurofeedback for Performance Enhancement of Precision Motor Behavior" (2009); Kraemer (2011); and McGee (2008), p. 217.

[92] For an overview of human cognitive biases – especially with regard to their impact in organizational settings – see Kinicki & Williams, *Management: A Practical Introduction* (2010), pp. 217-19. Note that if a neuroprosthetic device is involved in regulating biological processes such as breathing, digestion, or circulation, it may be more likely to be a motor neuroprosthesis rather than a cognitive neuroprosthesis. The device's classification depends on the nature of the output or impact produced by the device and the system upon which it acts.

[93] Regarding such phenomena, see *Primer on the Autonomic Nervous System*, edited by Robertson et al. (2012), and Muscolino, *Kinesiology: The Skeletal System and Muscle Function* (2017), pp. 609-38.

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1. Ideation and Imagination

A neuroprosthetic device may participate in the process of imagination and the mind's generation of new ideas. Some aspects of that process lie beyond an individual's conscious control, while other aspects can be consciously steered or nurtured in an effort to generate certain kinds of new ideas. Anecdotal accounts of increased creativity have been reported, for example, among patients who have received treatment for medical conditions with DBS devices.[94]

2. Dreaming

A neuroprosthetic device could potentially affect the dreams of its user – for example, by suppressing the individual's ability to dream, intensifying the experience of dreams (e.g., by facilitating lucid dreaming in which an individual is consciously aware of being in a dream state), or modifying or controlling the contents of dreams. A sufficiently sophisticated neuroprosthesis may also allow at least some features of the contents of a sleeping individual's dreams to be detected and interpreted by external systems.[95]

D. Memory and Identity

A neuroprosthetic device may access or affect those cognitive processes by which its host encodes, stores, and retrieves memories and creates a consistent identity that persists over time. Such processes include those relating to sensory, short-term, and long-term memory; personality; habit; and belief.

1. Memory

A neuroprosthetic device may access, modify, control, or otherwise relate to its host's processes of encoding, storing, and retrieving memories. Such 'mnemoprostheses' may involve one or more type of memory.

a. Sensory memory (SM)

A neuroprosthetic device may affect or access the contents of iconic memory, echoic memory, haptic memory, and other forms of sensory memory that the human brain employs to briefly (e.g., for a few hundred milliseconds) store incoming sense data before it is processed by short-term and working memory.[96]

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[94] See Cosgrove, "Session 6: Neuroscience, brain, and behavior V: Deep brain stimulation" (2004); Gasson (2012); and Gladden, "Neural Implants as Gateways" (2016).

[95] For an overview of the neuroscience of dreaming, see Kalat, *Biological Psychology* (2007), pp. 286-91, and "Section X: Dreaming" in *The Neuroscience of Sleep*, edited by Stickgold & Walker (2009).

[96] For an overview of the biological basis of sensory memory, see Chapter 4, "Sensory and Short-Term Memory," in Radvansky, *Human Memory* (2016).

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b. Short-term memory (STM)

A neuroprosthesis may affect or access the contents of its host's short-term memory, which is capable of storing a small number of items (e.g., a handful of numerical digits) in memory for a matter of a few seconds. A device's ability to enhance short-term memory could compensate for short-term memory problems resulting from neurodegeneration caused by aging, injury, or illness.[97]

c. Long-term memory (LTM)

The notion of developing neuroprosthetic devices that can access and manipulate the contents of a host's long-term memory is one whose theoretical possibility and practical feasibility are much contested. Recent achievements in artificially modifying the memories of mice[98] suggest that a limited ability to alter some of a human subject's memories in a fairly non-targeted way may someday be possible. However, if certain hypotheses regarding the holographic nature of long-term memory storage in the brain[99] were to be demonstrated to be correct, it might be difficult or impossible to access or manipulate particular complex long-term memories without decoding or disrupting the complete contents of an individual's long-term memory; it may also be impossible to edit the information stored in the brain's long-term memory structures and processes through the relatively gross electrical stimulation of neurons that is employed by technologies such as those for DBS or to access and fully decode such information using conventional monitoring and imaging technologies such as EEG, MRI, CT, and PET, each of which possesses limitations that make it inadequate for such purposes.[100]

Regardless of whether the targeted creation, editing, or deletion of long-term memories through the use of neuroprosthetic devices might someday prove feasible, mnemoprostheses might be able to affect the structures and processes of long term-memories in a more generalized way – for example,

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[97] See Chapter 4, "Sensory and Short-Term Memory," in Radvansky (2016).

[98] See Han et al., "Selective Erasure of a Fear Memory" (2009), and Ramirez et al., "Creating a False Memory in the Hippocampus" (2013).

[99] Such models have been described, e.g., in Longuet-Higgins, "Holographic Model of Temporal Recall" (1968); Westlake, "The possibilities of neural holographic processes within the brain" (1970); and Pribram, "Prolegomenon for a Holonomic Brain Theory" (1990). An overview of conventional contemporary models of long-term memory is found in Rutherford et al., "Long-Term Memory: Encoding to Retrieval" (2012).

[100] Regarding various approaches to the neuroimaging of memory mechanisms, see, e.g., *Neuroimaging and Memory*, edited by Foster (1999); Greve & Henson, "What We Have Learned about Memory from Neuroimaging" (2015); Rugg et al., "Encoding and Retrieval in Episodic Memory: Insights from fMRI" (2015); and Peigneux, "Neuroimaging Studies of Sleep and Memory in Humans" (2015).

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by providing increased storage capacity, encoding and retention of memories in a manner that is less compressed and does not degrade over time, or enhanced recall speed and ability.[101]

2. Personality

A neuroprosthesis may alter its host's long-term formation and storage and short-term manifestation of distinct personality traits.[102]

3. Habit

A neuroprosthetic device may participate in the processes by which the mind of its host forms, stores, and is influenced by subconscious habits or preferences of which the mind may or may not be consciously aware.

4. Belief

In many cases, beliefs are tied to specific long-term memories: for example, an individual may believe that he or she is an attorney because he or she possesses a distinct memory of passing the bar exam and working in a law firm as an attorney for the past several years. In other cases, belief may also involve the contents of sensory memory, short-term memory, and working memory: for example, a person may believe that a bluebird is sitting outside his or her windowsill because he or she is experiencing certain visual sense data that correspond to his or her recollection of the appearance of a bluebird. (Implicit in such a belief is the host's additional supposition that he or she is not hallucinating and is not being supplied fabricated sense data by an artificial eye that has been hacked by some adversary.)

In other cases, beliefs may not be tied directly to specific memories (and may even be contradicted by such memories); such beliefs might include an individual's conviction that he or she is a talented singer, the belief in a particular theological or philosophical doctrine whose truth has not been directly demonstrated through a sensory experience, an intuitive feeling that someone is glancing over one's shoulder, or the belief that the mission of

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[101] A device might potentially allow enhanced storage in a manner that is longer-lasting and more accurate than documented cases of eidetic memory and less constrained in subject matter than hyperthymesia (or 'superior autobiographical memory') – perhaps resembling the phenomenon of 'photographic memory' whose existence in natural biological human beings has yet to be demonstrated. Regarding hyperthymesia, see Taylor, "Hyperthymesia" (2013); regarding cases of supposed eidetic memory, see Moxon, *Memory* (2000), p. 15, and Schwartz, *Memory: Foundations and Applications* (2014), p. 172.

The neuroprosthetic hippocampal bridge described in Soussou & Berger (2008) that is designed to span a damaged area of the hippocampus and restore normal memory functionality represents an example of a mnemoprosthetic device that supports memory processes generically without directly altering the contents of specific long-term memories.

[102] For the possibility of developing personality-related neuroprosthetics, see Soussou & Berger (2008).

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one's employer is just. It may be possible for a neuroprosthesis to directly affect such immediate or long-term beliefs in a way that is distinct from the typical manipulation of memories or sense data.

E. Reasoning and Decision-making

A neuroprosthetic device may access, modify, control, or otherwise relate to those executive functions by which the mind of its host reasons, makes decisions, and embarks on a course of action. Such processes include those relating to working memory, attention control, volition, metavolition and conscience, and a host's internal monologue.

1. Working Memory (WM)

While short-term memory stores a small number of items that are the subject of one's mental focus, working memory is the executive function that allows those items to be manipulated by one's mind. From a cybernetic perspective, working memory is thus better understood as a part of the mind's reasoning and decision-making apparatus than as a conventional form of memory through which information is encoded, stored, and retrieved.[103]

While the existence and importance of working memory is generally accepted, different scientific theories attribute somewhat different roles and limits to working memory and describe its relationship to short-term and long-term memory in various ways. A neuroprosthetic device that affects processes of working memory would impact its host's most fundamental ability to think and interact with the external environment.

2. Attention Control

A neuroprosthetic device may participate in its host's experience of attentiveness and ability to focus attention on one sensation or cognitive phenomenon rather than another at a particular instant in time.[104] Such a device may affect the phenomenon of 'metacognition' by which the mind recognizes and corrects its periodically wandering and wayward attention.

3. Volition

In the philosophical sense employed here, a particular 'volition' combines a desire and a belief.[105] For example, an individual may wish to reach down to

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[103] For different perspectives on working memory and reasoning processes, see, e.g., Kyllonen & Christal, "Reasoning ability is (little more than) working-memory capacity?!" (1990); Baddeley (2000); Baddeley, "Working memory: theories, models, and controversies" (2012); and Ma et al., "Changing concepts of working memory" (2014).

[104] For an overview of processes of attention control, see Mangun, *The Neuroscience of Attention: Attentional Control and Selection* (2012).

[105] For a discussion of the nature of volition (and its relationship to conscience and moral responsibility), see Calverley, "Imagining a non-biological machine as a legal person" (2008).

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grasp a drinking glass and raise it to his or her lips and believe that this can be accomplished by willing the muscles in his or her arm to contract in a particular sequence. A neuroprosthetic device may participate in its host's processes of forming and storing volitions as well as acting on those volitions whose effects are internal to the mind and do not entail the execution of motor activity.

4. Metavolition and Conscience

A neuroprosthetic device may participate in its host's process of forming volitions *about* the kinds of volitions that he or she wishes to possess. This phenomenon of 'metavolition' often manifests itself as a desire to change one's personal habits or preferences and is closely tied to the notion of conscience.[106] Insofar as a neuroprosthesis affects an individual's ability to form desires and beliefs, it will affect the nature of his or her metavolitions – and may either strengthen or weaken the individual's ability to form and follow the guidance of his or her own conscience.

5. Internal Monologue

A neuroprosthetic device may participate in or affect its host's processes of carrying out an 'internal monologue,' which is used both for conceptualizing and formulating speech that is to be verbally articulated for sharing with others, for giving verbal internal form to one's imaginings, and for reasoning internally about some question or problem and attempting to arrive at a conclusion.[107]

6. Savant Skills

A small percentage of natural biological human beings possess savant skills that allow them to instantaneously perform extraordinary mental feats of calculation, memory, or creativity that are not possible for typical human beings. Such skills are discussed here as a form of reasoning, insofar as the most common savant skills are those involving the ability to calculate the day of the week of calendar dates in the distant past or to solve other mathematical problems; however, other savant skills (such as the ability to recall and perform a just-heard musical work note for note) are closely related to perception and memory.[108]

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[106] Regarding metavolition and conscience, see Negoescu, "Conscience and Consciousness in Biomedical Engineering Science and Practice" (2009), and Gladden, *Sapient Circuits and Digitalized Flesh* (2016), p. 120.

[107] For an overview of such cognitive processes, see "The Internal Monologue" in Butler, *Rethinking Introspection* (2013).

[108] The nature of savant skills is discussed in Treffert, "The savant syndrome: an extraordinary condition. A synopsis: past, present, future" (2009), and Rodriguez, *Autism Spectrum Disorders*

Such savant skills naturally occur primarily in individuals suffering from autism or another medical condition (such as illness or injury) affecting the left temporal lobe. The neurological phenomena that grant individuals savant skills appear to do so by providing the human mind with conscious access to and the ability to control cognitive processes at a profound level of detail that is normally hidden from us.[109] Savants' ability to directly access the 'inner workings' of perception and memory might be understood as roughly analogous to the ability to directly manipulate the operations of a desktop computer through the use of low-level binary machine code: most computer programmers lack such a skill and must instead use a higher-level programming language (or at least, assembly language) in which the ultimate details of processor instructions are hidden from the programmer's view. While writing programs directly in machine code offers some advantages (such as the ability to maximally optimize some performance characteristics), the fact of being forced to operate at the finest level of detail and unable to create complex persistent objects or to more holistically manipulate abstract information structures severely limits the feasibility of such an approach.[110]

Individuals undergoing damage to the left temporal lobe as adults can experience acquired savant syndrome, in which they suddenly acquire such savant skills,[111] and recent research suggests that it is possible to temporarily grant savant skills to individuals by temporarily disrupting the functioning of the left anterior temporal lobe through the use of neurotechnologies such as transcranial magnetic stimulation.[112] An implantable neuroprosthetic device that is capable of briefly disrupting the behavior of the left temporal lobe in such a way might be able to temporarily provide its host with savant skills when desired, while at other times avoiding the deficits in shared attention, social cognition, and empathy that often accompany damage to the left temporal lobe.

III. Motion

Some neuroprostheses execute or participate in behaviors designed to produce a physical action or effect within the world outside of their host's

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(2011), pp. 36-39.

[109] See Snyder, Allan, "Explaining and inducing savant skills: privileged access to lower level, less-processed information" (2009).

[110] See Dandamudi, *Introduction to assembly language programming: from 8086 to Pentium processors* (1998); Dumas (2006); and Streib, *Guide to Assembly Language: A Concise Introduction* (2011).

[111] Regarding acquired savant syndrome, see Treffert, "Accidental Genius" (2014).

[112] See Snyder et al., "Savant-like skills exposed in normal people by suppressing the left fronto-temporal lobe" (2003), and Snyder (2009).

brain: either in some other part of the host's body or in the external environment. **Motor neuroprostheses** are those neuroprosthetic devices whose primary purpose is to fill such a role; they currently include systems such as robotic prosthetic limbs and wheelchairs whose movements can be controlled by their user's thoughts by means of a neuroprosthetic interface.[113]

Many motor neuroprostheses function by detecting a host's thoughts or volitions (such as the desire to reach out with his or her arm and grasp for an object) and translating them into electrical or electrochemical signals that induce a corresponding action in some biological motor organ (such as a muscle or gland) or in an artificial effector (such as an electric motor, electroactive polymer, piezoelectric bimorph, audio speaker, or display screen). Other motor neuroprostheses – such as those designed to treat sleep apnea or epileptic seizures[114] – themselves autonomously determine when to execute a physical act and what sort of act to execute. In such cases it is the neuroprosthesis and not its host's brain that serves as the direct initiator of motor action.

Below we consider in more detail these different ways in which a neuroprosthesis can participate in its host's processes of motor action.

A. Detection of Action Potentials or Other Motor Instructions within a Motor Neural Pathway

Many motor neuroprostheses include electrodes or other sensors that allow them to detect motor instructions that have arisen within a motor neural pathway of their host's natural biological organism. Such devices may, for example, detect motor instructions as they are being generated within the brain's motor cortex, as they are being carried toward a motor organ by the upper and lower motor neurons of the corticospinal tract, or at the neuromuscular junction synapse where the signals are transmitted electrochemically from a motor neuron to a muscle.

The detection of motor instructions may be accomplished with varying degrees of speed and accuracy using technologies such as EMG, EEG, MEG, fMRI, and PET.[115] The use of targeted muscle reinnervation (TMR) surgery

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[113] Such motor neuroprostheses are discussed in Edlinger et al., "Brain Computer Interface" (2011); Lebedev (2014); Merkel et al. (2007); and Widge et al., "Direct Neural Control of Anatomically Correct Robotic Hands" (2010).

[114] For existing or anticipated neuroprostheses of this sort, see Taylor, "Functional Electrical Stimulation and Rehabilitation Applications of BCIs" (2008), and Van Drongelen et al., "Seizure Prediction in Epilepsy" (2005).

[115] Regarding various technologies that can be used for this purpose, see Patil & Turner, "The Development of Brain-Machine Interface Neuroprosthetic Devices" (2008); Principe & McFarland, "BMI/BCI Modeling and Signal Processing" (2008); Ayaz et al., "Assessment of Cognitive

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allows a motor nerve that had previously controlled a limb or organ that is now missing to be rerouted so that it innervates a remaining muscle in a different part of the body, thereby allowing motor instructions sent by the brain to the missing component to be detected as contractions in the muscle to which the nerve has been rerouted.[116]

B. Fabrication of Cellular Action Potentials within a Motor Neural Pathway

While some motor neuroprostheses detect motor instructions that have been generated by the brain of their human host and transmit those instructions to a biological motor organ or artificial effector, other motor neuroprostheses autonomously fabricate motor instructions – perhaps because the brain of their host is unable to do so (e.g., as a result of injury or illness) or because the neuroprosthesis can do so more effectively (e.g., when creating motor instructions for some non-human motor organ that the human brain is not well-suited to control). For example, while some invasive neuroprostheses (e.g., DBS devices) treat Parkinson’s disease and essential tremor by stimulating regions of the brain, other less invasive motor neuroprostheses treat the same condition by gyroscopically detecting the occurrence of a tremor and then electrically stimulating muscles to stabilize a limb through muscle co-contraction.[117] In the latter case, a device’s actions are not determined by instructions consciously or unconsciously generated by its host’s brain but by instructions generated by the device’s autonomous internal computer.

C. Storage of Instructions for (Repeated) Motor Execution

A motor neuroprosthesis may store motor instructions within itself temporarily or permanently; the instructions stored may correspond either to naturally generated instructions produced in the host’s brain or spinal cord or to fabricated instructions that were procedurally generated by the device itself. Such storage can employ different memory types and information formats.

Neural Correlates for a Functional Near Infrared-Based Brain Computer Interface System” (2009); Miller & Ojemann, “A Simple, Spectral-Change Based, Electrocorticographic Brain–Computer Interface” (2009); and Lebedev (2014).

[116] See *Targeted Muscle Reinnervation: A Neural Interface for Artificial Limbs*, edited by Kuiken et al. (2014).

[117] See Gallego et al., “A neuroprosthesis for tremor management through the control of muscle co-contraction” (2013).

1. Memory Type

a. Volatile memory

A motor neuroprosthesis such as a robotic prosthetic arm will typically need to store newly detected motor instructions within itself (or within its external controller, if the device's data processing is performed by an external computer) at least briefly in order to process the data and compute the pattern of motor actions that will be initiated in order to carry out the instructions. Such data may be stored using random-access memory (such as a DRAM or SRAM chip) that requires a continuous electrical power supply in order to preserve the data. A loss of power to the device would result in loss of the data.[118] In principle, RAM can be used by a neuroprosthesis to store motor instructions for an indefinite period of time, as long as the device does not power down.

b. Non-volatile memory

A motor neuroprosthesis may also store motor instructions using non-volatile systems that allow the data to be preserved even after the device is powered down. There is generally less need for a motor neuroprosthesis to possess such functionality than there is for a sensory neuroprosthesis to be able to store a permanent non-volatile record of incoming sense data: while ordinary persons might periodically find it useful to replay the audio recording of a conversation in one's mind hours after the conversation first took place or to relive the visual experience of an important event, motor actions are often performed in response to some immediate environmental stimulus – in order to manipulate the external environment as it exists at a particular moment in time.

NEUROPROSTHETICALLY AIDED EXECUTION AND REPETITION OF PHYSICAL ACTIONS

The ability to 'record' a wave of one's arm or the creation of a facial expression and then to repeat that exact movement at a later moment may thus, for most people, have limited utility. However, for some types of individuals, such capacities might prove highly useful: for example, a professional pianist might record the muscle movements that were executed during the flawless performance of a work, so that the performance might be repeated in the future. Similarly, a professional athlete might record the motor instructions involved with the perfect execution of a kick or throw, so that the action might be executed again with perfect consistency whenever needed in the future. A soldier or aircraft pilot might possess a motor neuroprosthesis that has been programmed with a full suite of recorded movements that can be executed flawlessly by the device even under the most difficult circumstances – for example, allowing the individual to call for help, activate an emergency medical

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[118] Regarding different memory mechanisms for computerized devices, see Dumas (2006).

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device, or even engage in hand-to-hand combat, fire a weapon, or land a plane when he or she is in shock or unconscious as a result of injuries sustained.

However, the importance of real-time feedback to the successful execution of motor movements must not be overlooked. While it might be possible for a sensory neuroprosthesis to store received sense data in a lossless digital form that does not degrade over time and is experienced in an identical fashion every time it is replayed, the recreation of neuroprosthetically stored motor instructions by a natural biological muscle or organ is subject to greater variation. Even an identical set of motor instructions will be executed by biological components in a slightly different fashion every time it is reenacted: the performance of 'the same' physical gesture may vary from one instance to the next, depending on factors such as a muscle's degree of fatigue, the weight and construction of the clothing being worn by a device's host at the moment, or the current orientation of the host's body (and corresponding direction of gravitational forces). It would be possible to achieve much greater precision and invariability when a stored set of motor instructions is repeatedly executed by an artificial limb or organ utilizing electromechanical components.

2. Information Format

a. Digital data files

A neuroprosthesis may store motor instructions in the form of binary digital files that can be readily exchanged with desktop computers or other external conventional computing systems. Data may be stored in a raw format that preserves all available information (e.g., the activity detected in the motor cortex at a particular moment) but requires large file sizes or in a processed and compressed format that preserves only selected information (e.g., the sequence of stimuli to be transmitted to a lower motor neuron) with correspondingly smaller file sizes.

b. Neural network activation patterns

A neuroprosthesis may store motor instructions within the components and processes of a physical artificial neural network that mimics the functioning of the brain's biological neural network and which may directly interface with, complement, or partially replace neurons and neural structures within its host's brain.[119] As noted earlier in the discussion of the storage of sense data by sensory neuroprostheses, a neural network of this sort stores information within its topology and activation patterns in a manner that external computing systems may be unable to detect and decode and that may be interpretable only by the neural network in which it is stored – potentially

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[119] The use of memristors is one approach to developing such a neural network. See e.g., Snider (2008); Versace & Chandler (2010); *Advances in Neuromorphic Memristor Science and Applications* (2012); and Lohn et al. (2014).

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implementing a form of information-theoretic security that surpasses the security of common encryption methods. Such a system would resemble those mechanisms of procedural memory (or the somewhat misleadingly named 'muscle memory') by which the brain learns to perform complex actions such as playing a musical instrument, manipulating a video game controller, or typing letters on a keyboard without conscious attention.[120]

D. Transmission of Cellular Action Potentials within a Motor Neural Pathway

A neuroprosthesis can serve as a 'bridge' that receives motor instructions in the form of electrochemical signals that were generated by the brain or spinal cord of its human host and retransmits them along their path to a motor organ such as a muscle or gland. For example, an upper motor neuron lesion can disrupt the transmission of motor instructions through the nerve, resulting in muscle weakness and a loss of motor control in the corresponding muscles in a limb (i.e., upper motor neuron syndrome);[121] in such a case, a neuroprosthetic device might detect electrochemical signals produced by the motor cortex that correspond to motor instructions and then bypass the damaged upper motor neuron, retransmitting the instructions directly to the lower motor neuron that innervates the relevant muscle in the limb.[122] Even in healthy individuals that do not require these types of devices in order to enjoy typical motor functionality, such neuroprosthetic bridges could potentially prove useful for purposes of human enhancement, allowing motor instructions to travel from the brain or spinal cord to the relevant muscle or organ faster than is possible with natural biological mechanisms of neurotransmission (e.g., through the use of a wireless or hardwired electronic signal transmission) – thereby increasing the speed of an individual's reflexes and voluntary actions.

E. Effectuation of Physical Action

Motor neuroprostheses are generally designed to effect some physical action in the world – either within the body of their host or in the external environment. Within a natural biological human organism, the effectuation of

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[120] Such phenomena are discussed in, e.g., Ericsson & Charness, "Expert performance: Its structure and acquisition" (1994), and Chafe & O'Modhrain, "Musical muscle memory and the haptic display of performance nuance" (1996).

[121] See *Upper Motor Neurone Syndrome and Spasticity: Clinical Management and Neurophysiology*, edited by Barnes & Johnson (2008).

[122] For a discussion of current efforts to develop neuroprostheses of this sort, see, e.g., Sakas et al., "An introduction to operative neuromodulation and functional neuroprosthetics, the new frontiers of clinical neuroscience and biotechnology" (2007), and Logan, "Rehabilitation techniques to maximize spasticity management" (2011).

motor action typically takes one of two forms: the stimulation of muscles causing their contraction or the stimulation of glands causing them to secrete a hormone or other substances.[123] When motor neuroprostheses are employed, the range of available physical actions becomes much wider; for example, a device might be designed to produce specialized patterns of visible light, sound waves, radio signals, heat, electric current, or other effects.

Below we discuss in more detail ways in which a motor neuroprosthesis might produce some action in the world, either through the stimulation of the natural biological components of a host's body or the control of artificial effectors.

1. Stimulation of Natural Biological Effectors

A motor neuroprosthesis may produce two main types of physical effects in the natural biological components of its host's body: the contraction or relaxation of muscles (through the excitation of muscle fibers or inhibition of motor neurons) or the regulation of glands' secretion of hormones and other substances.

a. Contraction and relaxation of muscles

A motor neuroprosthetic device may control the physical activity of natural biological muscle tissue by exciting muscle fibers (which results in muscle contraction) or inhibiting the motor neurons innervating muscle fibers (which results in muscle relaxation).

i. Voluntary functions

The somatic nervous system regulates the voluntary movement of skeletal muscles, allowing the purposeful movement of body parts such as limbs, the neck, eyes, and the mouth and tongue. The motor instructions governing such actions may be generated within the brain or (in the case of some reflex actions) the spinal cord.[124]

ii. Autonomic functions

The sympathetic and parasympathetic branches of the autonomic nervous system (ANS) regulate physical actions involving muscles such as an increase or decrease in heart rate, dilation and constriction of pupils, dilation or constriction of bronchi in the lungs, coughing, sneezing, swallowing, vomiting, an increase or decrease in muscular activity of the digestive organs, relaxation or constriction of the urinary bladder, and the muscular aspects of sexual function.[125]

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[123] See Rosenbaum, *Human Motor Control* (2010), and "The Endocrine System" in Starr & McMillan, *Human Biology* (2016).

[124] For an overview of such structures and mechanisms, see Rosenbaum (2010).

[125] See *Primer on the Autonomic Nervous System* (2012) and Starr & McMillan (2016).

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b. Regulation of gland cells' production and release of chemicals

Within a natural biological human organism, many endocrine and exocrine glands are not directly regulated by signals received from neurons; their production and secretion of hormones and other substances is instead regulated by other phenomena, such as the presence or lack of particular chemical substances in the bloodstream. However, the functioning of other glands is indeed regulated by electrochemical signals from neurons that innervate a gland; for example, the adrenal gland's behavior is regulated by stimuli from preganglionic neurons of the sympathetic nervous system. In such ways, the autonomic nervous system at least partially controls the production and secretion of substances such as epinephrine (or adrenaline), saliva, and gastric acid.[126]

A motor neuroprosthesis might be able, for example, to artificially stimulate the release of epinephrine in order to treat urgent medical conditions such as anaphylaxis, cardiac arrest, and asthma attacks; dilate the airway in order to prepare the body for a period of intense physical activity; induce fear and a fear response; or enhance the consolidation of the long-term memory of a significant event.[127]

2. Control of Artificial Effectors

A motor neuroprosthesis may produce various types of physical effects through its control and utilization of artificial effectors; the effects generated by such effectors may mimic those typically produced by the natural biological components of a human body, or they may display characteristics that are impossible for a body's natural biological effectors. Below we discuss a range of physical products or phenomena that may be generated by a neuroprosthetic device through the use of artificial effectors.

a. Electromagnetic emissions

A neuroprosthetic device may generate various types of electromagnetic phenomena.

I. PHOTONS

A neuroprosthesis may emit photons which – depending on their frequency – may take forms such as those of X-rays, ultraviolet radiation, visible

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[126] See Sherwood, *Fundamentals of Human Physiology* (2012), pp. 70-105, 494-543, and Starr & McMillan (2016), pp. 197-266, 287-306.

[127] The wide-ranging effects of epinephrine are discussed in *Epinephrine in the Central Nervous System*, edited by Stolk et al. (1988), and Goodman, *Basic Medical Endocrinology* (2009). Regarding the impact of epinephrine in memory consolidation, see, e.g., McGaugh & Roozendaal, "Role of adrenal stress hormones in forming lasting memories in the brain" (2002), and Cahill & Alkire, "Epinephrine enhancement of human memory consolidation: interaction with arousal at encoding" (2003).

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light, infrared radiation, microwaves, or radio waves. Such capacities might be demonstrated, for example, by an implantable Wi-Fi radio transmitter, laser, or percutaneous LED display screen.

II. Electric current or charge

A neuroprosthetic device may generate an electrical current or charge. When done in a targeted fashion, this might allow a neuroprosthesis to transmit data through, for example, Ethernet or USB cables or proprietary channels to control peripherals such as an exoskeleton, vehicle, weapons system, 3D printer, medical device, or other equipment.

III. Magnetic fields

A neuroprosthetic device may generate magnetic fields either for a particular functional purpose or as an unintentional side-effect of its internal electrical activity. A magnetic field might, for example, be purposefully generated by a subcutaneous component of a neuroprosthetic device in order to hold external components in place.[128]

b. Mechanical effectors

Some effectors are utilized primarily for the purpose of generating a particular type of motion or mechanical effect within the body of a device's human host or within the external environment.

I. Sound waves

A neuroprosthesis might incorporate components such as a conventional audio loudspeaker, earphones, piezoelectric buzzer, or electrolarynx[129] that allow it to directly generate sound waves. Such technologies might allow a device's host to produce audible speech or to produce sounds that are not audible to the natural biological human ear but which might be detected by hosts of appropriate neuroprosthetic auditory implants or which might be used for other signaling or data-transmission purposes.[130]

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[128] A common technique for holding the external portion of a neuroprosthetic device in place over the correct portion of its host's body is to insert one magnet in that external component and another magnet in the implantable portion of the device that may be percutaneous or hidden beneath the surface of its host's skin. The use of such mechanisms to secure, e.g., the external portion of middle ear implantable hearing devices (MEIHDs), cochlear implants, and auditory brainstem implants is discussed in Dormer, "Implantable electronic otologic devices for hearing rehabilitation" (2003).

[129] For an overview of such technologies, see Liu & Ng, "Electrolarynx in voice rehabilitation" (2007).

[130] Note that such technologies that directly produce sound waves are distinct from technologies that utilize, e.g., the microwave auditory effect; in the latter case, a device's immediate physical effect is the production of microwaves, not sound waves. See, e.g., Lin, "Hearing microwaves: The microwave auditory phenomenon" (2001).

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ii. Particle kinetic energy

A neuroprosthesis may transfer energy to the body of its human host or to the external environment in the form of heat. A neuroprosthetic device’s heating component might be used, for example, to regulate the body temperature of its host or (if attached to an external robotic arm) as a part of a welder or firelighting instrument.[131]

iii. Motion of an actuator

A neuroprosthetic device might incorporate or control the action of actuators that move in order to alter the position of some portion of its host’s body or of some object in the external environment. Such actuators may include electric motors, hydraulic actuators, pneumatic actuators, electroactive polymers (or ‘synthetic muscles’), or piezoelectric bimorphs. They may also incorporate servomechanisms that utilize feedback for automated error-correction.[132]

Such actuators may constitute key components of neuroprosthetic artificial limbs, artificial hearts, and other neuroprostheses involved with gestures or locomotion.

c. Chemical production and release

A neuroprosthetic device may produce or store chemicals which it releases either into a specific targeted substrate or into the environment more broadly under certain conditions.

i. Release of airborne chemicals into atmosphere

A neuroprosthesis might release into the atmosphere external to its host’s body substances such as perfumes, pheromones, inhalational anesthetics, or chemicals that generate a smoke screen; it might release into its host’s lungs gases such as oxygen that can affect the host’s physical performance.

ii. Release of chemicals into a liquid mixture

A neuroprosthesis may alternatively release substances into a liquid mixture such as the bloodstream of its human host. Such substances might include drugs, hormones, chemical neurotransmitters, or substances added to the saliva in the host’s mouth that will be experienced by the host through the sensory modality of taste.[133]

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[131] For the use of welding electrodes or gas cutting torches as robotic end effectors, see, e.g., Saha, *Introduction to Robotics* (2008), pp. 18, 26, and Niku, *Introduction to Robotics: Analysis, Control, Applications* (2011), p. 7.

[132] See Saha (2008), pp. 32-50; Niku (2011), pp. 266-318; Shahinpoor et al., *Artificial Muscles: Applications of Advanced Polymeric Nanocomposites* (2007); and Kim et al., *Biomimetic Robotic Artificial Muscles* (2013).

[133] The use of implantable neuroprostheses as drug-delivery devices is discussed, e.g., in Merkel

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d. Xenoactive phenomena

Many of the physical effects described above can be manifested in the form of effects that are already commonly produced by natural biological human beings. For example, the human body regularly produces sound waves, the motion of limbs, endocrine and exocrine secretions, exhaled gases, and electromagnetic fields.

However, some of the physical effects described above can also be manifested by a neuroprosthetic device in the form of 'xenoactive' effects that the natural biological human body is not capable of producing. For example, a neuroprosthesis that generates radio transmissions, microwave signals, visible light, or chemically synthesized pharmaceuticals is generating physical effects that exceed those that are normally possible for the human organism.[134]

F. Modalization of Motor Action

Sensory neuroprostheses allow a human host to experience reality through various *sensory modalities.* In that context, the word 'modality' does not directly describe the physical stimuli that give rise to a sensory experience nor the physical organ or mechanism by which the host's body detects the stimuli; instead, they reflect the distinct ways in which various types of sense data are experienced by the mind and include phenomena such as vision, hearing, taste, smell, and touch. By analogy, one can understand **motor modalities** as the distinct avenues by which a human being employs the motor capacities of his or her body in order to manifest his or her volitions within the world. A motor modality is not inherently identified with a particular motor organ or category of physical effect but with a desired means of expression. For example, using one's legs to walk across a room and using one's hands to play a musical instrument both involve similar kinds of motor action, if viewed at the microanatomical level of muscles being electrically stimulated by motor neurons that innervate them; however, from the perspective of the person performing these actions, each kind of action has a different purpose and constitutes a different sort of conscious experience. Several key types of motor modalities are discussed below.

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et al. (2007); Bhunia et al., "Ultralow Power and Robust On-Chip Digital Signal Processing for Closed-Loop Neuro-Prosthesis" (2014); and Mercanzini & Renaud, *Microfabricated Cortical Neuroprostheses* (2010).

[134] In a sense, all fully implantable neuroprostheses that communicate with external systems using wireless (e.g., radio) transmission are xenoactive neuroprostheses. For an overview of such technologies, see, e.g., Wise et al., "Wireless implantable microsystems: high-density electronic interfaces to the nervous system" (2004); Wise et al., "Microelectrodes, microelectronics, and implantable neural microsystems" (2008); and *Implantable Biomedical Microsystems: Design Principles and Applications*, edited by Bhunia et al. (2015).

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1. Symbolic Action

A neuroprosthetic device may participate in or control physical actions that generate or manipulate written or spoken language or other types of symbols that can be used for purposes of information storage and communication.

a. Language classified by its mechanism of production

Languages expressed through the use of a neuroprosthesis may be classified according to the mechanism of their production.

I. ORAL LANGUAGE

Some neuroprosthetic devices allow their hosts to communicate through the generation of oral language – for example, through the use of a natural biological voice box, prosthetic larynx, or mechanism for the production and transmission of spoken language within a virtual world.[135]

II. WRITTEN LANGUAGE

Some neuroprostheses allow their hosts to communicate through the production or manipulation of written language. This might be accomplished, for example, by a robotic prosthetic arm that allows its host to type on a keyboard or write within a stylus or pen or by an artificial eye that allows its host to 'type' words on a monitor by focusing his or her gaze on particular letters.[136]

III. SIGN LANGUAGE

A neuroprosthetic device may allow its host to communicate through the use of sign language, in which the movements of the host's biological, synthetic, or virtual limbs is not used to generate symbols within some other physical medium but instead become the symbols.

b. Language classified by its historical origin

Languages expressed through the use of a neuroprosthesis may be classified according to the historical process through which the languages were developed.

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[135] See, e.g., Kshirsagar et al., "Personalized Face and Speech Communication over the Internet" (2001); Tang et al., "Humanoid audio–visual avatar with emotive text-to-speech synthesis" (2008); and *Computer Synthesized Speech Technologies: Tools for Aiding Impairment*, edited by Mullennix & Stern (2010).

[136] Various neuroprosthetic approaches to allowing those who are paralyzed to control a computer cursor are discussed, e.g., in Kostov & Polak, "Parallel man-machine training in development of EEG-based cursor control" (2000); Taylor et al., "Direct cortical control of 3D neuroprosthetic devices" (2002); Black et al., "Connecting brains with machines: the neural control of 2D cursor movement" (2003); and *Brain-Computer Interfaces: Principles and Practice*, edited by Wolpaw & Winter Wolpaw (2012).

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I. NATURAL HUMAN LANGUAGE

A neuroprosthetic device may allow its host to communicate using a natural human language such as English, Polish, or Japanese that evolved organically through a gradual historical process of everyday use within one or more human cultures.[137]

II. SYNTHETIC LANGUAGE

A neuroprosthesis may allow its host to communicate with other human beings using a constructed language such as Esperanto or the 'artistic languages' developed within works of science fiction or fantasy to depict the language of intelligent nonhuman civilizations.[138] A host might use a constructed language such as the Robot Interaction Language (ROILA) to communicate with an array of compatible robotic entities using a form of linguistic social interaction.[139] A sufficiently sophisticated neuroprosthesis might allow its human host to directly control external computerized devices such as desktop computers, web servers, or mobile devices by 'thinking' directly in a programming language, command language, or even in machine code.

A synthetic language may be expressible through conventional speech or written text, or it may involve the use of icons or other forms (perhaps three-dimensional) that can only be expressed and represented with the aid of particular technologies or within a specific virtual world.

III. LANGUAGE OF THOUGHT

A neuroprosthetic device may allow its user to communicate or store information employing the modality of a hypothesized language of pure thought that is used internally by human minds to conceptualize ideas before translating them into natural human language.[140] It is unclear to what extent such a language of pure thought exists and, if it does exist, whether it takes essentially the same form for each human being or whether it differs in critical characteristics among human beings. It is also unclear to what extent it

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[137] For an overview of the development of such human languages, see, e.g., Campbell, *Historical Linguistics* (2013), and *Evolutionary Linguistics*, edited by McMahon & McMahon (2013).

[138] See, e.g., Peterson, *The Art of Language Invention: From Horse-Lords to Dark Elves, The Words Behind World-Building* (2015).

[139] See Mubin et al., "Improving speech recognition with the robot interaction language" (2012), and Mubin et al., "Talk ROILA to your Robot" (2013).

[140] For just a small sampling of the many debates that touch on such issues, see, e.g., Smolensky, "The Constituent Structure of Connectionist Mental States: A Reply to Fodor and Pylyshyn" (1988); Braddon-Mitchell & Fitzpatrick, "Explanation and the Language of Thought" (1990); Clark, "Systematicity, Structured Representations and Cognitive Architecture: A Reply to Fodor and Pylyshyn" (1991); Cory, "Language, Brain, and Neuron" (2000); Taylor & Taylor, "The Neural Networks for Language in the Brain: Creating LAD" (2003); and Katz, "The Hypothesis of a Genetic Protolanguage: An Epistemological Investigation" (2008).

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could be expressed using either synthetic or virtual effectors – given the fact that, by definition, it is not directly expressed in its normally occurring form through motor activity and does not otherwise naturally exist outside of a mind's internal cognitive processes. If neuroprostheses can indeed be constructed that are capable of accessing, interpreting, or producing such language of thought, they may thus be better classified as cognitive rather than motor neuroprostheses.

If each such language of thought is indeed unique to a particular person and can only be produced or accessed by a single human mind (or group of minds that are related in some way), it could potentially be understood and exploited as a means of encryption.[141]

2. Nonsymbolic Action

A neuroprosthetic device may participate in or control the generation of physical actions that do not involve the production of written or spoken words or other types of symbols.

a. Paralanguage

A neuroprosthetic device may allow its host to communicate using the modality of paralanguage (which includes elements such as tone of voice, voice volume and pitch, and throat-clearing sounds) as expressed through the motor organs of natural, synthetic, or virtual body components.[142]

b. Oculesics

A neuroprosthesis may allow its host to communicate using the modality of oculesics (which includes elements such as the direction of one's gaze, eye movement, pupil dilation, and use of eye contact) as expressed through the motor organs of natural, synthetic, or virtual eyes or other visual organs.[143]

c. Kinesics

A neuroprosthetic device may allow its host to communicate using the modality of kinesics (which includes elements such as facial expressions, gestures, and posture) as expressed through the motor organs of a natural, synthetic, or virtual body.[144]

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[141] The idea of utilizing thoughts as a means of user authentication within the field of information security has already been raised; see, e.g., Thorpe et al., "Pass-thoughts: authenticating with our minds" (2005).

[142] For an overview of such phenomena, see Johar, *Emotion, Affect and Personality in Speech: The Bias of Language and Paralanguage* (2016).

[143] For an overview of oculesics in relation to other forms of nonverbal communication, see Andersen & Andersen, "Measures of Perceived Nonverbal Immediacy" (2005).

[144] For an overview of kinesics, see Andersen & Andersen (2005).

d. Haptic communication

A neuroprosthesis may allow its host to communicate using the modality of haptics (which includes specialized forms of touching such as handshakes, hugging, kissing, and tickling) and which is expressed through the fine manipulators and other motor organs of a natural, synthetic, or virtual body.[145]

e. Proxemics

A neuroprosthesis may allow its host to communicate using the modality of proxemics (which involves positioning the body in order to control space and interpersonal distance) and which is expressed through the natural, synthetic, or virtual motor organs that control locomotion and posture.[146]

f. Internal organ activity

A neuroprosthetic device may control or otherwise participate in the actions of internal biological or synthetic organs within its host's body. In this way, a neuroprosthesis may impact its host's cardiac activity, breathing, digestion, blood chemistry, and other phenomena.[147]

G. Mapping of Motor Routes

A motor neuroprosthetic device creates a 'mapping' by which a particular set of motor instructions is generated (e.g., within the brain or spinal cord or by an electronic computer), transmitted to a particular motor organ, and executed to produce some physical effect within the host's body or the external environment that displays a particular motor modality. Within the organism of a natural biological human being, a wide range of such motor routes or mappings can already be found: for example, a complex set of motor instructions generated in the brain may cause the lungs, throat, jaw, lips, and tongue to move in a way that produces a particular sequence of sound waves that allows an individual to impact his or her environment through the modality of *speech*;[148] if other human beings, voice-activated electronic devices, or audio recording devices are present to detect the speech, it may have a significant effect on the environment.

On the other hand, it is possible for a neuroprosthesis to participate in a 'non-standard' motor mapping. For example, some types of robotic prosthetic arms utilize the technique of targeted muscle reinnervation to allow an arm's movements to be controlled by its host's thoughts. In that procedure, nerves

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[145] The significance of haptics as a form of communication is also discussed in Andersen & Andersen (2005).

[146] The phenomena constituting proxemics are also reviewed in Andersen & Andersen (2005).

[147] For discussion of such neuroprosthetic devices that affect the internal biological processes of their human host, see McGee (2008), p. 209, and Gasson (2012), pp. 12-16.

[148] For an overview of the brain regions and mechanisms involved with speech production, see Blank et al., "Speech production: Wernicke, Broca and beyond" (2002).

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in the remaining portion of the biological limb are surgically relocated so that the innervate healthy muscle tissue within the host's chest: sensors are affixed to the relevant portion of the chest, and whenever the host attempts to move his or her arm, the motor instructions generated by the brain cause muscles in the chest to move; the data regarding such movement is detected by the sensors and transmitted to the neuroprosthetic arm's controller, which interprets the signals and causes the robotic arm to move in the way that its host desired.[149] In this case, the ultimate result of the host's motor instructions – the movement of the (artificial) arm – is typical, but the motor route used to effect it is not.

In the following sections we consider different ways in which a motor neuroprosthesis can link together motor instructions with a motor organ and motor modality to create a coherent avenue for motor expression by its human host.

1. Routing Natural Motor Instructions to Their Biologically Normal Effector

A neuroprosthesis may receive or generate motor instructions of a sort that are typically produced by a natural biological system (e.g., the brain or spinal cord) and convey them to a biological or artificial effector, where they produce some physical effect using the motor modality whose activity is naturally associated with that form of motor instruction. An example would be a robotic prosthetic leg that replaces a biological leg lost to illness or injury and which detects motor instructions that are produced in its host's motor cortex and conveyed through the sciatic nerve and converts those instructions into electrical signals that govern the movements of the robotic leg's actuators, allowing its host to act in the physical environment through the motor modality of locomotion.[150]

2. Routing Fabricated Motor Instructions to an Arbitrary Effector

Instead of detecting motor instructions generated within its host's brain or spinal cord and conveying them to a motor organ, a neuroprosthesis might instead generate such motor instructions itself, as determined by the programming of its internal computer or other built-in control mechanisms. An artificially intelligent neuroprosthesis might, for example, issue motor instructions in the form of electrochemical signals transmitted to natural biological motor neurons, muscle tissue, or gland cells in order to regulate its

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[149] See *Targeted Muscle Reinnervation: A Neural Interface for Artificial Limbs* (2014).

[150] An overview of such a robotic prosthetic leg is provided in Hargrove et al., "Robotic leg control with EMG decoding in an amputee with nerve transfers" (2013).

host's heart rate, induce the secretion of hormones into the bloodstream, or disable or override the host's own voluntary control of skeletal muscles.[151]

3. Remapping Natural Motor Instructions to a Biologically Atypical but Natural Effector

It is possible for a neuroprosthesis to detect motor instructions that are generated naturally by the biological components of the brain or spinal cord and convey them to an effector which – while naturally occurring in human beings – is not the organ by which such motor instructions are typically expressed.

One variation of such a routing is for a neuroprosthetic device to map motor instructions that naturally govern the activity of a motor organ whose impact is largely felt outside of the host's body so that they instead control some effector within the host's body. An example would be a neuroprosthetic device that can detect motor instructions generated in the host's brain that cause muscles in the throat, tongue, jaw, and lips to produce a subvocalized sequence of sounds (e.g., a predetermined trigger word) and which – whenever the trigger word is subvocalized – stimulates the adrenal grands to release epinephrine into the bloodstream, thereby preparing the host's body for particular types of physical activity.[152] Conversely, a neuroprosthetic device may map motor instructions that typically regulate the activity of an effector within the body (such as cardiac muscle tissue) so that they instead control some effector whose impact is manifested in the environment external to the host's body. An example would be a neuroprosthesis that – upon detecting that preganglionic nerve fibers in the spinal cord are stimulating the adrenal gland to secrete epinephrine into the bloodstream – stimulates the secretion of sweat from sweat glands to cool the host's body in preparation for anticipated physical activity.

4. Routing Motor Instructions Using a Non-human Xenoexpressive Mapping

A neuroprosthetic device may incorporate into its motor mapping some form of non-natural 'xenoexpression' that is not manifested in the motor mappings of natural biological human beings. Through the use of such motor mappings, a neuroprosthetic device's human host may be able to produce physical effects that exceed the natural capacities of the human organism and

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[151] Examples already in use or under development include some types of neuroprostheses designed to treat conditions such as epilepsy and Parkinson's disease. See Fountas & Smith, "A Novel Closed-Loop Stimulation System in the Control of Focal, Medically Refractory Epilepsy" (2007), and *Deep Brain Stimulation for Parkinson's Disease* (2007).

[152] Regarding the mechanisms of subvocalization, see, e.g., Pollatsek, "The Role of Sound in Silent Reading" (2015).

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which – to unwitting observers – might appear inexplicable or even 'paranormal' in nature.[153]

a. Mapping motor instructions to a non-human xenergetic effector

One type of xenoexpressive mapping involves a neuroprosthetic device that is capable of expressing motor instructions through a non-human, 'xenergetic' effector of a type that is not present in the organism of a natural biological human being. Such effectors might potentially include electromechanical components such as wings or wheels, soft robotic limbs such as tentacles, electronic effectors such as radio transmitters or LED displays, or complete external vehicles or other systems.[154] By definition, such neuroprostheses utilize effectors for which the human mind has no corresponding natural default motor mapping; if such a device is to be controlled by its host's thoughts, then its designer must decide how to construct a cybernetic control pathway that allows such effectors' activity to be regulated by motor instructions generated by the brain.

b. Mapping motor instructions to manifest a non-human xenopractic motor modality

Another type of xenoexpressive mapping involves a neuroprosthetic device that expresses motor instructions using a non-human, 'xenopractic' motor modality that is not normally available to natural biological human beings. An example might include a neuroprosthesis that allows its host to inhabit and control a virtual body consisting of a swarm of spatially disjunct components existing in four-dimensional rather than three-dimensional space. It is not clear to what extent such fashioning of new motor modalities (or 'unlocking' of latent modalities) is theoretically and practically possible; the field of body schema engineering investigates such possibilities.[155]

Conclusion

In this text we have developed an ontology that attempts to envision, capture, and describe the full range of ways in which a neuroprosthesis may participate in the sensory, cognitive, and motor processes of its human host. By considering anticipated future developments in neuroprosthetics and adopting a generic biocybernetic approach, the ontology is able to account not only for therapeutic neuroprostheses already in use but also for future types of

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[153] Here one may recall the potential indistinguishability of advanced technology and magic, as famously discussed in Clarke, "Hazards of Prophecy: The Failure of Imagination" (1973), p. 36.

[154] For example, neurotechnologies have been developed to allow a human being to successfully pilot an aerial drone in the primary physical world and drive a car within a virtual environment by means of his or her thoughts; see LaFleur et al., "Quadcopter control in three-dimensional space using a noninvasive motor imagery-based brain-computer interface" (2013), and Zhao et al., "EEG-Based Asynchronous BCI Control of a Car in 3D Virtual Reality Environments" (2009).

[155] See Gladden, "Cybershells, Shapeshifting, and Neuroprosthetics" (2015).

neuroprostheses that are expected to be developed and deployed for purposes of human enhancement. It is hoped that the use of such an ontology will allow biomedical engineers, ethicists, futurologists, and others to more easily, systematically, and robustly analyze, describe, and plan the biocybernetic role of neuroprostheses within their unique host-device systems.

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