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REVIEW

Brain control and information transfer

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Abstract In this review, we examine the importance of having a body as essential for the brain to transfer information about the outside world to generate appropriate motor responses. We discuss the context-dependent conditioning of the motor control neural circuits and its dependence on the completion of feedback loops, which is in close agreement with the insights of Hebb and colleagues, who have stressed that for learning to occur the body must be intact and able to interact with the outside world. Finally, we apply information theory to data from published studies to evaluate the robustness of the neuronal signals obtained by bypassing the body (as used for brain–machine interfaces) versus via the body to move in the world. We show that recording from a group of neurons that bypasses the body exhibits a vastly degraded level of transfer of information as compared to that of an entire brain using the body to engage in the normal execution of behaviour. We conclude that body sensations provide more than just feedback for movements; they sustain the necessary transfer of information as animals explore their environment, thereby creating associations through learning. This work has implications for the development of brain–machine interfaces used to move external devices.

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Keywords Information theory · Sensorimotor behaviour · Feedback · Learning · Systems neuroscience · Brain–machine interfaces

Abbreviations

BMI	Brain–machine interface
EEG	Electroencephalographic activity
fMRI	Functional magnetic resonance imaging

Introduction

The way the brain controls body movements has been an active field of study in systems neuroscience and in the development of brain–machine interfaces used in the control of external devices by paralysed patients (Georgopoulos et al. 1986; Birbaumer et al. 1999; Donoghue 2002; Alfalo and Graziano 2006; Chen and Tehovnik 2007; Tehovnik et al. 2013; Baranauskas 2014; Chen et al. 2014; Schiller and Tehovnik 2015). Although some might believe that the brain can operate independently of the body, a central part of brain control depends critically on having an intact body to allow maximal feedback by way of the senses to produce correct motor responses (Gibson 1979; Sainburg et al. 1995; Clark 1998; Tehovnik et al. 2013). When the feedback is compromised (as in paralysed patients), it causes a measurable reduction in information transfer even if the neural signals are collected directly from the brain to move external devices for the purpose of bypassing damaged circuits (Birbaumer 2006; Dornhege 2006; Tehovnik et al. 2013; Tehovnik and Teixeira-e-Silva 2014). Thus, we reason that information transfer via the brain decreases as sensorimotor feedback decreases. Here we are referring to the information transferred by the whole brain in terms of bits per second to yield a motor response.

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Our hypothesis as argued below is supported by four observations: First, the volitional control of neurons in behaving monkeys drops when the proprioceptive inputs to the brain are severed. Second, proprioception as well as the other senses via the body is necessary for the execution of normal body movements. Third, for learning to occur an intact sensory feedback system is required to accurately associate events over time. Finally, the amount of information transferred by the brain via current brain–machine interfaces is far below that transferred by an intact brain with full access to sensory feedback. We use information theory to make cross-study comparisons using bits per second (Shannon 1948; Georgopoulos and Massey 1988; Dornhege 2006; Tehovnik et al. 2013). We suggest that the poor performance of current brain–machine interfaces is related to a diminished sensory feedback.

Volitional control of neural circuits

Eberhard Fetz was one of the first investigators to train monkeys to regulate volitionally the activity of neurons in the motor cortex (Fetz 1969). His studies have become central in the development of brain–machine interfaces (Tehovnik et al. 2013). Fetz trained monkeys to increase the firing rate of a single neuron by 50–500 % in exchange for a food pellet that was dropped into a dispenser in front of an animal's mouth. After conditioning, the neurons would burst for 100–800 ms. For optimal performance, 5–12 food pellets were delivered per minute putting the average trial time at 5–12 s. All recordings were done in the hand area of the motor cortex, albeit hand retrieval of food pallets was not needed. Some 3–8 training sessions conducted over days were required for a monkey to gain control over a neuron. One cell was examined per session. For all experiments, the monkeys were free to move their head and limbs as they learned to control the firing rate of cells, and in some cases, movement of the forelimbs was coincident with the neural response. For trials in which a reward was denied, there was rapid extinction of the response, and random reinforcement outside the context of the task failed to drive the cells. In this case, the reinforcement between a given body movement with a goal in the extrapersonal space completes the loop for the volitional control of the neural circuits (Fig. 1a), something that has received much attention in the study of normal behaviour (Kobayashi and Schultz 2008; Shadmehr 2010) and brain–machine interfaces (Rajalingham et al. 2014).

The role of body movement in the conditioning response was later investigated in detail (Fetz and Finocchio 1971). The arm contralateral to the recording site in the motor cortex was secured by a cast, as a monkey was rewarded for contraction of one of the four muscle groups, i.e. flexors or

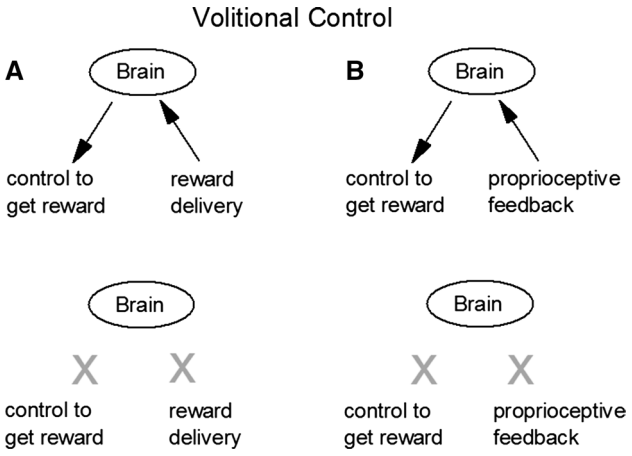

Fig. 1 Volitional control of neurons by the brain of monkeys. **a** The volitional control of neurons yields a reward delivery (*top panel*). When reward delivery is disrupted there is no longer any volitional control (*bottom panel*). **b** The volitional control of neurons with proprioceptive feedback yields a reward delivery (*top panel*). When proprioceptive feedback is disrupted there is no longer any volitional control (*bottom panel*)

extensors of the wrist or flexors or extensors of the elbow. After training, a single muscle group could be contracted, which was accompanied by the firing of a unit. Such units typically fired in advance of a muscle contraction. The monkey was then trained to discharge a unit while suppressing all muscle contractions. Although the four muscles under study could be made not to contract as a neuron was made to discharge, it is unclear whether muscles outside of the four under study were now contributing to the unit response. In subsequent experiments, it was found that training monkeys to suppress the bursting of a neuron while eliciting a muscle contraction could never be achieved in the hand or leg regions of the motor cortex (Fetz and Finocchio 1972; Fetz and Baker 1973). It is noteworthy that most precentral cells were found to respond to the passive movement of the forearm even when all recorded muscle activity was suppressed even though these same cells typically responded in advance of a muscle contraction when using a conditioning paradigm (Fetz and Finocchio 1972; Fetz and Baker 1973). Note that the somatosensory cortex is connected to the motor cortex for the transmission of kinaesthetic and other somatosensory information (Kalaska et al. 1983; Mountcastle et al. 1992). The forgoing suggests that the responsivity of neurons in the motor cortex is affected by both volitional and passive movements.

Wyler et al. (1979) determined how dependent the conditioned response of neurons in motor cortex is on proprioception as conveyed by Fig. 1a, b afferents. Following disruption of the proprioceptive feedback from the contralateral forearm (via C_5–C_7 ventral rhizotomies) of a monkey, they reported that the volitional control of the

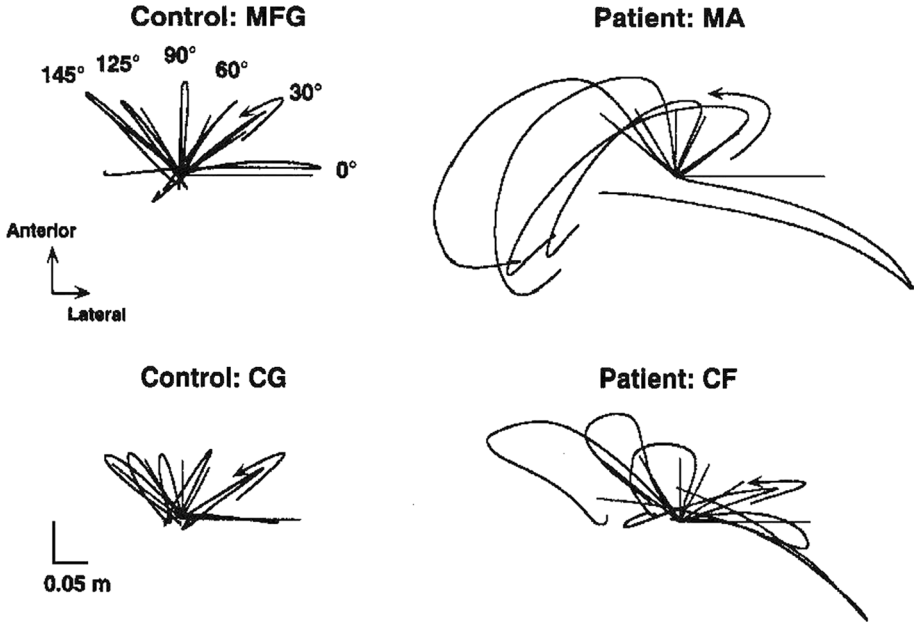

Fig. 2 Hand paths of controls (MFG, CG) and deafferented patients (MA, CF) showing the consequences of lacking visual and proprioceptive feedback in arm movements. Subjects were required to execute a movement in one of the six directions and then reverse the movement. *Arrow* indicates the path towards the 30° location for each subject. Data from Sainburg et al. (1995)

neurons was abolished (Fig. 1b). It is noteworthy that this monkey could improve his performance by manipulating his flaccid arm with his functional hand to activate specific joints and tendons to better drive the motor cortical neurons. In the same study, destruction of the pyramidal tract in the spinal cord (which also included the spino-cerebellar pathways that carry proprioceptive information) produced only a minor drop in performance. A previous study by the same group showed that bilateral lesions of the dorsal column pathways (which transmit proprioceptive information as well) also affected the conditioning responses (Wyler and Burchiel 1978). Just how the proprioceptive afferents contribute to the volitional control of the cortical motor neurons needs further clarification given the challenges of completely and precisely eliminating all proprioceptive inputs anatomically to the neocortex. Nevertheless, regardless of the details of how proprioception contributes to this control, it is very clear that information from the body must also participate in this process for maximal effectiveness.

Knowing where the body is

As indicated "knowing where the body is" is important for the volitional control of neurons and hence body movements. The skeletomotor system is equipped with muscles spindles and tendon organs (plus maybe even cutaneous receptors, Collins et al. 2005) to register the position of the body parts (Feuerbach et al. 1994; Dover and Powers 2003). Much experimentation has been done on the proprioception of skeletal muscles (Jones 1988; Ghez et al. 1990; Ghez and Sainburg 1995; Gordon et al. 1995; Sainburg et al. 1995; Bagesteiro et al. 2006; Sarlegna and Sainburg 2007; Sarlegna et al. 2009; Sarlegna and Sainburg 2009). Sainburg et al. (1995) show that patients lacking proprioceptive input (caused by large fibre sensory neuropathy resulting in the loss of stretch reflexes) were deficient in performing multi-joint movements. They were required to trace the out-and-back movement of a template line displayed on a computer screen while not being able to see their moving hand. Electromyograms of the elbow muscles were measured, and all movements were assessed by recording the movements of a hand-held pen. Large distortions of hand path occurred when the direction of movement was reversed (our Fig. 2, Sainburg et al. 1995). This was related to the poor timing between the joints of the elbow and shoulder which is a consequence of decreased proprioceptive feedback. Not surprisingly, deafferented patients can use visual information to guide the trajectories of their movements (Ghez et al. 1990; Ghez and Sainburg 1995; Gordon et al. 1995).

The proprioceptive system has also been studied by delivering a vibratory stimulus to muscles which cause human subjects to systematically mislocate the position of their body parts (Lackner and Levine 1978, 1979; Jones 1988). This mislocation is presumed to be caused by the mechanical activation of afferents of muscles spindles (Goodwin et al. 1972a, b). Craske (1977) blindfolded subjects as one forearm was stimulated using vibration of the elbow and as the other forearm was used to indicate the position of the stimulated forearm. The stimulation induced a 23° deviation (on average) between the actual versus the perceived location of the stimulated forelimb. If the limb was now positioned at its extension or flexion limit, such stimulation could induce a perception of hyperextension or hyperflexion. Here subjects perceived their arm as being

curved, or as oscillating between two positions, or even as being dislocated and broken.

Vibratory stimuli have also been used to evoke the waist-shrinking illusion which distorts the perception of one's body size (Ehrsson et al. 2005). As a subject is made to put his hands on his waist and hips, the application of a vibratory stimulus to the wrist extensors produces the illusion that the hands are being bent inward and that the body is being reduced in size at the waist.

As with the skeletomotor system, delivering vibratory stimuli to the muscles of the eyes has been shown to cause human subjects to mislocate the position of visual targets in space (Valey et al. 1994, 1995, 1997). It has been found that when a vibratory stimulus was applied to the inferior rectus muscle, a vertical displacement of a stationary spot of light (presented in total darkness) was experienced by subjects (Valey et al. 1997). The illusion of target displacement did not result from stimulation-evoked eye movements (as measured with an eye tracker) as the movement perturbation was short-lived and eye position was restored to its original. Yet, the proprioceptive illusion was sustained for ~10 s following the restoration, while both the visual stimulus and the eyes remained stationary in space.

The view that extraocular proprioception updates the spatial frame of references has been supported by recent studies. Goldberg and colleagues showed that a putative ocular proprioceptive representation exists in the somatosensory cortex (Wang et al. 2007) and that this representation participates in the late phase of visuomotor coordinate transformation (i.e. at 200 ms after movement offset, Xu et al. 2012; cf. Graf and Andersen 2014). As a result of this late phase, however, eye proprioceptive representation in the somatosensory cortex is unlikely to participate in the real-time control of eye movement, in line with the notion originally postulated by Robinson (1981). Nevertheless, given the serious oculomotor deficits that ensue following damage to oculo-propioceptive inputs—unstable fixations, ocular drift, and impairments in vergence and binocular fixations (Fiorentini and Maffei 1977; Porter et al. 1982; Guthrie et al. 1982, 1983)—the role of proprioception in the execution of oculomotor responses needs to be re-examined.

In addition to proprioception, the brain receives inputs from the visual and vestibular systems to stabilize the eyes and head as one navigates through space. The terminal nuclei in the brainstem obtain visual inputs to mediate optokinetic nystagmus whose function it is to stabilize images on the retina as the visual scene moves about (Knapp and Schiller 1984; Simpson 1984; Schiller and Tehovnik 2015); motion and orientation sensors situated next to the cochlea subserve vestibular responses to right the head with respect to gravity (Leigh and Zee 2006; Schiller and Tehovnik 2015). Disruption of these systems either through blindness or by vestibular damage greatly curtails one's ability to orient through space (Leigh and Zee 2006; Tehovnik and Slocum 2013; Schiller and Tehovnik 2015).

One of the best examples to appreciate how good the brain is at correcting for changes in body position is to note that when a skier skies down a slope, the visual scene experienced by him remains stable. This is because the vestibular system corrects all the movements of the head via the vestibulo-ocular reflex to thereby stabilize the visual image (Leigh and Zee 2006). If one were to put a movie camera on the head of the skier, the camera would register all the abrupt jumps of the visual scene as the skier descends down the slope. The camera has no vestibular apparatus.

In conclusion, the brain is equipped with inputs from the proprioceptive, visual, and vestibular systems to help it compute how the body is situated in space. We know that the brain has a tremendous capacity to predict the future position of its body with respect to the outside world (Rizzolatti et al. 1996; Eskander and Assad 1999; Chen et al. 2014). When the brain is mastering such predictions, the lack of sensory feedback inevitably leads to severe debilitation. It is no surprise, therefore, that the volitional control of neurons requires feedback from the body to compute its location with the ultimate goal of executing body movements.

Learning via the volitional control of neural circuits

In 1949, Donald Hebb wrote a book entitled the "The Organization of Behavior" in which he proposed that the development of the mind (or brain control) occurs through learning at the synaptic level of neural circuits, a notion that is largely accepted today (Montague et al. 1995, 1996; Schultz et al. 1997; Kandel et al. 2013). In this work, Hebb emphasized the consequences of growing up without an intact body, i.e. without a functioning visual system due to congenital blindness. He noted that if such individuals recover vision later in adulthood (after having lost vision before the age of four), they are impaired at figure-ground segregation and they fail to perceive objects such as circles, squares or triangles. These patients have been studied in detail by Gregory and colleagues (Gregory and Wallace 2001; Fine et al. 2003). It was found that such patients developed no object vision even though colour and motion perception (including biological motion) were intact. Additionally, they had no depth perception unless defined by motion. Finally, perspective and the ability to resolve occlusions were totally absent.

Hebb surmised (Hebb 1949, pp. 33) that "…we are able to see a square as such in a single glance only as the result

of complex learning". This learning he believed comes about as children scan their world with their eyes and other senses and as they actively engage the world: "…it will be found, for example, that with a large figure merely imagining eye-movements (of following the contours) will restore [the] definition of the figure". Moreover, "each grossly different pattern of stimulation, as the object is seen from one side or another, requires the establishment of a separate set of cell-assemblies. …when this happens the various sets of assemblies would gradually acquire an interfacilitation…" (Hebb 1949, pp. 91). Finally, "…it is again fashionable to think of groups of connected neurons … as the carriers of individual items of meaning or, if we wish, as the morphemes in the language of the brain" (Hebb 1949, pp. 141). This idea concurs with the modern view of how groups of neurons throughout the brain code for objects (Freiwald and Tsao 2010) and language (Ojemann 1983) which would have each individual harbour a unique distributed neural connectivity based on a particular developmental history of sensorimotor interactions (Hebb 1949).

Hebb's views on requiring an intact body for development and learning have been supported by a functional magnetic imaging (fMRI) study. A patient who had recovered vision later in life after having lost it at the age of three had his brain scanned with fMRI while being subjected to various visual psychophysical tests (Fine et al. 2003). The medial temporal cortex responded normally to moving stimuli, a region of the brain known for the processing of motion information (Tootell et al. 1995). The lingual and fusiform gyrus that mediates object vision (Schwarzlose et al. 2005), however, was dysfunctional which fitted with the patient's inability to identify objects. Hence, for development to occur it is critical that the senses be intact from an early age to thereby permit maximal interaction between the brain and the world via the body.

The importance of these interactions is best illustrated by the now famous studies of Held and Hein (1963). One kitten (the active kitten) was reared with normal vision and allowed to move freely within the visual world; a second kitten (the passive kitten) was confined to a gondola and given the same visual experience as the first kitten but had all its locomotion controlled by a connection to the first kitten. The passive kitten was free to move its eyes and head. Both kittens were in a visual environment containing vertical black and white stripes. The kittens were later tested on a visual-cliff avoidance task, which required the discrimination of a shallow and deep side. Unlike the active kitten, the passive kitten failed this test of depth perception. Hence not being able to move in the world prevents against the development of the visual system. This outcome is reminiscent of congenitally blind patients who with vision restored later in life fail to exhibit the full repertoire of visual capabilities. Hebb (1949) might say that the reason for this is that the cell assemblies that needed to be developed failed to do so because the individuals were not allowed to effectively move their bodies about to create the necessary paired associations over time for learning to occur.

Learning has been studied in depth in behaving primates. Conditional oculomotor experiments were performed by Chen and Wise (1995a, b, 1996, 1997) on monkeys viewing a TV monitor (also see Mitz et al. 1991). As monkeys fixated a centrally located spot of light on the monitor, the spot of light was exchanged for a novel complex visual stimulus. This was followed by the presentation of four identical targets located seven degrees from the fixation spot: up, down, left, and right. It was the task of a monkey to generate a saccadic eye movement to the target that would yield a juice reward. As a monkey learned this trial-and-error task, single-cell recordings were made of neurons in the frontal lobes (i.e. the frontal and supplementary eye fields). It was found that some cells had an increase in activity as a function of learning, others had a decrease in activity, and still other had an increase followed by a decrease. It was of interest that the cells that increased their activity following learning tended to show an activity evolution that lagged behind behavioural improvement; the cells that increased their activity transiently during learning, thus decreasing their activity following learning consolation, tended to show an activity evolution that preceded behavioural improvement (Fig. 3 of Mitz et al. 1991; Figs. 10 and 11 of Chen and Wise 1995a). Such a process to be effective, however, is created through development and learning as suggested by Hebb (1949) which uses post-movement feedback loops to carry environmental information (at latencies >15 ms, Liddell and Sherrington 1924; Lisberger 1984; Miles et al. 1986; Myklebust 1990; Corden et al. 2000; Barnett-Cowan and Harris 2009) and which explains why, once the learning of a task has been completed, movement execution becomes faster and more accurate. The completion of this process can take a very long time when mastering a language or becoming a world-class athlete.

It is now believed that the dopaminergic projections originating in the substantia nigra and innervating vast portions of the cerebral cortex are involved in this process by providing a reward signal to reinforce behaviour (Berger et al. 1986, 1988; Ljungberg et al. 1992; Schultz et al. 1993; Mirenowiez and Schultz 1994; Schultz et al. 1997; Hikosaka et al. 2000; Matsumoto and Hikosaka 2009). The dopaminergic modulation strengthens the synaptic connectivity between neurons (Reynolds and Wicken 2002) as information about the body is being transmitted by various sensory feedback loops (Kato et al. 1995; Kawagoe et al. 1998; Sato and Hikosaka 2002). This process of transfer of information constitutes the volitional control of

movements, and a disruption of it leads to locked-in syndromes such as Parkinsonism (Kato et al. 1995).

Information transfer

Hitherto we have argued that sensorimotor information, as processed through learning, is conveyed between the body and the brain (Gibson 1979; Clark 1998). Without sensory and motor learning, there is little information transferred as evidenced by totally locked-in patients (i.e. those exhibiting no skeletal, ocular, and sphincter movements under volitional control) who lose the ability to control their brain activity using biofeedback (Birbaumer 2006). In these studies, these subjects could no longer use their electroencephalographic activity (EEG) to control external devices which was attributed to a diminished reward contingency that depends on sensory feedback to the central nervous system. This concurs with observations made in monkeys denied reward delivery during the volitional control of neurons that abolishes the control (Fig. 1a). So, a patient in a vegetative state transfers little information. On the other hand, a paralysed person who can still move his eyes to dictate to a PC computer can generate goal-directed movements and is therefore functional albeit at a reduced level.

The brainstem and spinal cord have the capacity to produce organized yet simple ocular and skeletal movements, yet damage to these structure results in severe paralysis (Leigh and Zee 2006; Borton et al. 2014). Ethier et al. (2012) trained two monkeys to grasp a ball and drop it in a container. As the monkeys performed this task, a group of cells was recorded from the motor cortex and their activity was correlated with the activity of the hand muscles engaged during the task. The spinal nerve projecting to the hand muscles was anaesthetized and the signal from the cortical motor neurons was used to trigger an electrical stimulator that activated the hand muscles. Following anaesthesia of the nerve, the performance of the monkeys was <10 % correctness. Under neuronal control, the monkeys performed at 76 to 80 % correctness; normally the monkeys performed the task at over 98 % correctness using the intact brain. In this experiment, all the remaining muscles and pathways were functional such as the muscles and pathways to support the arm as the monkeys reached to the container with the grasped ball. How many pathways projecting to and from the brainstem and spinal cord of monkeys would need to be disabled in order to abolish all information transfer as observed by Birbaumer (2006) in his totally locked-in patients? This would be no easy experiment to accomplish, but an answer to this would move us closer to determine whether the mind can be separated from the body experimentally. We suspect that a transition between the two might not be abrupt, but rather exhibit a gradual degradation of behavioural performance as additional pathways are cut (Birbaumer 2006).

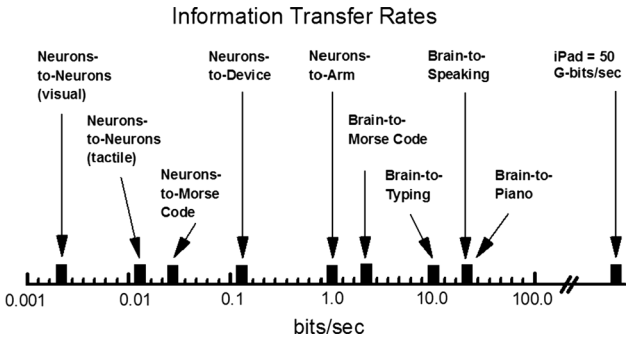

Fig. 3 Information transfer rates. The values for neurons-to-neurons interfaces are from Tehovnik and Teixeira-e-Silva (2014), the value for neurons-to-Morse code is from Dewan (1967), and the values for neurons-to-device and neurons-to-arm are from Tehovnik et al. (2013). The values for brain-to-Morse code, brain-to-typing, brain-to-speaking, and brain-to-piano are from Reed and Durlach (1998). The value for an iPad was deduced from that posted in Wikipedia for an iPad 2 using an Apple A5 systems-on-chip device, rated at 6.4 GB/s

The brain is an organ designed for the transfer of information. Transfer rates can be as low as 0.004 bits/s for neurons-to-neurons communication and as high as 40 bits/s for the production of human language (Fig. 3). A transfer rate of 40 bits/s translates into over 1 trillion possibilities per second given that:

$$\text{Number of possibilities} = 2^{\text{bits}}$$

The low transfer rate exhibited for neurons-to-neurons communication is related to the fact that the transfer was based on recordings from many dozens of neurons in the brain (Pais-Vieira et al. 2013), while the high transfer rate for speech production could be due to a larger portion of the human brain, which contains billions of neurons (Herculano-Houzel 2009), being involved in the execution of this behaviour (Ojemann 1983, 1991). To reinforce this point, Levy et al. (2004) estimated using fMRI that many millions of neurons in the human visual system are involved in the coding of a single visual image.

Furthermore, when recording from an isolated group of neurons to transfer information, the sensory feedback loops carrying information about the body are not as available to those neurons due to the anatomical restrictions on the cells producing the signal. For example, using EEG from the occipital cortex to transmit Morse code transferred 0.05 bits/s of information (Dewan 1967), while using the entire brain (a human subject depressing a key to generate Morse code) to accomplish this task transferred 4 bits/s (Reed and Durlach 1998) (Fig. 3). One way of appreciating this difference is that to generate one letter using EEG took about 1 min while to produce one letter by hand required

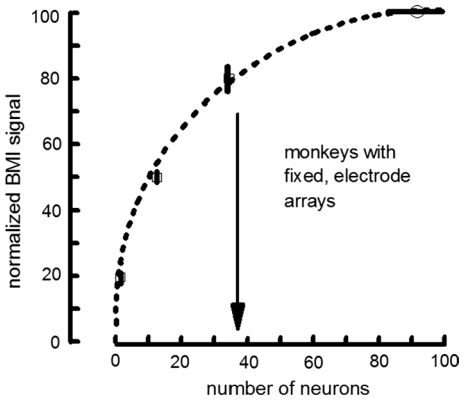

Fig. 4 Normalized brain–machine interface (BMI) signal is plotted as a function of the number of neurons used to derive the signal based on neural recordings with wire electrodes fixed in the brains of monkeys. The signal saturates after 40 neurons. Data obtained from neural drop experiments: Wessberg et al. 2000; Carmena et al. 2003; Hatsopoulos et al. 2004; Musallam et al. 2004; Sanchez et al. 2004; Carmena et al. 2005; Lebedev et al. 2005; Achtman et al. 2007; Wahnoun et al. 2006; Batista et al. 2008; Cunningham et al. 2008; Mulliken et al. 2008; Bansal et al. 2011, 2012. Values were deduced for 20, 50, and 80 % of maximal signal strength by averaging over 14 experiments. The maximal response occurred at 92 cells on average

0.3 s (Dewan 1967; Reed and Durlach 1998). This represents a 200-fold difference in latency. A recent neurons-to-neurons communication experiment conducted by Grau et al. (2014) in human also transferred information at the exceedingly low rate of 0.03 bits/s which is comparable to the 0.05 bit-rate value for EEG-generated Morse code (Dewan 1967; also see Rao et al. 2014). Furthermore, Birbaumer et al. (1999) showed that using EEG a paralysed patient transmitted information at a rate of 0.04 bits/s to communicate several lines of text; this communication took 16 h to complete which is well in excess of the time required by normal subjects using verbal or written communication.

An important issue for many brain–machine interfaces used in paralysed patients and in intact monkeys is that training often has to occur every day in order for task performance to be maintained (Ganguly and Carmena 2009), and the responsive neuron counts are exceedingly low, as the information transfer rates saturate after 40 cells regardless of the state-of-the-art recording electrode arrays being used (Fig. 4). Whether this is related to a drop in the richness of sensory feedback to the cells mediating the behaviour is currently being studied by using electrical stimulation of the somatosensory and visual systems in behaving monkeys to provide a feedback signal (e.g. London et al. 2008; Schiller and Tehovnik 2008; O'Doherty et al. 2011; Tehovnik and Slocum 2013; Zaaimi et al. 2013; Godlove et al. 2014; Klaes et al. 2014).

A musician playing *Mozart* on a piano can transfer information at a rate of 40 bits/s (Reed and Durlach 1998). Verbal communication between people also transfers information at a rate of 40 bits/s. It is without question that a brain with an intact body transfers information better than a brain without a body [Fig. 3, cf. right values for rates >2 bits/s (brain-to-Morse code, brain-to-typing, brain-to-speaking, brain-to-piano) vs. left values for rates <2 bits/s (neurons-to-neurons visual, neurons-to-neurons tactile, neurons-to-Morse code, neurons-to-device, neurons-to-arm); for comparison the information transfer rate of an iPad is indicated on the extreme right].

Quantification of information transfer rates

One of the challenges in systems neuroscience is to have a universal metric by which to compare the various neurobehavioural studies. We have suggested that the use of Shannon's formulation of information transfer (Shannon 1948) could be one solution to this problem (Tehovnik and Teixeira-e-Silva 2014). The use of information theory in neuroscience is not a novel idea (e.g. Miller 1956; Georgopoulos and Massey 1988; Reed and Durlach 1998; Sporns et al. 2000; Wolpaw et al. 2002; Dornhege 2006; Tononi 2008; Tehovnik et al. 2013; Yuan et al. 2013). Tononi (2008) has suggested that having a million photodiodes with each being able to transfer 1 bit of information means that the total information transferred is 1 million bits for a non-integrated system. In reference to the brain, he has argued that by having those one million photodiodes (i.e. neurons) connected, the information transfer would now be able to surpass 1 million bits. Behaviourally, information transfer depends on the sensory resolution, the stimulus–response feedback, and the amount of prior learning and recall (Miller 1956; Reed and Durlach 1998). Just how the brain might accomplish this transfer is depicted using the scheme of Tononi (2008): the information transfer rate should increase across species as the connectivity between the neurons is increased (Fig. 5, exp > 1). The transfer of information by disconnected neurons is shown for comparison (Fig. 5, exp = 1). A single-cell amoeba (Mast 1931) can orient towards a light source or away from a predator, just like the behaviours exhibited across various organisms. In this case, information is transferred and quantification of its transfer rate may be possible. Nevertheless, the details behind this process for single and multicellular organisms are not known at this point.

Information theory can be used to assess how much information is being transmitted by the lateral intraparietal cortex, for example, to make a decision about target choice using the data of Shadlen and Newsome (1996). Figure 6a plots the choice prediction for four levels of visual stimulus saliency (i.e. 0, 6.4, 12.8, and 51.2 % of moving dots)

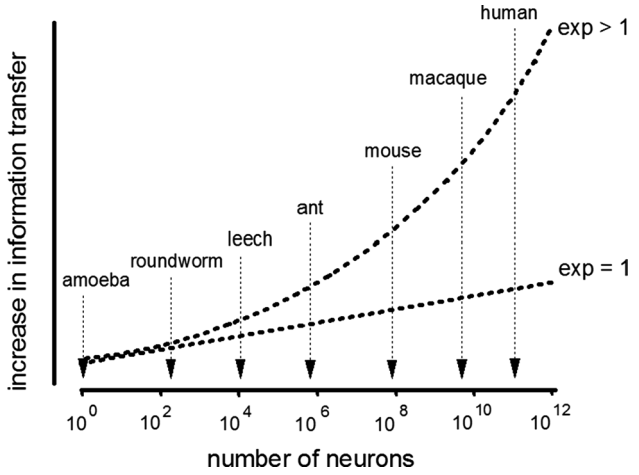

Fig. 5 Information transfer is plotted as a function of number of neurons using a linear and exponential model. The number of neurons contained within the brains of various species is indicated. Values for the amoeba, roundworm, leech, ant, mouse, macaque, and human were derived, respectively, from: Mast (1931), White et al. (1986), Kuffler and Potter (1964), Hölldobler and Wilson (1990), Herculano-Houzel et al. (2006), and Herculano-Houzel (2009). Two models are proposed based on the ideas of Tononi (2008). Exp = 1: the information transfer rate increases linearly with the number of neurons so the exponent is 1. This model assumes no connectivity between neurons. Exp > 1: the information transfer rate increases exponentially with the number of cells so the exponent is >1. This model assumes connectivity between neurons

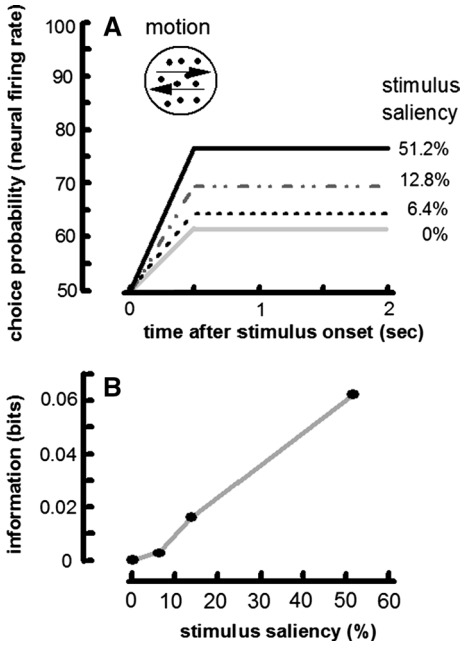

Fig. 6 Transmission of information during choice behaviour. **a** Choice probability is plotted as a function of time after stimulus onset for different levels of stimulus-direction saliency for 47 neurons recorded from the lateral intraparietal cortex of monkeys as they performed a two-choice motion discrimination task. **b** The amount of information in bits transmitted by the neurons as a function of stimulus saliency to initiate the two-choice discrimination task is shown. Calculations are based on monkeys generating eye movements to indicate *leftward* and *rightward dot* motion (see *inset* in **a**). The formula used to deduce the bit rates is: Bits $= \log_2 N + P \log_2 P + (1 - P) \log_2 [(1 - P)/(N - 1)]$, where N is number of targets (i.e. two) and P is per cent-correct (from A). Note that adjustments were made to the score since the 0 % saliency condition generated predictive neural activity at 61 % correctness since the cells were partially tuned for eye movement direction irrespective of the stimulus saliency. This value (11 % above chance: 61–50 %) was subtracted from the other performance values (61, 64, 69, and 76 % for 0, 6.4, 12.8, and 51.2 % stimulus saliency, respectively) to yield 50, 53, 58, and 65 % correctness scores for 0, 6.4, 12.8, and 51.2 % stimulus saliency. These final values were then used to compute the bits of information as shown in **b**. Figure **a** is based on figure 3 of Shadlen and Newsome (1996)

by measuring the choice probability of a population of lateral intraparietal neurons ($n = 47$) studied as monkeys discriminated the direction of dot motion. Monkeys were required to generate an eye movement to one of the two targets specifying the direction of the motion presented on a monitor facing an animal. One of the targets always fell in the motor receptive field of the neuron under study, while the moving dots were always positioned well outside of any receptive field. The bits of information transmitted by the population of neurons were computed from the choice probability scores (Shannon and Weaver 1964; Wolpaw et al. 2002). The amount of information transmitted increased from 0 to 0.066 bits as the saliency of the moving dots was enhanced from 0 to 51.2 % (Fig. 6b). Based on the time to complete one discrimination trial, which was about 3 s for a monkey, the maximal information transferred by cells in the lateral intraparietal cortex was some 0.02 bits/s. A monkey performing at 100 % correctness on the discrimination task (i.e. at 1 bit on a two-choice task) can transfer some 0.33 bits/s using a 3 s trial time. Thus the information transfer rate by several dozens of cells in the lateral intraparietal area transfers some 6 % (0.02/0.33 bits/s) of the needed signal to perform this two-choice discrimination task at 100 % correctness. This low transfer rate concurs with the observation that lesions of the lateral intraparietal area fail to abolish choice behaviour (Schiller and Tehovnik 2003, 2015). Furthermore, this affirms once again that large populations of networked neurons are normally engaged when behaviour is being executed and this calls for a complete understanding of the neural systems that mediates these functions (Schiller and Tehovnik 2001). If neural recordings could have been made at all the critical nodes in the network mediating the decision process, we believe that the neural information transfer rate would begin to approximate the behavioural information transfer rate of 0.33 bits/s. The exercise of converting per cent correctness scores (a common measure in neuroscience) into bits per second could be accomplished for the various per

cent-correct data sets existent in behavioural neuroscience so as to evaluate quantitatively how important a particular node within a neural network is in the execution of a behavioural response (Tehovnik et al. 2013; Tehovnik and Teixeira-e-Silva 2014).

Despite the attractiveness of using information theory to establish a standard metric in neuroscience, there are some caveats. In the paper of Tehovnik et al. (2013), the bit rate for the brain–machine interface performance of a centre-out motor task was computed by dividing each bit-rate value by the trial time used to execute the behaviour. This value for behaving human and nonhuman primates was estimated to be approximately 4–6 s. Others have used neural time as the denominator of the bit-rate calculation which increases the rate by one order of magnitude (Santhanam et al. 2006). Thus the standards used in making a bit-rate calculation need to be uniform.

Yuan et al. (2013) point out that when deducing the bit rate from per cent correctness data [e.g. using the formula of Wolpaw et al. 2002: Bits $= \log_2 N + P \log_2 P + (1 - P) \log_2 [(1 - P)/(N - 1)]$ where N is number of targets and P is the per cent correctness score, one must pay attention to the number of test trials used to deduce a performance score. This can only be done by having a sufficiently large sample size to reduce the variance of the per cent correctness score to below 5 %. Furthermore, the formula used to deduce bit rates from per cent correctness data glosses over details such as target size (Baranauskas 2014). Anyone who studies the visual system can appreciate that visual targets as small as 1 min of visual angle can be resolved by the retina (Schiller and Tehovnik 2015). Given the myriad of parameters used by behavioural tasks studied in neuroscience, information theory will need to be expanded to accommodate these parameters (Baranauskas 2014). We believe that this could be done in order to better quantify behavioural performance so that it can be more effectively correlated with neural activity.

Implications for brain–machine interfaces

It has been established that current brain–machine interfaces transfer information via the brain at exceedingly low rates (Fig. 3, neurons-to-device transfers 0.2 bits/s on average, see Tehovnik et al. 2013 for details). We suggest that these low rates are related to bypassing the sensory input that results when neural signals to control external devices are collected directly from the brain. As mentioned earlier, efforts have been made to substitute the sensory input by electrically activating cells in the sensory cortex directly in behaving monkeys (London et al. 2008; Schiller and Tehovnik 2008; O'Doherty et al. 2011; Tehovnik and Slocum 2013; Zaaimi et al. 2013; Godlove et al. 2014; Klaes et al. 2014). So far this manipulation has not resulted in an increase in information transfer which was less than 0.2 bits/s when stimulating several sites in the somatosensory cortex (O'Doherty et al. 2011; Tehovnik et al. 2013; also see Godlove et al. 2014). Whether improving the resolution of neural excitation by using more targeted stimulation by way of optogenetics or by stimulating fibres electrically closer to the sensory organ will need to be investigated. In the end, a necessary requirement for future brain–machine interfaces might be to re-create the sensory world prosthetically as close as possible to that of a normal system (Schiller and Tehovnik 2008).

The information transfer rate of current brain–machine interfaces is also limited by the number of cells participating in the control of a device given that information saturates beyond 40 cells using current signal-collection methods (Fig. 4). As discussed, normal behaviours are controlled by many millions of neurons. This is especially true of a complex behaviour such as language whose execution depends on a high information transfer rate of 40 bits/s (Fig. 3). Whether future brain–machine interfaces can enhance information transfer by accounting for the vast numbers of neurons mediating behaviour as mimicked by a prosthetic device (which should include the neurons subserving sensory feedback) awaits further advances in recording technology.

Finally, it is well known that persons using a cochlear implant may require over a year of training to re-learn their language as transmitted through the device (Luntz et al. 2005). Such devices once mastered are able to transmit 10 bits/s (Dunn et al. 2010). Patients using future brain–machine interfaces will likely need extensive training so that the information transfer rate can be optimized.

Conclusions

We arrive at a number of conclusions. First, experiments on the volitional control of neuronal circuits suggest that the body is a central part of this control. Second, the brain receives sensory inputs from the proprioceptive, visual, and vestibular systems to code egocentric and gravitational space. These inputs are central to the volitional control of neurons. Third, learning depends on an intact body to generate the appropriate contingencies via feedback loops. Disruption of these loops diminishes the volitional control of neurons. Fourth, the highest information transfer rates in terms of bits per second are achieved via an intact body that permits for maximal sensorimotor feedback from the environment. Fifth, methods need to be developed to better understand how the neural connections within the brains of different animals participate in the transfer of information as behavioural tasks are being

executed. This should lead to a better understanding of how the brain mediates behaviour as well as to the development of improved brain–machine interfaces executing behaviours mimicked by a prosthesis. Finally, current brain–machine interfaces transfer insufficient information to move external devices. One of the reasons may be related to a diminished sensory feedback. Perhaps, sensory feedback could be enhanced by building prosthetic sensory systems that approximate the functionality of normal systems. Also neural recording methods will need to account for signals generated by large portions of the brain which in humans contains many billions of neurons. This is well in excess of the many dozens of cells now used by brain–machine interfaces to move external devices.

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