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Becoming a Network Beyond Boundaries: 

Brain-Machine Interfaces (BMIs) as the Actor-Networks after the Internet of Things

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Abstract

For the last few decades, actor-network theory has been usually criticized for its focus on Machiavellian human actors controlling the overall networking between other actors or blamed for its dissipation of human agencies within the global status of a network. However, at the moment of its development, the freshness of actor-network theory was more relevant to its focus on the meaning of what the hyphen signifies; not so much just a simple connection between two independent variables, but an ontological event itself, from which certain entities juxtaposed together become involved by exchanging stable influences each other thus settled down as the actors participating in a network being associated as the summing up of these settled influences. The aim of this paper is to refresh this bygone freshness of ANT from the recent development of the Internet of Things (IoT); which vividly exemplifies how a network and its actors are generated from a manifold technologically augmented entities—such as smart appliances in a house, migratory animals with RFID tags, and ensembles of neurons signaling beyond one’s brain through a bundle of microwires—each of which is physiologically or algorithmically adaptable to the environmental signals from other entities thus able to be settled down together into “new sensor/processor/actuator affiliations.” Brain-Machine Interface (BMI), developed by Nicolelis Lab at Duke University as a prototype of the future neuroprosthetics, shows a specific example of these networks of things; in which mutual adaptations of the technologically augmented entities—namely neurons and robot limbs—associate artificial sensory-motor circuits, programming its human/animal users’ possible motor behaviors as well as their motor intentions.

Keywords: Brain-Machine interface, Actor-network, Neuroprosthetics, Internet of Things, Nicolelis

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1. Introduction: ANT, IoT, and BMI

The popularization of the word ‘network’ in social theories has been in some ways paralleled with the emergence of World Wide Web and its settlement as a communicational infrastructure in 1990s. For actor-network theorists who have advertised their network concept as “series of transformations—translations, transductions—which could not be captured by any of the traditional terms of social theory,” the emergence of the Internet as human actors’ means for “transport without deformation, an instantaneous, unmediated access to every piece of information” however looked one of the reasons for the unintended transformation of their sociological method into a theoretical readymade (Latour, 1999: 15). In “On recalling ANT,” Bruno Latour shifts blame for the critiques of “managerial, engineering, Machiavellian, demiurgic character of ANT” on the single terms “actor” and “network” separated by a hyphen; the first is, according to him, responsible for making applications of the theory focus exclusively on how strong “male-like” actors mobilizes their wider accessibility to the network to fulfill thier interests, whereas the second is attacked for “its apparent dissolution of independent actors with morality and intentions in a ‘play of forces’ in which no change through human intervention seems possible.” (Gad, 2010: 61) At the moment of the ANT in the making, the “freshness” of the network concept was however relevant to its requirement to interpret the hyphen not as an epistemological limit of a subject situated in a node of networks by pre-given protocols of infrastructure, but as an ontological entity in itself, called “translation,” not so much considered a
byproduct of actor’s interaction with networks, but more properly describable as what Karen Bard calls “intra-action” from which both networks and their actors generate (Barad, 2003).

It is interesting that, in the same year, 1999, when Latour asked to recall this freshness of ANT in its early times, another technological infrastructure, called the Internet of Things (IoT) was announced as what would refresh this communicational network and generate more intra-actions from there. For the last decade, the wide distribution of RFID tags and micro sensor technologies into our urban and ecological environments has changed the whole information economy of the Internet; as Kevin Ashton, an official namer of IoT says, the network has changed from that “almost wholly dependent on human beings” and their “limited time, attention and accuracy” of consciousness for the resources of information to the economy relying more on geographically distributed small artifacts which generate information about their status and environments autonomously (Ashton, 2009, Jun. 22). Throughout its evolution, the ubiquitous computing of IoT have integrated not only smart appliances such as toasters, refrigerators, and smartphones as its actors but also animal bodies and human organs whose territorial/migratory behaviors and physiological patterns become trackable by being combined with “new sensor/processor/actuator affiliations” of microelectromechanical systems (MEMS), often called “smart dust.” Insofar as their integration into the new networks of things has been concretized through each thing’s stabilization of its own sensori-actuator responses to the environments based on these organisms/processors’ “adaptive learning” at the micro-scale, the protocols of their networks are no longer relevant to “any pre-programmed definitions or specifications” but understood as the accumulated effects of intra-actions, in which correlations of manifold sensori-actuator responses of things are settled down so that the things emerge at last as actors of the
networks (Cradall, 2010: 83-84; Gabrys, 2016a). “Thingification,” that has happened to the entities in our urban and ecological environments to translate/transduct them into the “things” within technologically augmented sensori-actuator circuits, is therefore far from “turning of relations into ‘things,’ ‘entities,’ ‘relata’” as Barad means by this term (Barad, 2003: 812). Conversely, it is to refresh things/animals/humans’ relation-making processes with environmental entities by dislocating them temporarily from specific habituated contexts, such as the laws of nature, migratory/territorial patterns, physiological circulations, behavioral economies, in which their casual relations with other entities are ossified as inherent properties of subjects/objects.

Networks, hitherto territorialized as a means of people-to-people communications, are re-thingified as the assemblages of micromechanical, physiological, and zoological sensor-processor-actuators, whose interoperability should be negotiated through adaptive learning at the level below the “limited time, attention and accuracy” of human conscious. Networks are refreshed once again, as Latour recalls, by the emergence of “circulating entities” neither messengers of micro-individual nor structured by macro-social; conversely, structures in networks are just “local totalities” settled down by the summing up of intra-actions through those entities generating correlations, as much as “becoming an actor is a local achievement” of relations with neighbors (Latour, 1999: 18). Inasmuch as thingification appeared first as “an industry strategy that is meant to expand the reach, capacities, and economic growth of the Internet,” the refreshed adaptability of things to environments has been also mobilized as resources for the industrial expansion of the networks (Gabrys, 2016b: 181). From these emerging technoscientific networks of things after World Wide Web or ANT, we could expect the
actor-network theory to be renewed as “a theory of the space or fluids circulating in a non-modern situation,” where “subjectivity, corporeality, is no more a property of humans, of individuals, of intentional subjects, than being an outside reality is a property of nature.” (Latour, 1999: 22-23)

Brain-Machine Interface (BMI), a specific case of networks of things that this study analyzes, has been developed by Duke University Center for Neuroengineering as a prototype for future neuroprosthetic device under the leadership of professor Miguel Nicolelis since 2000, and succeeded its human application in the public demonstration at the opening ceremony of 2014 FIFA World Cup Brazil. Compared to other cases of IoT based on geographically distributed cloud computing such as that of smart cities and ecological field studies (Gabrys, 2016a), the entities “re-thingified” by Nicolelis Lab’s BMIs are more densely interconnected human/animal neurons, biological/robotic limbs, and computers in a lab. But, they might be still properly described by the ‘cloud metaphor,’ in that what the BMIs generate through the re-thingification of those entities by implanting micromechanical sensor-actuators into them is a nebulae of relations, freed from hardwired habitual contexts of physiological interactions, thus not settled down into a stable network yet, but ready to be mobilized for temporal conduits of sensori-motor reactions between neurons and robot limbs through those things’ neuronal and algorithmic adaptations. This surplus of relations, aroused by “new sensor/processor/actuator affiliations” of things, is where the embodied spaces for animal/human subjects-users’ motor activities are re-concretized with robotic prosthetics. At the same time, the correlations between these neuronal sensors and robotic actuators in this cloud computing are, as Mark Hansen discusses regarding what he calls “twenty-first-century media,” processed “directly at the microtemporal level of
their operationality,” “independently of consciousness’s mediation,” and then “fed-forward” into users’ “(future or ‘just-to-come’) consciousness in ways that can influence consciousness’s own future agency in the world.” (Hansen, 2015: 52-53) In other words, human/animal users’ embodied perception and conscious agency over their artificial limbs appear in BMIs as network effects of mutual adaptations of small things, happened just some milliseconds of “missing time” before. This gap in processual time between the network of small entities and subjects’ embodiment within the network—questioning the location of human agents and their subjectification in the twenty-first-century media’s cloud of things—is what this study opens up with actor-network theory. As Steven Brown and Rose Capdevila say, re-situated within this missing time of “electronic networks,” actor-network theory functions as a tool to investigate “the space for subjectivity and what is left of ‘the human’” within networks after ANT (Brown & Capdevila, 1999: 45, 47).

The Missing Times
On June 12 2014, Juliano Pinto, a 29-year-old former athlete who lost the use of his legs after a car accident in 2006 was entering to the Corinthian Arena in Sao Paulo where the opening ceremony of the 2014 FIFA World Cup Brazil was going on. He was wearing an exoskeleton which looked “as if came from the ‘Iron Man’ movies” and accompanying with a number of laboratory staffs working for Nicolelis who supervised the development of the exoskeleton for the last two years with about fourteen million dollars of Brazilian governmental funding. After Pinto’s name was announced worldwide as the person who would kick off this global sports extravaganza, the exoskeleton took its historical first step on the ground as a consequence of
action potentials from Pinto’s motor neurons scanned real time by an electroencephalogram (EEG) cap he was wearing. As the foot of the exoskeleton touched the grass, tactile stimuli sensed by the artificial skins of the soles were fed back to his arm skins instead of his paralyzed feet; based on this tactile perception caused by a microtemporal interoperation of neurons-robot limbs-grasses happened some imperceptible milliseconds before, Pinto (or his motor cortex) could prepare his/its next move. After couple of steps, he finally succeeded kick off the official ball. All of those were done and broadcasted just in couple of seconds at the beginning of the ceremony, and immediately drowned out by the overwhelming spectacles of the media event.

For the last few months before the World Cup opening, Pinto needed to spend lots of hours with seven other volunteers to train his motor cortex to adjust to how a machine felt the closed environment of Nicolelis’s lab. During these training sessions, several hundreds of his motor neurons were re-thingified by the EEG cap into the entities extending their ambiguous action potentials even beyond his cranium. But, in order for his neurons to be eventually settled down along the artificial sensori-motor circuits with robot legs, another several tens of minutes were required for the control system of exoskeleton’s statistical adaptation to these neural signals. Nonetheless, this gap in time between experimental juxtaposition of things and their association of causal relations was, in accordance with customs of scientific publications and public demonstrations, marginalized into short sentences in “method” sections in papers and black-boxed into a laboratory, whose information about the project going on there and its experimentees-trainees in that was kept secret before the D-day.¹

¹ Since sixty nine days before the World Cup opening, a mysterious rectangular banner, literally looked a black-box, began to be posted to Nicolelis’s Facebook page. While the information about the participants and their trainings...
For Pinto’s motor cortex to be re-thingified into this network of things, the exoskeleton, initially developed by French scientists, should be first transported to Nicolelis’s laboratory in San Paulo; and then re-coordinated by an engineering professor from Munich to be ready for reactions to the neurons de-contextualized from Pinto’s conscious motor intentions (Sample, 2014, Apr. 1). However, even long before its transportation and re-coordination, how the neurons and robot limbs would achieve stable connections in a laboratory setup had had to be experimented by more than one hundred scientists from different institutions cooperating under the banner of a consortium named the Walk-Again Project. The diagram embedded within the exoskeleton to juxtapose molecular sensors with micromechanical actuators was therefore not so much drawn by a single scientist, but the result of years-long negotiations of a manifold interests from scientists, patients, governmental officials; who expected Nicolelis Lab’s BMIs to demonstrate the validity of their scientific hypotheses, showcase the recent achievement of their ‘national science,’ fulfill their desires to walk again, or to draw public attentions enough to justify the governmental investments in their projects.

Compared to these long hours required for the intra-laboratorial adaptation of things and inter-laboratorial cooperation of complicated interests, “Pinto’s few seconds of fame” did not look worth all of those costs. It was only for the short seconds of the very beginning of the...
opening ceremony that these neatly coordinated neurons and robot limbs were temporarily aligned with Pinto’s conscious motor intentions as well as the institutional actors’ interests to re-dispose those biological and mechanical entities to be interoperatable with broadcasting technologies which drew public attention over the world to a single media event. Nevertheless, this short exposure was sufficient for Nicolelis’ lab at least to mobilize some news outlets over the world as its allies; who were willing to complain, in favor of Nicolelis, that “the historic event” signifying “the beginning of a future in which people with paralysis will be able to leave the wheelchair and literally walk again” was not given the attention “it deserved during the opening ceremony.” (Boyle, 2014, Jun. 12; Martins & Rincon, 2014, Jun. 12)

From this specific case of a flickering constellation of things, we can see the missing time in our question appearing as a threefold phenomenon. Besides the milliseconds of imperceptible gap between the neuronal/micromechanical sensor-actuators’ “prehension” of other entities and Pinto’s “deferred or after-the-fact experience of technically gathered sensory data” concerning his own efficacy over the digitally augmented environments, that Mark Hansen considers what characterizes the twenty-first-century media’s feed-forward of “worldly sensibility” from the networks of things towards human subjects (Hansen, 2015: 192), two other operations in much longer-terms were necessary to engineer a subject’s phenomenological experience of the gap; the first involved how the scientific, governmental, and individual interests were translated into a specific disposition of things inside a lab; the second involved how the neurons and robotic limbs were trained to adapt each other to associate an actual sensory-motor network of things. And those gaps in time black-boxed behind the “missing times” as worldly phenomena becoming prevalent in the twenty-first-century media’s re-thingification
of human brains are what this study would open up with the actor-network concept.

For this purpose, this paper examines news articles and Nicolelis lab’s scholarly publications about its BMIs since 2000 when these early twenty-first-century media’s human uses as robotic prosthetics began to be experimented within a specific arrangement of monkeys’ motor neurons, computer algorithms, and robot limbs; and then sees how those things’ adaptability to others has been mobilized by the scientists to associate a closed-loop of neuronal/mechanical sensor-actuators inside their lab, which have not only demonstrated the validity of the lab’s scientific principles but also promised to fulfill the complicated social and individual desires for “Walking Again” revealed through this loop’s later embedment within Pinto’s exoskeleton. However, before moving on the actual examination, it needs to be clarified in the next section the meanings of actors, networks, and their hyphenated conjunction used in this paper.

2. Some ontological implications of actor-network

The concept of actor-network seems to imply a paradox which should be settled before its application to an existing science lab given the hyphen connecting two seemingly incompatible theoretical variables, which Latour blames for ANT’s paradoxical fixation on either a strong single node or elusive global states (Latour, 1999). First there are actors whose existence and behaviors in the lab’s physical and social environments are supposed to be localized; at the same time, a network is understood as a global state hardly representable by a mere sum of these local actors. In order to resolve this controversy, we usually rely on the so-called ‘relational definition’ which the hyphen signifies; an actor can be defined only by how it is in the relation making with
others, whereas a network describes not so much the connections between independent actors but those relations in the making; the independent appearance of each actor is thus just effected by the accumulation of those relations in the constant making upon a node. However, this convenient definition also imply a problem when it easily inclines to dissipate the analytical usefulness of the term ‘actor’ in its rhetorical over-uses of the term network applicable to any haphazard relations, hardly stabilized thus not able to be identified as theoretical variables. Therefore, we should be careful to use the concept of actor-network with regard to certain detectable and patternizable relations between certain entities, but only in a way which does not reduce any haphazard relations simply to the background of a system being studied. There are some ontological implications involving this problem of defining an actor-network.

First, actors are not independent entities presupposed by a theory to explain the construction of a network from its atomic elements. Rather, actors are “those entities that exert detectable influence on others” including an observer (Law, 2012: 126), so that their existence is empirically inferred from concurrent influences by this observer and nonhuman others who “are also able to propose their own theories of action to explain” how the causes of these immediate influences they feel could be imputed to some distanced actors (Latour, 2005: 57). A network in this sense is involved only secondarily with its actors. Primarily, it describes the global state of influences, the sources and destinations of which are localizable into its nodes just as the consequence of an observer’s accumulated observations. An actor-network is therefore when certain entities juxtaposed together begin to exchange influences in a way sustainable for a long term, so that they are enrolled as “heterogeneous but mutually sustaining elements” of a system (Law, 2012: 115). In other words, an actor-network, like an internet of things, appears to an
observer as a hindsight phenomenon after some missing times spent by those entities to stabilize their interactions with others in sustainable ways (or to re-thingify themselves into the elements of IoT). However, this does not necessarily mean that only certain entities wielding detectable influences towards the association of a network could be defined as actors. On the other hand, we could suppose the existences of some other entities which might dissociate from the network under observation as the result of their preference to associate with “other actors in the environment in the course of the inevitable struggles.” As John Law says, the features of these others, constantly associating invisible networks conflicting with an artificial network of things “being built by people” such as a laboratory, are often branded as the “obduracy” of Nature (Law, 2012: 124). Missing times are therefore not just about association and stabilization, but about struggling and switching between networks.

According to this explanation, we can assume that there were some neurons in Pinto’s motor cortex not firing towards the exoskeleton during the demo because they were more strongly associated with other kinds of neuronal sub-networks relevant to the behaviors other than kicking off and to the stimuli other than tactility, despite EEG cap’s re-thingification of the neurons to switch their enrollments from the previous neuronal systems to another algorithmic system. Insofar as their denial to fire meant their obduracy in being associated with other sub-networks of Pinto’s brain, the actor-network in the World Cup demo did not operate just in an anonymous and undifferentiated environment; rather there might be many struggling networks, which denied to send detectable signals to the observers, who were also obdurate in their enrollment to a laboratory system through the mediation of sorting algorithms and broadcasting media. In this sense, actor-network theory does not presuppose a rigid dichotomy between
systems and their environments as long as their figure-ground relation is always switchable as an observer could move to different systems.

Second, a successful operation of a science laboratory as an actor-network thus depends not only upon the scientists’ decision how to dispose those entities, but upon the entities’ ability to fill the gaps within their disposition to associate an actual network. In this sense, scientists’ role is describable more properly as “juxtapositions” rather than “associations.” According to Michel Callon, “it is from these juxtapositions that the associations draw their coherence, consistency, and structure of relationships that exists between the components that comprise it.” (Callon, 2012: 89) In a laboratory setup, this coherence in relationships which those components associate is supposed to be the evidence demonstrating the scientific statements hypothesized; but more importantly, their juxtaposition should be first a proper spatial translation or diagrammatization of the rules of statements which define valid types of variables and restrict their possible interactions. Therefore, if something is expected to be justified through the experimental period deferred to be intervened by experimenters until the spatial gaps in an abstract diagram are fleshed out with actual connections associated by those entities (like a questionnaire whose juxtaposition of brackets is ready to be filled by participants’ coherent answers), it would be rather the validity of theoretical variables and experimental parameters as well as their communicational protocols which Nicolelis Lab’s “principles of neural ensemble physiology” exemplifies (Lebedev & Nicolelis, 2009). And as much as this deferred period is claimed to be concretized by the things themselves enrolled as actors of a network in the making without any intervention of scientists, the artificial disposition of things is eventually asserted as an experimental mirror of natural phenomena.
Although it was just for a few marginal seconds of the opening ceremony, 2014’s world cup demo was for Nicolelis Lab to show off that the ensembles of neurons, which they had trained to be re-thingified into the artificial sensory-motor circuits with robot limbs inside the lab for the last decade, could achieve a closed-loop of coherent relations even with an exoskeleton operating in a more natural environment. However, what the exoskeleton’s unnatural-looking movements in the stadium signified was not so much a network of things as a diagram translating natural phenomena within a laboratorial setup, but the shift of the place for the phenomena namely ‘physiological adaptations of neural ensembles’ to be simulated to the more opened and natural environments beyond both a laboratory and physiological boundaries of one’s body (Lebedev & Nicolelis, 2009: 534). And what the disposition of things within the exoskeleton diagrammatized were not just the lab’s scientific principles any longer; but the gaps in this diagram should be filled by the mutual adaptations of neurons and robots in order to make it a diagram for the complicated social desires of walking again as well.

In the rest sections of this paper, we will see how those gaps were juxtaposed along a feedback loop between animal brains and robot limbs in a lab first as a diagram of the lab’s scientific principles; how this network of things inside was supposed to draw a “positive feedback” with the social interests in BMIs’ possible uses as future neuroprosthetics outside (Latour, 1987); and how human and animal subjects were embodied within those gaps engineered by a technoscientific project, after certain hours of missing times.

3. A General Description of BMIs

Since Nicolelis designed his first BMI with a rat as a postdoctoral researcher in Hahnemanne
University in 1993, Nicolelis Lab’s BMIs have evolved through several different types varied in the species of animal subjects, numbers of neurons scanned by a computer, methods of scanning, types of motor functions simulated by machines, and pattern-recognition algorithms used for the prediction. However, it was after 2000’s version with an owl monkey named Belle, when the lab’s BMIs began to be discussed in relation to the future “neuroprosthetic device” which “could be used to restore basic motor functions in patients suffering from severe body paralysis.” (Nicolelis, 2003: 417)

Figure 1. A prototypical description of a BMI (Nicolelis, 2003)

According to the above figure Nicolelis provided in his Nature article in 2003, a general configuration of BMI is described as a network consisting of three ‘major’ actors. First, there is a monkey wearing a head-mounted device, consisting of one hundred of “Teflon-coated stainless-steel microwires” chronically implanted in the neurons in several regions of her motor cortex to re-thingify each neuron into an entity within an artificial network in the making beyond her cranium; she is located in front of a monitor and asked to operate a fake joystick with her right
hand to win the game and drink a sip of fruit juice as a reward. Second, along the parallel
distribution of neurons and microwires firing simultaneously, a series of a data acquisition
hardware called “Harvey Box” and computers with custom real-time pattern recognition
algorithms—linear and artificial neural network (ANN) algorithms—is juxtaposed; this series
can not only “properly sample, filter and amplify neural signals from many electrodes” evenly
distributed upon a subject’s motor cortex but also integrate the action potentials from
simultaneously recorded neurons every 50 to 100 milliseconds. Finally, there is a robot arm
operating a real joystick according to the serialized instruction from the computer; the joystick’s
movements and the robot’s grip forces are fed back in parallel to the cursor’s movement on the
visual field of the monitor and “small vibromechanical elements attached to the animal’s arm.”
(Nicolelis, 2003: 419)

During the monkey’s operation of the joystick (to the left or right), her arm is also re-
thingified by the “infrared markers” attached to each joint, which make her arm movements
measurable in terms of “motor parameters (such as arm position and velocity, or hand gripping
force)” used as a target for the pattern-recognition algorithms. Meanwhile, Harvey Box
calculates a certain linear integration of neural signals transmitted by microwiers, matched best
to the pattern of arm movements, also linearized as a sum of motor parameters. Based on this
reproduced patterns of “subject’s voluntary motor intentions,” the computer operates the robot
arm to win the game instead of the monkey so that she could get a reward (Lebedev & Nicolelis,
2009: 531). As the information describing the robot arm’s performance is “relayed back to the
animal” in a form of visual and tactile feedback delivered to the monkey’s perception, “a closed-
loop control BMI” is eventually completed within three parallel-serial junctures (Nicolelis, 2003:
in the first, the monkey’s interest in the sweet beverage is translated into stormy paralleled signals, and then sent to Harvey Box; in the second, the neural signals are integrated into a linear model to be compared with the monkey’s arm movements, and then sent to the robot arm as an instruction for its performance to imitate a biological arm; in the third juncture, the robot’s linear movements are translated into the “proprioceptive feedback” given to a manifold of visual and tactile receptors; and, based on this microtemporal alignment of neurons and robot which happened milliseconds before, the monkey prepare her next move. Between juxtaposition of the entities and association of an actor-network, these parallel-serial junctures (between motor neurons and the monkey’s arm movements, microwires and Harvey Box, the matrix of pixels and vibromechnical elements and the monkey’s integration of them into proprioception) appear as the gaps across which the entities facing each other are expected to exchange coherent relations within an missing time endurable for observers.

4. Defining Actors

Even though I simply defined the three ‘major’ actors in the previous section, it should be noted that they did not so much exist as independent even before the actual association of a network called BMI, but appear as actors only when they succeed to mobilize the paralleled many in the juncture into their linearized action upon other entities. John Law defines an actor and its agency as “an effect generated by a network of heterogeneous, interacting, materials.” (Law, 1992: 383) Even though this relational definition prevents us from localizing the agencies of a network into a small number of enclosed entities or nodes, the necessity of certain conduits—through which the influences from manifold actors circulate in recurrent and coherent ways—requires us to
assume that the agencies of the network is unequally distributed among the entities in relation making. In the above description of parallel-serial junctures, this inequality appears in terms of how many effects of neighbored nodes each actor could mobilize for its action to others, as a single actor at the serial pole integrates the simultaneous effects of the many in the parallel pole and transmit their linear sum to the network. In Latour’s terminology, this function of junctures to integrate and transmit the many is called translation, meaning a way in which scientists and experimental instruments represent the heterogeneous behaviors of voiceless actors in a form of graphical or mathematical inscriptions and mobilize them as the ‘resources’ to fulfill her/his/its own interest (Latour, 1987). In other words, these ‘major’ actors have more agency because they could be the representatives of voiceless others latent in the network.

Based on this understanding of actors, we can define the monkey as one of major actors insofar as she could translate the interests of manifold single neurons into her interest in a drop of juice and represent their “neuronal ‘vote’” of action potentials in her highly trained and integrative skill to control a fake joystick to right or left (Nicolelis, 2001: 404). On the other hand, Harvey Box and computers appear another major actors when they translates the “activation of large distributed populations of neurons” into their algorithms (Nicolelis, 2001: 404), “inscribed with certain interests” of the researchers who tried to vindicate their principles of neurophysiology through these algorithms (Johnson et al., 2014: 17). The robot arm becomes an actor when its design represents the researchers’ interest to restrict the monkey’s arm.

2 It seems noteworthy how conscious and careful Nicolelis is in his book Beyond Boundaries to describes one of the monkeys (named Aurora) in his experiments as highly sophisticated beings who were willing to cooperate with his project rather than just laboratory animals (Nicolelis, 2011b).
movements to a limited number of motor parameters and it translates the result of the computers’ prediction not only into its operation of a joystick but also into the visual and tactile stimuli fed back to the monkey to make her more addicted to the game and her arm movements more fit to the design of a robot arm.

However, it should be noted that, even for the observers in the lab, these actors are identifiable only in hindsight after passing “a few nerve-racking, nail-biting, soul-searching moments,” in which their dissimilar and conflicting interests need, behind the peaceful appearance of “nothing out of the ordinary happened,” to be negotiated and properly re-aligned within the parallel-serial junctures so that their relations of mutual mobilizations were stably measurable (Nicolelis, 2011b: 144).

In this sense, the “long-term training” required for both the monkey and computers to associate a closed-loop through their mutual adaptation was also necessary for the actor-network’s attainment to “a favourable balance of power,” by which Michel Callon means a state in which all “the concerned actors” (not only a monkey but also one hundred of voiceless neurons in this case) are eventually lured to be enrolled to the researchers’ project (Callon, 1986: 10). During the repeated trials, some of microwires became more strongly enrolled to the sorting algorithm of Harvey Box while some other unfavorable ones were detached from the juncture and sunken to the background of the loop as the monkey learned how to mobilize her motor neurons relevant to the motor parameters restricted by the design of joysticks, and inscribed by computers. From 2001’s prototype to 2014’s human application, this favorable balance was promoted in the news articles and the lab’s publications as one of the most important achievements of their BMIs, asserted to be genuinely done by “monkey’s thought”, “only her
brain activity” and the “Mind-controlled exoskeleton” (Blakeslee, 2008, Jan. 15; Smith, 2014, Jun. 13); or by “physiological adaptations at the level of neural ensembles”, “ability of cortical ensembles to adapt to represent novel external actuators”, “adaptive algorithms that continuously update the model parameters while the subject trains,” rather than being engineered within a disposition of things artificially diagrammatized (Lebedev & Nicolelis, 2009: 534; Lebedev & Nicolelis, 2006: 541; Lebedev et al., 2011: 30). The balance was, in this closed-loop, supposed to be automatically kept as “Brain cells that ceased to influence the predictions significantly were dropped from the model, and those that became better predictors were added,” as the result of the mutual adaptation between actors (Nicolelis & Chapin, 2008). While the three nonhuman actors were foregrounded in the lab’s public presentations, scientists’ managerial roles to maintain the loop were kept in the background with other neurons which disagreed to be enrolled to the network any longer.

5. A Closed-Loop or Favorable Balance of Power

The balance looked ‘naturally’ achieved “between the brain and artificial devices” is definitely necessary for the BMI’s potential use as a prosthetic because it “will probably help patients learn how to operate BMIs” without engineers’ recurrent intervention for their calibration to one’s brain (Nicolelis, 2001). When it comes to the BMIs’ function as an experimental instrument for a scientific project, the closed-loop is also important as a means to demonstrate the internal validity of the lab’s scientific principles (Cicurel & Nicolelis, 2015: Ch1). At a superficial level, the algorithmic predictions of the monkey’s behaviors from the randomly sampled neurons could be used as the evidence to show that the lab’s principles of “distributed coding”, “neuronal mass
effect”, and the “plasticity” are valid in the given cortical areas and motor parameters (See table 1). If a closed-loop is associated within a limited number of actors and sustained for a long-term so that the exchange of influences between all the relevant actors could be black-boxed into “a unified whole” (Latour, 1987: 131), the lab’s principles would be true in the given cortical areas and motor functions.

However, in the actual development of the BMIs, this prototypical closed-loop has been significant for the opposite reason to its possibility to be black-boxed; because the loop was also revealed to have an enough plasticity allowing the diagram a little latitude to reopen a temporally formed black-box and juxtapose new experimental parameters along the already stabilized loop in order to expand the range of the validity of the principles which the diagram represents within its disposition of things. Once the network reached to a state of autonomy, the scientists could manipulate “the feedback information that the animal receives” and “the kinematic properties of the motor actuator (robot arm)” to the extent that these newly introduced changes were endurable to the actors’ adaptability (Nicolelis, 2003: 419). They could also observe whether the actors would keep enrolled to their project even if they changed the location and size of cortical areas from which a population of neurons would be randomly sampled (for instance from the primary motor cortex to posterior parietal cortex in order to demonstrate the “neural degeneracy principle”), or added some new motor parameters such three dimensional arm movements (to demonstrate the “neuronal multitasking principle”). In other words, after the closed-loop was achieved, the diagram obtained more strategic advantages in its negotiation with actors, even though every new negotiation required a few hours or days of training.
Table 1. Principles of neural ensemble physiology (Lebedev & Nicolelis, 2009)

<table>
<thead>
<tr>
<th>Principle</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distributed coding</td>
<td>The representation of any behavioral parameter is distributed across many brain areas</td>
</tr>
<tr>
<td>Single-neuron insufficiency</td>
<td>Single neurons are limited in encoding a given parameter</td>
</tr>
<tr>
<td>Multitasking</td>
<td>A single neuron is informative of several behavioral parameters</td>
</tr>
<tr>
<td>Mass effect principle</td>
<td>A certain number of neurons in a population is needed for their information capacity to stabilize at a sufficiently high value</td>
</tr>
<tr>
<td>Degeneracy principle</td>
<td>The same behavior can be produced by different neuronal assemblies</td>
</tr>
<tr>
<td>Plasticity</td>
<td>Neural ensemble function is crucially dependent on the capacity to plastically adapt to new behavioral tasks</td>
</tr>
<tr>
<td>Conservation of firing</td>
<td>The overall firing rates of an ensemble stay constant during the learning of a task</td>
</tr>
<tr>
<td>Context principle</td>
<td>The sensor responses of neural ensembles change according to the context of the stimulus</td>
</tr>
</tbody>
</table>

To the extent that the additions or deletions of experimental parameters are sufficiently contiguous to other parameters already integrated in the network and this contiguity makes the actors more adaptable to the changes, the lab’s principles could be vindicated farther to the various cortical areas relevant to the more motor functions integrated into the research. Within the limits of the actors’ adaptability and the neural population’s “experience dependent plasticity,” many endurable changes have been juxtaposed upon the closed-loop in subsequent experiments. Consequently, the inner network of Nicolelis Lab has been densificated in terms of the number of voiceless actors, re-thingified by “Teflon-coated microwires,” “wireless electrodes,” and “EEG devices” which made their action potentials farther beyond a monkey’s restricted cortical areas to generalize the lab’s principles towards more unrestricted settings.

Even though many single neurons once enrolled to the loop were also dropped from the junctures as the BMIs evolved into many different forms with different experimental parameters,
those detached were however never left simply to the unfavorable environment after the first prototypical loop was achieved. Conversely, insofar as they remained still associated with other latent networks, not detectable in current observations, but already catalogued in computer data and publications, these neurons could function as a sort of reserve army of networks, ready to be re-mobilized anytime soon. Throughout the loop’s expansion, the “complexity” of many paralleled sub-networks of a brain, supposed to “simultaneously embrace a multitude objects,” has been inscribed in a form of what Shirley Strum and Bruno Latour call “complications” meaning the sum of linear translations of paralleled complexities, as each sub-network once integrated to the BMI has been archived as “a succession of simple operations” translated into an algorithmic model. Responding to the unfavorable environments of a multitude of struggling networks, the “greater stability” of the BMIs was acquired not just within the actors whose firings were encoded into the loop currently sustaining, but “only with additional resources; something besides what is encoded” right now; namely the compilations of neurons left to the data as the BMI moved across different regions of primate brains and motor functions (Strum & Latour, 1999: 119-120).

6. Closing the loop to become beyond boundaries

Just after the first BMI with a primate brain in 2000 succeeded to predict and imitate how Belle, an owl monkey, “intended to move their natural arms,” what Nicolelis Lab set to work was a new BMI to replicate their previous success with the three macaque monkeys whose “brains contain deep furrows and convolutions that resemble those of the human brain.” (Nicolelis & Chapin, 2008) It was with these more human like primates that the lab’s BMI eventually completed the
visual and tactile feedback between the monkey and robot arm depicted in the above prototype. Once the favorable balance of influences was formed along the arrangement of neurons, computers, motor parameters, and the robot, a change the scientists first made within the range of the loop’s plasticity was the removal of the fake joystick hitherto held by the right hand of Aurora, “an elegant female” macaque monkey. By doing this symbolic action to forfeit a primate’s bodily extension to fulfill her interest in fruit juice, they expected she would restore her previous influences over the population of neurons soon to mobilize their firing for her desire for the reward, but without moving her hands this time;

After being puzzled, Aurora gradually altered her strategy. Although she continued to make hand movements, after a few days she learned she could control the cursor 100 percent of the time with her brain alone. In a few trials each day during the ensuing weeks Aurora did not even bother to move her hand; she moved the cursor by just thinking about the trajectory it should take (Nicolelis & Chapin, 2008).

According to Nicolelis, this success with the “wired-up brains” meant much more than what it offered to these Old World monkeys namely “out-of-body experiences” in a lab. Promoting the monkeys’ closeness to their human relatives and similar behavioral condition with human patients, the actor-network wired inside began to be claimed to supposedly represent the interests of humans outside; not only who aim to renew “hope of restoring mobility to people who are paralysed,” but also try to develop “the conduit through which our brains control all our tools, to extend our reach, presence and communication with the universe.” (Nicolelis, 2011a) As Nicolelis said in the interview with the Washington Post, in order to mobilize “enough political will and investment” for his project, the lab had “to galvanize people’s imagination” about the
BMIs’ expandability and applicability (Powel, 2013, May 6).

In closing this loop between a brain and a virtual body using BMI technology, we now know the primate brain can operate beyond the boundaries and physical constraints of its body and interact with any world presented to it (Nicolelis, 2011a).

Here the target happens to be a robot. It could be a crane. Or any tool of any size or magnitude. The body does not have a monopoly for enacting the desires of the brain (Blakeslee, 2008, Jan. 15).

Even though this alleged potential of BMIs to close the loop with various motor apparatuses such as a crane was told as the condition for their network to be free from the physical constraints of the lab and bodily boundaries of these experimental animals, this meant conversely the fact that, for the loop to become beyond these boundaries, it should be constantly re-opened to accommodate new experimental parameters to translate more outside human interests in the possible uses of BMIs into its experimental protocols. Its favorable balance of influences needed to be renegotiated in every new training session for the actors’ re-adaptation. Throughout the lab’s publications, the BMI’s performance has been therefore measured in terms of how intactly it’s diagram could enclose more complex motor parameters and different types of robots into its autonomous loop; on the flipside, this possibility to enclose a variety of motor functions is, in Nicolelis’ recent book The Relativistic Brain, discussed as the BMI’s possibility as “a biologically-inspired hypercomputer” functioning like a biological version of universal Turing machine potentially capable to control every “artificial, real or virtual actuator.” (Cicurel & Nicolelis, 2015: Ch7) Whereas this possibility of BMIs to wield their action potentials beyond boundaries of biological bodies and experimental setting is explained as “what a naturally
evolved brain can produce” with its “self-adaptable (i.e. plastic) elements,” it was still marginalized the questions of what happened to Aurora and other unnamed macaque monkeys for “a few nerve-racking, nail-biting, soul-searching moments” of missing times in which they might feel not only just “being puzzled” but disabled and unable to translate their interests in juice into action potentials reachable to the robot; how the voiceless neurons dissociated from the loop or associating new connections during these soul-searching moments deferred to be investigated by the scientists were indeed disposed to do so according to an invisible diagram, spatially translating the lab’s scientific principles as well as complicated interests in the possible uses of BMIs; and what kind of “special care was taken to keep experimental conditions controlled and restricted to specific task requirements,” in other words, to keep those actors intact even in this artificial disposition of things (Kim et al., 2006: 159). So long as these invisible actors’ indirect interventions during the training sessions were dropped from their publications, the closed-loop was more easily black-boxed as the natural progress of a system.
Figure 2. Janus’ dicta in *Science in Action* (Latour, 1987)

However, when we shift our focus to the inside of these “nerve-racking” hours in which the gaps within the disposition should be filled by the physiological and algorithmic adaptations of things, what looked natural before appears problematic again. As Latour says through the voices of his Janus in *Science in Action* whose faces represent two different perspectives on science (one from the outside seeing science as a readymade product, another from the inside where it is in the making) (Figure 3), we can say that the so-called ‘natural’ progress of neural ensembles—which the lab promoted as “the cause that allowed controversies to be settled”
within the parallel-serial junctures and made the relevant actors evolve into an autonomous loop—was, in this moment of network making, revealed as “the consequence of the settlement” between conflicting neurons along a diagram consciously engineered as a spatial abstraction of the lab’s principles. Whereas the BMI as “Ready Made Science” expanded its influences upon the public by convincing people outside with the future this naturally-inspired hypercomputer promised, the BMI in the making only began to “work when all the relevant” actors—neurons, computers, and robot limbs—were convinced by the diagrams’ re-distribution of their biologically or algorithmically programmed interests along the loop. From this perspective of the network in the making, the lab’s principles of neural ensemble physiology—supposed to mirror the natural phenomena which the technology should imitate—are no longer “the cause that allows projects to be carried out,” but what need to be naturalized by an experimental setting’s inner densification (in terms of the number of relevant actors enrolled to a closed-loop) and outer expansion (in terms of a variety of social and individual interests in “Walk-Again” which the lab’s BMIs promise to fulfill). In other words, these scientific principles function as the behind force of the project not as natural causes newly discovered, but as a diagram which re-disposes a variety of actors both in the lab’s physical and social environments along the ontology it draws (Latour, 1987: 10, 99, 175).

From this gap between the opposite sides of Janus representing the missing time between the microtemporal operations of the small things’ mutual adaptations and human/animal users’ perception of them as their means for bodily extensions, we can also see the experimental subjects appearing as ambivalent figures; whereas Pinto was introduced in the World Cup demo as a readymade subject, already trained to know how to control and exploit those small things’
network making to fulfill his desires to become beyond the boundaries of his handicapped body, the monkey’s perceptual consciousness and motor intentions in the lab appear restricted by a specific disposition of things, whose settlement as the artificial sensory-motor circuits determines the ranges of possible perceptual stimuli and motor cortical responses of the monkey’s brain, within which her desires for the juice would be embodied after several milliseconds of the missing time.

Insomuch as it was necessary for the lab’s financial and institutional sustainability to diagrammatize BMIs’ possible uses and users’ possible desires into a disposition of things inside, what Donald MacKenzie once said regarding the role of scientists as system builders is also true for the operation of the diagram as an abstraction of the lab’s scientific principles in our specific case of a network of things;

No laboratory development is ultimately self-sufficient. If the environment is not right or is not made right by the system builders, any line of laboratory development will lack external influence and may indeed cease altogether. (MacKenzie, 2012: 208)

7. Expansion of a Network and Mobilization of Interests
Since Nicolelis Lab’s BMI reached to its first closed-loop with Aurora in 2001, the loop has been constantly reopened to experiment the range of its plasticity and adaptability to accommodate more actors and experimental parameters. While the number of neurons connected to the loop has been increased from about 100 to 800; the simple task of controlling a joystick towards left or right has been substituted by three dimensional reaching and grasping task (Carmena et al.,
2003), walking on a treadmill (Fitzsimmons et al., 2009), and bimanual arm movements (Ifft et al., 2013). While the motor parameter scanned from infrared markers upon animals’ body has been more complicated from the triad of hand position, velocity, and gripping force with smaller degrees of freedom to the simultaneous muscle activities of biceps, triceps, deltoid, extensor digitorum measured by the surface electromyographic (EMG) (Santucci et al., 2005), to “Muscle Geometry” consisting of “the insertion point, origin point, and line of action of each muscle group” adapted from the field of biomechanics (Kim et al., 2007), and to the “walking parameters” such as step time, step length, foot location, and leg orientation (Fitzsimmons et al., 2009); the prosthetics operated by brains have been also changed from a robot arm, locomotion apparatuses of a humanoid robot (Nicolelis & Chapin, 2008), and “a realistic, virtual monkey avatar.” (Ifft et al., 2013) While the physical range of the closed-loop has been extended from a bipartite laboratory room in North Carolina, the partitioned areas of which separated a monkey from the robot arm, to a laboratory in Kyoto whose humanoid robot was connected to the monkey’s brain in North Carolina through a high-speed internet link “literally expanding that primate’s brain reach to the other side of the earth” (Nicolelis & Chapin, 2008); the physical medium implanted to the brain for its extension to the machine has been also renovated not only to send signals to the computers wirelessly (Schwarz et al., 2014), but also to receive the proprioceptive feedbacks from robotic prosthetics immediately in a form of intracortical microstimulation (ICMS) without passing the sense receptors on the skin’s biological boundaries (Brain-Machine-Brain Interface, BMBI) (O’Doherty et al., 2009). Throughout these experimentations of the BMIs’ adaptability to other ready-made apparatuses, such as treadmill, humanoid robot, EMG, Muscle Geometry, and noninvasive EEG used in the World Cup Demo, it
has been also experimented upon the loop which types of algorithms—from the linear, such as Wiener filter, LMS adaptive filters, gamma filter, subspace Wiener filters, to the nonlinear, such as time-delay neural network, local linear switching models, and finally Unscented Kalman Filter—would be the most optimal in its mathematical modeling of the cortical complexity (Kim et al., 2006; Li et al., 2009).

In more recent research, Nicolelis Lab juxtaposed three monkey brains along the one virtual avatar monkey to experiment the possibility of Brain to Brain Interfaces (BtBIs), and reported that, after “several weeks of training,” the three monkeys and one avatar eventually associated an organic computing device which they named Brainet, “a self-adapting computation architecture capable of achieving a common behavioural goal” such as three-dimensional reaching and grasping task (Ramakrishnan et al., 2015: 10; Pais-Vieira, 2015). In this setup, each monkey was seated in a separate room facing a computer monitor showing only a two-dimensional projection of the avatar and target in three-dimensional space from an X-Y, Y-Z, or X-Z reference frame, and trained to control the avatar’s movement just in a two-dimensional plane (Figure 3). In order for a Brainet to work for a common goal defined in three-dimensional virtual reality, all the relevant monkeys, whose reality was artificially shrunken to a two-dimensional computer monitor, had to be, as the right side of Janus says, convinced by what this closed-loop of a shared BMI promised to them as the reward for their collaboration, namely a fruit juice. Insofar as the scientists asserted that this “shared BMI allowed multiple monkey brains to adapt in an unsupervised manner,” all the relevant neurons’ enrolment to this common goal seemed to be a natural progress of their plasticity and adaptability, rather than the consequence of the operation of an abstract diagram to separate three brains in order to juxtapose
their cognitive production along a Taylorist-like coordinate system. So long as this brain network could be black-boxed into a convenient term “self-adapting computation architecture,” more relevant actors outside would be convinced by its operation and agree to form the social extensions of this neuronal network (Ramakrishnan et al., 2015: 10).

Throughout the evolution of the BMIs, the scientists’ selection of experimental entities to be included in the loop has been therefore directly related to the loop’s expansion towards the bigger neuronal, geographical, interdisciplinary, and industrial networks. Whenever those entities were chosen as possible contributors for the lab’s expansion, the publications described them in relation to their possible representativeness of human interests outside. From rats as an umbrella species for the whole upper vertebrates to New World (such as owl monkeys) and Old World Monkeys (such as macaque monkeys) and to human patients, the subjects of experiments have
been chosen with regard to how similar the anatomical structure of those animals’ brain to their human relatives’ (Nicolelis & Chapin, 2008); the motor parameters involving monkeys’ behaviors from the simple arm movements and reaching-grasping task, to the bimanual and bipedal movements, and to the control of an avatar have been chosen under the consideration of how they “could be used in human neuroprosthetic applications” and “contribute to the development of future clinical neuroprosthetics systems” aimed at restoring motor behaviors of the patients in natural environments (Santucci et al., 2005: 1537; Ifft et al., 2013: 8; Li et al., 2009); the wireless electrodes chronically implanted upon the brains instead of previous microwires were expected to “reduce the risks of infection introduced by the use of cables that connect brain implants to external hardware” when they are applied to human patients (Lebedev & Nicolelis, 2006: 540); the three monkey brains connected through BtBIs were supposed to provide other scientists with “the core for a new type of computing device: an organic computer.” (Pais-Vieira, 2015: 1); when the geographical distances between the brains in Nicolelis Lab and the robots in another places were extended along the internet communication protocols such as TCP/IP (Wessberg et al., 2000: 363), it was promised that the BMIs would fulfill the general human desire for the telepresence “beyond boundaries.” (Nicolelis & Chapin, 2008; Nicolelis, 2011a)

8. Conclusion: A Diagram as an Obligatory Passage Point

The more biological and technological actors were juxtaposed along the closed-loop inside, the more interests Nicolelis Lab needed to promise to the actors outside. The more this loop looked adaptive to the opened social and natural environments and capable to fulfill various interests
outside in “an unsupervised manner,” the more Nicolelis Lab could acquire credits from academia, patients, government, industries, and audiences of the World Cup demo. However, in a sense that all these interests raised by the lab “promising too much” (Miller, 2014, May. 16) draw attentions from the outside only through the scientists’ conscious selection and juxtaposition of entities within the experiments, there was always the supervision of an abstract diagram working behind this mobilization of interests for the sustainment and expansion of the actor-network. The monkeys’ interest for juice and each neuron’s firing towards the machines could be transformed into the parts of the BMIs only when they were redistributed by the diagram in a balanced and sustainable way to other technological and neuronal actors, which could be otherwise unfavorable to the project. Likewise, the possible interests in social uses of BMIs should be also translated into specific dispositions of things in order to draw the public attentions for the financial sustainability of Walk-Again project. In a sense that all the dissimilar interests of the relevant (or potentially relevant) actors—such as the physical (neurons and muscles), technological (filtering algorithms, robots, and brain scan apparatuses), and the societal (patients, a scientific consortium, news media, and the Brazilian government)—should be passed through the diagram’s mediation in order to be represented within the dispositions of things intentionally selected and juxtaposed inside the lab, this diagram as an spatial abstraction of the scientific principles has also functioned as what Michel Callon calls “obligatory passage point” (OPP) (Callon, 1987: 7). And as long as these possible interests were translatable by this obligatory point into a specific arrangement of neurons, computers, and robot limbs, the BMIs could mobilize them as the potential resources for the expansion of these networks of things.

Throughout the missing times between the diagram’s re-dispositions of things and their
socio-biologically programmed interests along a closed-loop and these small entities’ fleshing out the gaps within this abstract diagram, the experimental subjects and their desirable environments were embodied within the networks as the consequences of those things’ microtemporal adaptation and subjection to the diagram. In that this diagram has, for the last decade, engineered the possible evolutions of the neural ensembles in primate brains under the selective pressures from their re-thingified environments transformed into the “new sensor/processor/actuator affiliations” through technological augmentations, there could be no such a subject who freely intend to reach out beyond the boundaries according to “what a naturally evolved brain can produce”; but only afterimages of microtemporal adaptations and negotiations of things just happened some imperceptible milliseconds before.
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Highlights

1. An actor-network analysis of Brain-Machine Interface (BMI), developed by Nicolelis Lab at Duke University Center for Neuroengineering.

2. How the neural ensembles and robotic limbs were juxtaposed together according to a diagram as a spatial abstraction of the lab’s scientific principles and how they formed artificial sensory-motor circuits which programmed the animal/human users’ possible motor behaviors as well as their motor intentions.