

Metastability of Cognition in Body - Mind - Environment Network

Dmitry Paranyushkin

Version April 2012

Published in Nodus Labs

Received 2 February 2012, Accepted 29 March 2012, Published 14 April 2012

Dmitry Paranyushkin
Nodus Labs,
4, Rue de la Martinique,
75018 Paris, France

Web: www.noduslabs.com
E-mail: dmitry@noduslabs.com
Tel: +33 6 20 28 44 80

Metastability of Cognition in Body - Mind - Environment Network

Dmitry Paranyushkin

Nodus Labs, Berlin, Germany, e-mail: dmitry@noduslabs.com

Abstract

We start from an overview of recent research in cognitive science, specifically the study of neural dynamics, the structural and functional properties of the neural networks, and their integrative mechanisms modulated through synchronization. We invoke the notion of metastability to refer to non-equilibrium stable states emerging as a result of the brain network's small-world topology. We then bring forward the concepts of embodiment, affordances, extended mind, enactivism, and actor-network theory to demonstrate how cognitive network extends beyond the brain into the body and into the environment.

Our aim is to explore how the notion of metastability could apply to this extended body-mind-environment network. We discuss how the concept of metastability and the main posits of radical embodied cognitive science make a case for an epistemological claim, which may have a dramatic impact on our behavior. While considerably more research is needed in this direction supported by empirical and experimental studies, we hope to show how the study of dynamical processes inside the brain can inspire a new kind of social and environmental practices, which operate on the basis of metastability: robust, flexible, stable, and evolvable.

Keywords: metastability, cognitive science, network science, small-world networks, embodiment, psychology, brain

1. Introduction

"Every standard comes into being within ourselves, freshly here and now, each time, relatively through relationships. Becoming aware of these relationships allows you to truly become one with the original nature itself, develop a clearer understanding of how your mind/body operates, and get a greater appreciation of the involvement of your thought process in all your physical acts."

- Michizo Noguchi

The human body is made of networks: a multiplicity of interacting components that produce complex phenomena. Neural pathways inside the brain modulate cognition, protein networks regulate the cells' metabolism, capillary networks supply the nutrients, blood and oxygen to the vital organs (Wagner et al 2007; Kashtan et al 2005; Sporns 2010). Even the body itself, on a larger scale, is a network: push your feet into the ground and feel the subtle repercussions of that movement travel through the knees and the hips into the lower back and through the chest into the arms and the neck and into the head (Noguchi 1979; Kasai 1999). Constant interaction between these networks produces complex patterns of non-equilibrium stability, where the body maintains certain states through continuous renegotiation of its internal network dynamics (Thompson & Varela 2001; Thompson 2007). These states are sometimes referred to as "attractor states", which can describe a certain regularity in synchronized neural activation (Rabinovich & Muezzinoglu 2010), continuous coordination between different groups of muscles while walking and swaying the arms (Kugler et al 1980; Yamada 1995), interactions between the organism and the environment (Kitano 2004; Brooks 1991; Pfeifer & Bongard 2007), or the complex dynamics of body-mind-environment interaction (Chemero 2009; Cosmelli et al 2006; Sporns & Lungarella 2006; Klyubin et al 2008). The ability of the body to maintain several distinct states simultaneously is referred to as metastability (Bystritsky et al 2012; Rabinovich 2008; Sporns 2010; also see Figure 1) and studies have shown that transitions between these states occur following a chaotic variability (Tsuda 2001; Katerndahl et al 2007).

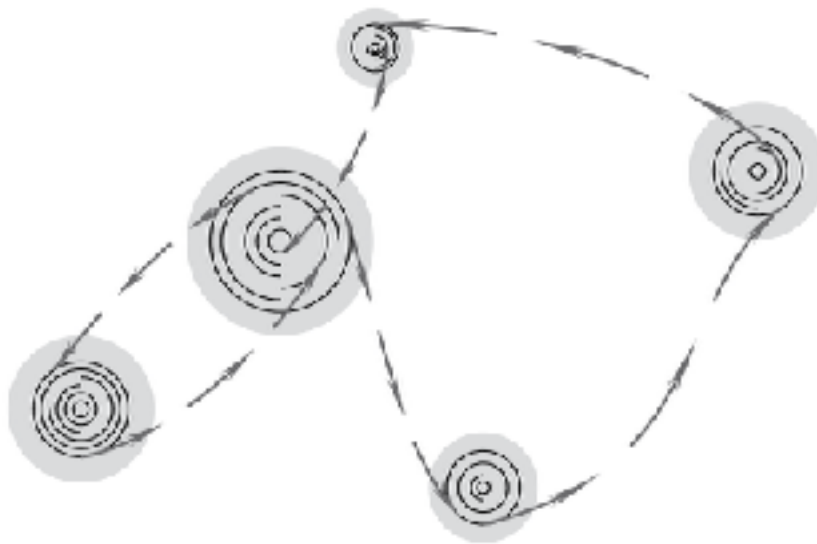


Figure 1: Metastability

The gray circles indicate the different global body-mind-attractor states. Each state is characterized by the different dynamics of all the variables affecting the state (shown as the black arcs inside the gray circles). Over time the interrelations of variables within the state change, however, the system maintains a stable dynamic state resistant to external and internal perturbations. Once perturbations are strong enough or the system goes out of sync, it seeks the new attractor states where the dynamics is different to accommodate for the change in internal or external parameters (also see Kitano 2004 on robustness; and Rabinovich 2008 on metastable states). The transitions between the states are characterized by chaotic itinerancy (Tsuda 2001).

Perhaps the easiest way to become aware of this is to register one's own breathing and heartbeat while walking. In this case three distinctly noticeable periodic processes are interacting with one another to produce the movement. Speed up the step, start running, and the breathing rate will increase, the heartbeat will become faster to cope with the rising demands on the body. Think about a destination point in front of you that you have to reach soon and the continuously activated neural circuits inside your brain will add more urgency to the situation. Notice how the softness of your feet makes it easier for your body to adjust to the hard surface of the ground and reduce the shock from running. All these ongoing active circuits of interconnecting elements come into relation to one another and produce the meaning for that particular situation that is as much understood as it is embodied (see also Johnson 2008; Kugler et al 1980 for the dynamic modeling of walking; and Chemero 2009 for a discussion of dynamic systems modeling of the body movement and the notion of dynamic touch, where the morphological properties of the body - such as soft fingertips - aid sensory exploration of the environment).

It has been demonstrated that the ability of the body to maintain several simultaneous states is supported by the small-world structure of the functional neural circuits within the brain (Sporns 2010; Variano & Lipson 2004; Barahona & Pecora 2002). The neural assemblies interact through synchronization in order to perform complex sensorimotor tasks (Varela et al 2001; Engel et al 1999; Fontanini & Katz 2008). The robust structure of the brain and its inherent degeneracy (the ability to perform the same functions using different structural constellations) ensure that the system is stable against external perturbations (Kitano 2004; Sporns 2010). Psychological diseases, as well as altered states of consciousness, were shown to be closely related to disturbances in the brain's small-world network topology and synchronization dynamics (Stam & Reijneveld 2007; Micheloyannis et al 2006; Rubinov et al 2009).

There is a growing evidence that cognition and sensorimotor activity extend beyond just the neural assemblies of the brain (Chemero 2009; Sporns 2010; Johnson 2008; Clark 2008; Thompson & Varela 2001; Thompson 2007). Disciplines such as embodied cognitive science, extended cognition, ecological psychology, and enactivism explore how cognitive processes (and the production of meaning, to that extent) occur through our interactions with the environment, object manipulation, bodily movement, social interactions. In short, they conceive of the mind as an integral part of the system that includes the body and the environment. Interactions between them influence the various dynamic processes that occur within and thus our neural assemblies shape our capacity to think or to act as much as the activity that we perform with our bodies and the features of the environment that we perceive (Chemero 2009). Moreover, recent experiments in robotics have shown that all information that's necessary for sensorimotor activity and cognition may be already contained within the environment (Pfeifer & Bongard 2007), which also closely correlates with the main posits of Gibson's theory of affordances - environmental opportunities, which guide the action (Gibson 1979; Turvey 1992). This strand of research is closely related to phenomenological tradition of Husserl and Merleau-Ponty, American pragmatism (particularly James and Dewey), eliminative materialism (see Chemero 2009 for a discussion), speculative realism (Brassier 2007), and actor-network theory (Latour 2011). All these approaches emphasize the importance of conceiving the body-mind-environment as an interconnected interactive system - a network - in order to understand cognition.

To summarize, body-mind-environment functions as a network. The features of the environment (affordances) influence the development of abilities, which modulate the dynamics of neural assemblies, which, in turn, generate the abilities that affect the affordances (Chemero 2008). Neural dynamics is an integral part of this process and we've mentioned above that metastability is one of its main properties, which enable it to maintain stable states, perform several independent functions, and stay robust against internal and external perturbations (see Figure 2).

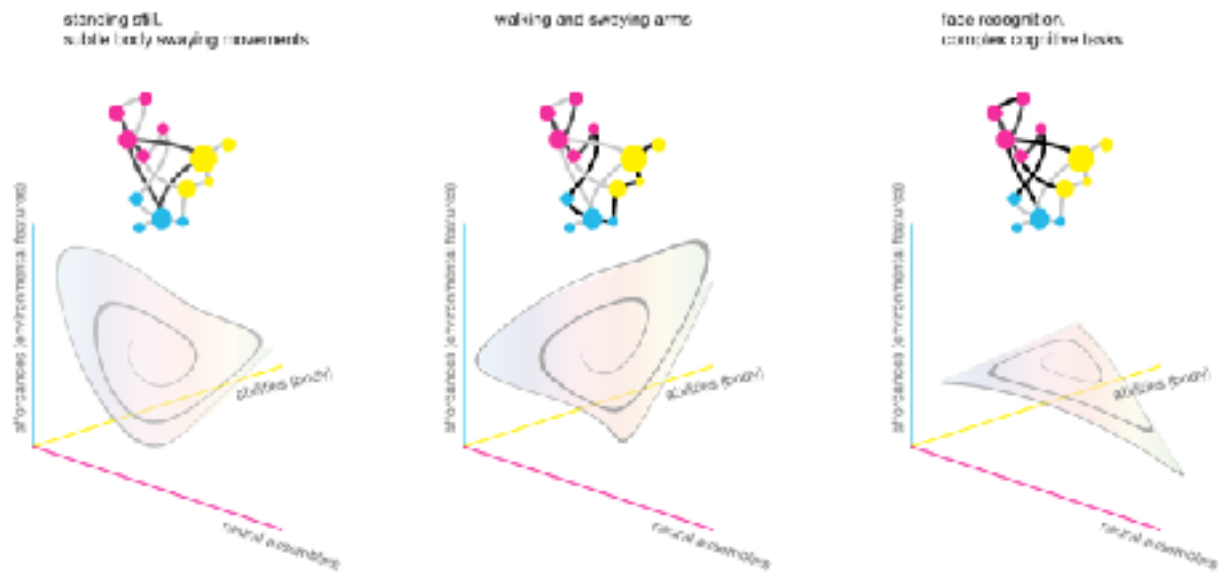


Figure 2: Strange Attractors and Body-Mind-Environment Network

Neural assemblies reach non-equilibrium stable states through synchronization (Rabinovich & Muezzinoglu 2010). These states produce certain actions (such as walking or swaying arms or subtle body swaying when standing still), which are also characterized by dissipative structures or stable states far from equilibrium (Kugler et al 1980). Over time, the abilities of the organism form a niche of affordances: things that it's able to do, which, in turn, influence the further development of its abilities, which affect neural assemblies (Chemero 2009). All these patterns of non-equilibrium stability come into play within the body-mind-environment to produce global states. The dynamics of these states depend on the ongoing interactions between the neural assemblies, environmental opportunities, and abilities – which are themselves defined by the dynamic interaction of the components they are composed of.

In this research we are interested to extend the concept of metastability beyond the network of the brain and explore the implications it may have on the larger body-mind-environment system. Metastability plays an important role in maintaining robustness and flexibility of the brain. We are interested if this dynamics extends into the body-mind-environment system and the impact it may have. We are also interested how the perceived features of the environment (affordances) change under the influence of epistemological claim made by embodied cognitive science, dynamical systems theory, and the science of networks.

2. Modularity and the Small World of the Brain

The human brain is structured in a way that's neither entirely random nor entirely regular. Instead, it's characterized by high heterogeneity of degree distribution across the nodes and high modularity (Sporns 2010; Soltesz 2005). Brain networks have so-called small-world structure, where there are many distinct modules of nodes that are more densely connected together than with the rest of the network. These modules maintain connection to one another, so the average path length between the nodes is relatively short (see Figure 3). Such heterogeneous interconnected structure allows the brain to have high computational capabilities while maintaining distinct regions, which can couple and synchronize (often through hubs) to perform complex cognitive tasks. It has been shown that the small-world architecture of the brain, characterized by high clustering, low average path, and high modularity, may be a result of the random axon growth affected by limitation of the available space and by the different time frames in which this growth occurs (Kaiser et al 2009; Kaiser & Hilgetag 2006; Sporns 2010). It has also been shown that the structure of brain networks is constantly shaped by the ongoing activity and that complex networks are often formed by simple local growth rules (Gross & Blasius 2007; Holme & Ghoshai 2006).



Figure 3: Small-World vs Random network with normal (Gaussian) degree distribution

Both networks have the same number of nodes (912) and edges (4150), similar average path (3.4 in the SW and 4.0 in the random network). However, clustering is 0.248 in the small-world network versus 0.011 in the random network, and the average diameter in the SW network is 9 vs. 13 in the random network. The community structure is much more prominent in the SW network: there are distinct modules that are more densely connected within than to the rest of the network. These modules in SW network are also connected, ensuring low average path and diameter, making communication efficient across the different modules.

The structure of the brain network evolves with age. Brain networks, both in children and adults, were shown to have small-world topology, the communities of neurons in children brain are arranged on the local anatomical level, while adult brain tends to have more distributed community organization (Fair et al 2009). At first, the network has small-world topology with several distinct regions responsible for performing specific tasks that can be globally integrated. As a person ages and the network develops, more communities are being formed while the small-world topology is maintained. The existing communities become more integrated through long-range connections, so there's a shift from a local or segregated to a distributed or integrated mode of organization. The nodes change the communities they belong to, becoming more "globally" connected. Short-range connections dominate during childhood, while longer-range connections appear in adolescence (Sporns 2010). Other studies have also shown that the density of connections within the modules

tends to decrease with age, while the density of connections between different modules tends to increase (Meunier et al 2009). These findings support the hypothesis that brain undergoes a continuous structural change over its lifespan. Small-world topology is maintained, while community structure is constantly changing by bridging dispersed clusters of neurons together and disintegrating the existing communities in order to form the new ones (Figure 4).



Figure 4: Evolution of the brain network with age

Children's brain has small-world modular structure, short-range connections dominate (stage 1). As the person ages, the structure becomes more integrated by adding the new nodes and long-range connections between the existing modules, the existing nodes may change the modules they belong to (stage 2). Further on, the density of connections between the modules tends to increase, small-world topology is still maintained (stage 3). See Meunier 2009, Sporns 2010, Fair et al 2009.

Knowing the structural properties of the brain can give an idea about the kind of dynamics that occurs within the brain networks. Small-world networks are known for their ability to synchronize (Watts & Strogatz 1998; Barahona & Pecora 2002) as easily as random networks due to short average connection paths and different structural motifs that produce network-wide periodic (node circuits) and chaotic (subnetworks) behaviors (Zhigulin 2004). If the connectional load is homogeneously distributed across the nodes, small-world network will synchronize better (Nishikawa 2003; Bernardo 2005). The presence of several prominent modules that are more densely connected together than to the rest of the network, as well as a combination of stable and unstable motifs (Prill et al 2005), keeps the whole system from falling into periodic sync (Bragard et al 2007). Instead, synchronization occurs locally within densely interconnected modules of neurons, which couple dynamically to produce global short-lived activation patterns. This way the brain is constantly kept at the verge of chaotic behavior, where there can be several different patterns of synchronization occurring simultaneously, involving the different regions of the brain network. Modularity plays an important role in supporting asymptotically stable linear dynamics in networks and limits the spread of perturbations across the whole network (Variano & Lipson 2004; Barahona & Pecora 2002). Hierarchically arranged modules in network's architecture make it more robust against random perturbations (Variano & Lipson 2004). Thus, the network that has fractal properties (hierarchical modular structure implies just that) and a certain degree of randomness (which is not too high to avoid global synchronization) has the capacity to maintain itself in a near-chaotic state, producing localized areas of non-equilibrium stability (Bragard 2007). It has also been shown that functional networks across different frequencies also exhibit self-similarity, scale-invariance and fractal patterning (Bassett et al 2006).

Recent research has shown that modularity is an important feature for the networks that process several different tasks simultaneously (Wagner et al 2007; Kashtan et al 2005). Modular structures in brain networks emerge as a result of evolutionary changes that an organism needs to go through in order to adapt to the constantly changing environment (Lipson et al 2002). Increasing connectedness may improve computational capabilities of a network, but will decrease its capacity to evolve, adapt, and simultaneously maintain several states (Bullinaria 2007; Kashtan et al 2005). This property of the brain is known as modularity: simultaneous presence of several dynamical patterns of activation, each of which is responsible for a certain cognitive task: visual perception, memory, movement (Sporns 2010). It's important to notice that this concept of modularity is different from Fodor's proposition (Fodor & Pylyshyn 1988) that different isolated modules of the brain are responsible for "storing" the capabilities to perform different tasks. Instead, multistability and capacity to perform complex tasks emerges through interactions between these different modules, rather than solely within them. One of the main properties of the brain is its particular ability to use various structural pathways to perform similar tasks – the quality referred to as "degeneracy" (Edelman & Gally 2001; Price et al 2002). Modularity, therefore, is the optimal structural solution to accommodate for the complexity of the cognitive tasks and to ensure the existence of several different routes to perform them.

The neural modules are not there to "represent" certain parts of our reality, but rather to ensure that the overall structure is robust, adaptable, and capable for multi-processing.

It has been shown that modular small-world networks are robust against random node removal (Newman et al 2001; Newman et al 2006) and that brain networks also have the ability to rewire and redistribute its activity to successfully perform necessary cognitive tasks, as the studies of brain-damaged patients have shown (Damasio & Damasio 1989).

To summarize: the structure of the human brain is between the order and randomness. High modularity and small-world topology of its network allows it to maintain numerous states simultaneously, stay responsive to ever-changing demands of the environment, and robust against perturbations. Cognitive and perceptual tasks are achieved through synchronization across various modules of neurons, which can couple in many different ways to produce different behaviors.

3. Communicating through Synchronization

Numerous studies have shown that brain is always active. There's a constant ongoing neural activity even when the subject is in the "resting" state (Arieli et al 1995; 1996) and the responses of neurons are predetermined by existing brain-states rather than simply by an externally applied stimulus (Leopold et al 2003). Another study has shown that there's spontaneous flow fluctuations in the human visual cortex even in the absence of visual stimuli (Nir et al 2006). Therefore, the brain is sort of constantly going through all the different states (and multiplicity of possible responses) constantly reiterating connectivity cycles within its structural network. Once the sensory input reaches the network, certain neurons that were active at that moment synchronize at a higher frequency and produce a temporary state (functional connectivity) to perform a specific task (Fontanini & Katz 2008), then this temporary structure dissipates again into the fluctuating activity. In other words, the constant fluctuating low frequency activity of the neurons is reiterating all the possible states of network, functionally maintaining small-world topology within the brain, keeping it in the "always ready" stand-by mode. Sensorimotor and cognitive processes activate some of these neurons at a higher frequency (usually over long-range connections), leading to temporary spatial reconfiguration (connecting different modules of the brain required), while maintaining the same small-world topology but with increased clustering and shorter path length – the functional connectivity associated with cognitive and perceptual tasks (Bassett et al 2006; Smith et al 2009).

Synchrony among different neural regions has been shown to play an important role in performing cognitive and sensorimotor tasks (Varela et al 2001; Engel et al 1999). Studies have shown that face perception as well as motor response induces long-distance synchronization at high frequency gamma (30-80 Hz) range (Rodriguez et al 1999) – frequencies thought to be responsible for conscious integrative processes and working memory activation (Figure 5). A short moment of desynchronization between the task of perception and the motor response was explained by the necessity to decouple neural ensembles in order to proceed from one cognitive state to another (Rodriguez et al 1999; Varela 1995). On the other hand, during sleep, especially the REM phase, different regions of the brain concurrently synchronize at lower frequencies aiding the processes of memory consolidation and neuroplasticity (Hobson & Pace-Schott 2002), while blocking sensory input and motor output.



Figure 5: Synchronization, sensorimotor and cognitive tasks.

During the state of cognitive rest the brain maintains low-frequency ongoing activity. Cognitive tasks (e.g. reading or face recognition) or sensorimotor tasks (e.g. walking) are associated with high-frequency synchronization across different modules of the neural network (usually over long distance). See Rodriguez et al 1999, Varela et al 2001; Engel 1999; Bassett et al 2006.

Studies suggest that brain oscillation is used as a mechanism for cerebral integration. It exists across a number of functional domains where every domain is associated with a different frequency of neural synchronization – both in the active and resting states (Knyazev 2007; Chen et al 2008). Various psychological disorders are characterized by disruption in this activity. Chen et al (2008) found that in the patients with bipolar disorder synchronization significantly increases in the slow delta (2-4 Hz) frequency rate (normally associated with the activity of motivational and inhibition systems) and significantly decreases in the fast beta (12-24 Hz) range (normally associated with an active state). Many other psychological diseases are associated with disrupted synchronization across a range of frequency bands (mainly in the beta, alpha and gamma ranges), as well as topological changes in the small-world structure of functional (active) networks (Stam & Reijneveld 2007; Michelloyanis et al 2006). Specifically, in Alzheimer disease as well as schizophrenia patients the functional networks were characterized by the lower clustering and shorter path length interpreted as randomization of small-world network (Stam & Reijneveld 2007; Rubinov et al 2009). Schizophrenia is often referred to as “disconnection syndrome” (Rubinov et al 2009) due to the inability of randomized small-world functional networks to maintain the balance of “segregation” and “integration”. It’s also characterized by the emergence of the new hubs, which is a further evidence that functional networks in the people affected by schizophrenia are structured differently than in the healthy individuals (Sporns 2010). It has also been suggested that autism may result from overabundance of short-range pathways, interfering with the functional differentiation of brain regions, and the loss of long-range pathways that support global integrative processes (Cherkassky et al 2006). A similar shift of topology from small-world towards regular network with the increased local efficiency and decreased global efficiency was found in children with ADHD (Wang et al 2009).

Emotional states were also shown to depend on reciprocal relationships between different frequencies. One study has found that simultaneously increasing activity in the alpha (8-12 Hz) range and decreasing activity in the delta (2-4 Hz) range (so-called “breaking” from one frequency towards another) in adults is positively correlated to anxiety and depression (Knyazev et al 2008). Another study has shown how two frequency ranges (alpha and gamma) can interact in order to prioritize unattended stimuli (Jensen et al 2012) through phase-locking of both frequency ranges and a temporary “breaking” from alpha to gamma frequency.

Studies have shown that psychoactive drugs affect synchronization and suppress or amplify oscillation activity across several frequency range bands. For example, MDMA was shown to decrease lower frequency and especially delta wave (1.5 - 6 Hz) activity in the frontal cortex, which was interpreted as having disinhibition effects, while activity in the higher frequency range - particularly beta 3 (21.5 - 30 Hz) increased, leading to an increase in attention and vigilance (Frei et al 2001). This study has also shown that increased high-frequency synchronization occurred in the areas of the brain responsible for emotional activity. There are indications that regular use leads to permanent neuronal changes, decreasing intra- and inter-regional synchronization at the lower frequency range (Salomon et al 2011).

Studies of topological changes in structural brain connectivity of cannabis users have shown that the neuron network structure has small-world characteristics, however with the decreased global efficiency and increased clustering coefficient when compared to control subjects (Kim et al 2012). Another study has shown that long-term cannabis use decreases synchronization capacity across various regions of the brain, which may lead to short-term memory deficiencies (Soltesz & Staley 2006). Both studies suggest that cannabis might temporarily aid intraregional synchronization while reducing inter-regional synchronization across a wide frequency range. In this way its effect is different to that of MDMA discussed above, which seems to have an opposite effect at least in the higher frequency range (Figure 6).

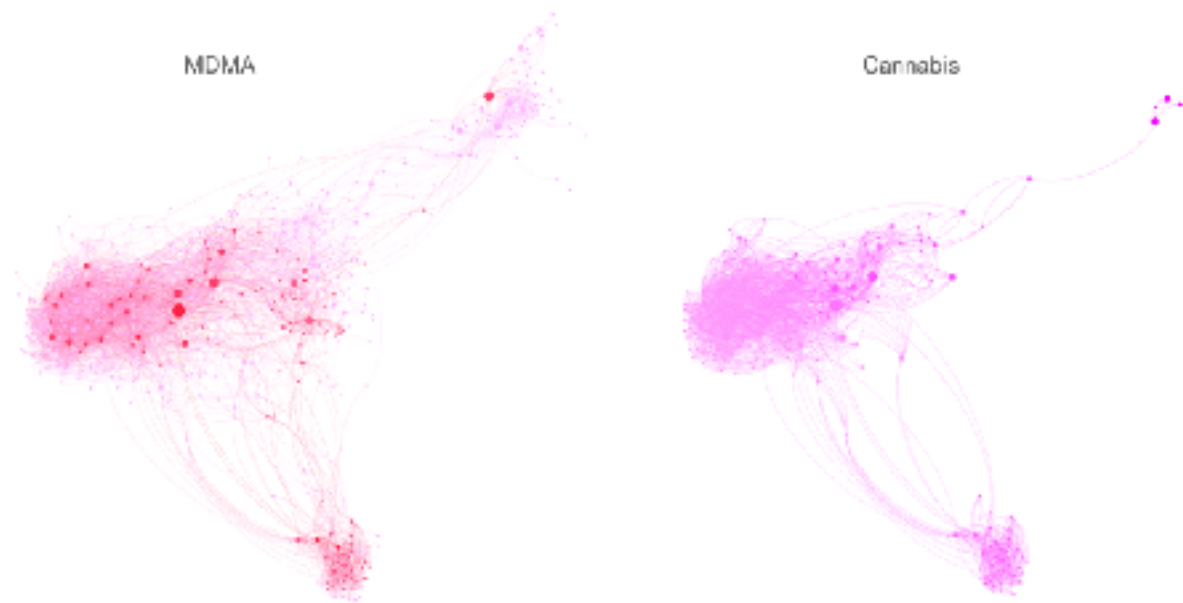


Figure 6: Drug effects on brain connectivity and synchronization patterns.

MDMA has effects on synchronization. It decreases low-frequency synchronization in the frontal cortex (disinhibition effect) and increases high-frequency synchronization (increasing attention and vigilance), especially in the regions responsible for emotional activity. Regular use leads to disruption of synchronization in affected areas and wearing off of the neurons involved in high-frequency synchronization

Cannabis affects topology of the functional networks. It increases the clustering coefficient (density of connections within the modules), while decreasing the global connectivity. It also affects synchronization across various brain regions, which may be associated with short-term memory disruption. *(The latter image was produced from a standard SW network by filtering out a small percentage of nodes with a low number of neighboring triangles, that is, discarding the nodes, which are not part of the well-embedded communities. This produced a much higher clustering coefficient and lower average path.)*

To summarize, brain oscillation is not only a mechanism used for integrating various neural regions together via various synchronization frequencies. These neural regions also engage in reciprocal relationship and phase-locking to perform various sensorimotor and cognitive tasks, as well as to regulate emotional states. When the functional networks formed by the neurons oscillating at the similar frequency range display small-world properties (high local clustering, short path length), they are able to perform their integrative function while maintaining different regions supporting distinct independent activities. Deviations from small-world topology and alteration of synchronization patterns in functional and structural networks was shown to be a characteristic feature of many psychological disturbances as well as altered states of consciousness.

4. Robustness and Metastability

It has been shown above that one of the core emergent properties of small-world brain networks is robustness: their ability to maintain the functions despite external and internal perturbations. Kitano (2004) has shown that robustness depends on the four main elements: feedback control system, modularity, redundancy, and decoupling. Networks that exhibit all of these qualities are resistant to perturbations and can maintain several distinct stable attractor states. Robust adaptation will then ensure that small perturbations do not bring the system out of its current attractor state. If perturbations are too high, the system will simply shift to a different attractor state that enables it to cope better with the internal or external change that lead to the perturbations (Kitano 2004).

Prominent community structure allows the network to be robust and to simultaneously maintain several distinct states – the quality referred to as metastability. Global integration is achieved via the more interconnected core control center, which acts as an interface between the distinct communities and may be realized as a supranetwork of interconnected hubs enhancing communication between different areas of the network (Kitano 2004; Sporns 2010). The Global Workspace Theory (Baars & Franklin 2009) proposes that consciousness itself is the product of the core control center, which integrates information from functionally independent modules of network (Figure 7).



Figure 7: Global high-frequency activation.

Various distinct states maintained within the different modules of neural networks are integrated globally through the global workspace (indicated with yellow) – a densely interconnected network of hub nodes with long-range links between the modules.

It has been shown earlier that synchronization is the mechanism that enables the neurons to form communities and for these communities to interact to one another. The dynamics of this synchronization is maintained at a near-chaotic state in small-world networks, with spatially distributed areas of non-equilibrium stability characterized by so-called strange attractors (Rabinovich & Muezzinoglu 2010). Strange attractors express a certain regularity in relation between various parameters over time. Small-world network modular structure allows the emergence of strange attractors through neural synchronization on the intra- and inter-community levels. High modularity of small-world networks organized hierarchically (small clusters form larger clusters etc.) ensures simultaneous emergence of several strange attractors within different clusters and among them (Kaiser et al 2008; Sporns 2006), thus enabling the system to perform

complex cognitive and sensorimotor tasks that require cooperation between distinct states. When the network topology shifts towards a more random structure, global synchronization occurs which may lead the system towards uncontrollable oscillations and reduce its metastability because globally synchronized network does not allow for simultaneous existence of several different states (Gomez-Gardenes et al 2008; Sporns 2010). When the network topology shifts towards higher clustering and reduced intermodular connectivity, the capacity of distinct communities to synchronize, and thus interact to one another, also declines. That reduces the global efficiency of the network and does not allow for metastability to emerge either. Therefore, robust structure that's resistant to external perturbations (noise) – but at the same time flexible enough to respond to the demanding internal and external multi-tasking demands – must be in a constant state of flux, rewiring its connectivity to maintain its degeneracy while maintaining the small-world (prominent community) structure to allow for metastability.

An emerging new field of nonlinear dynamical psychiatry can provide computational methods as well as phenomenological insights for a better understanding of cognition (Bystritsky et al 2012). The core of this theory is the proposition that mental and emotional states are characterized by nonlinear dynamics and metastability. Rabinovich & Muezzinoglu (2010) propose to model a dynamical system where the change of emotional and cognitive functions over time is plotted into the phase space. The data can be gathered by detecting synchronization between various groups of neurons responsible for emotional and cognitive activity (at the according frequency range and cortical locations within the brain). The authors propose to model the interaction between the emotional and cognitive processes as winner-less competition (Just & Varma 2007), using Lotka-Volterra equations applied to model prey-predator dynamics. This interaction plotted in the phase space produces strange attractors, which are characteristic for open dissipative systems where the density of all interacting flows (energy, material, information) is stable (see Figures 1 and 2). The strange attractors may be associated with a certain emotional state, cognitive activity, or memory (Rabinovich & Muezzinoglu 2010; Wills et al 2009). These local “wells” of non-equilibrium stability interact on a wider scale through the global workspace (a core network of long-range connections performing integrative function usually associated with consciousness). They synchronize at a higher gamma (30-80 Hz) frequency to produce global attractors. Small perturbations do not affect these stable states: robustness of the system (Kitano 2004) ensures that it comes back towards attractor even when disturbed. A certain level of noise ensures that the system is not “asleep” (Rabinovich et al 2008). A change in dynamics between emotion and cognition processes provokes activation of different local attractor states, which, in turn, provoke global shifts of the system. Therefore, the system is metastable in that it has several possible dynamic states but only one is actualized at every moment of time. Local shifts in emotion-cognition dynamics provoke global shifts of the system from one state to another along a stable heteroclinic channel, which traces the transition of the system across equilibrium points over time (Rabinovich et al 2008; Rabinovich & Muezzinoglu 2010; Bystritsky et al 2012). The idea that brain networks evolve along a trajectory of attractor points accompanied by a certain level of chaotic noise was also expressed by Tsuda (2001) in his discussion of “chaotic itinerancy” found in multi-dimensional dynamical systems. Temporary global stability of such system may be referred to as mood (an state emerging as a result of global integration between various strange attractors). A study (Katerndahl et al 2007) has shown that mood transitions in mentally healthy patients have a chaotic variability (Figure 8).

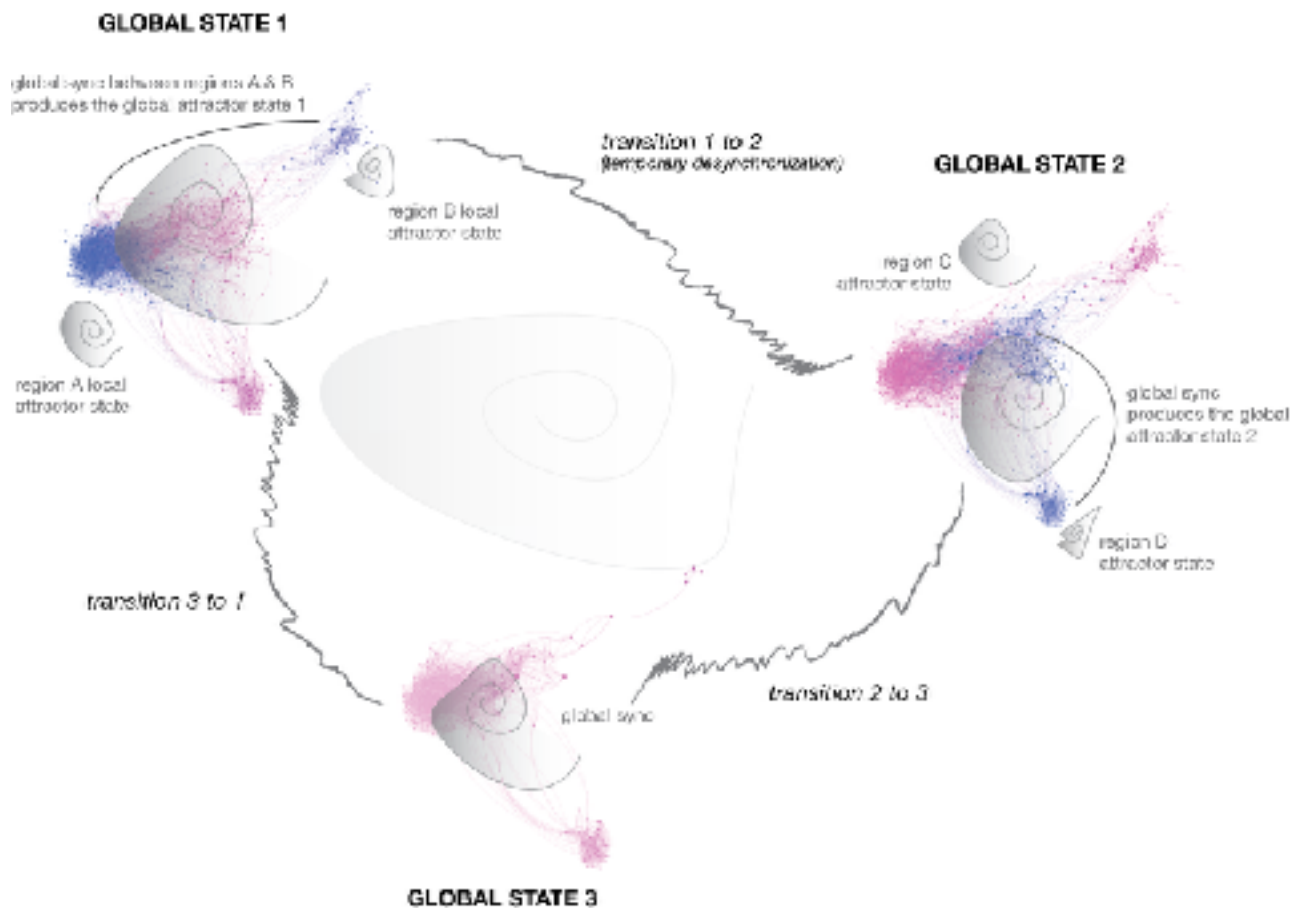


Figure 8: Metastability, local attractor states and global sync

In the global state 1, neural assemblies in regions A and B synchronize locally to produce local dissipative structures - patterns of non-equilibrium stability (plotted as attractor states in the graph above). The regions synchronize globally through phase locking to produce global attractor states for the system (winner less competition dynamics, similar to patterns of non-equilibrium stability produced by prey-predator systems).

When perturbations are strong enough or when there's a different sensorimotor input, the different attractor states emerge after a moment of desynchronization (decoupling). The system falls into the new global attractor state 2. The new perturbations or sensorimotor input, produced by internal change or a change in environment leads to the global state 3. Then back into global state 1 again. The dynamics between the states has chaotic variability and may itself be plotted as a strange attractor (in the center) into the phase space of the system, which reflects the tendency of the system to be attracted to a certain dynamics over time.

5. Embodied Cognition and Body-Mind-Environment Network

Chaotic variability has been detected not only in the brain dynamics and mood shifts, but also in body movement of healthy individuals.

Chaotic swaying was found in the small balancing movements of healthy individuals whose only task was to stand still (Yamada 1995). The dynamics of this swaying was reconstructed in phase space where it was found to have chaotic attractors. It was also shown that the ability of the body to receive information while in chaotic swaying movement was superior. This dynamic stable state characterized by chaotic dynamics enabled the body to adopt and to flexibly integrate other movements and information from the environment.

Another research demonstrated that patterns in bodily fluctuations correlate with cognitive-affective states (D'Mello et al 2011). Specifically, when performing cognitive tasks the body fluctuations (the small movements detected by camera and physical devices measuring the pressure between the body and the sitting surface) exhibited chaotic 1/f (pink) noise fluctuations. During emotionally intense states this dynamics shifted to that of the white noise fluctuations. The authors interpreted these results as supporting the notion of mind-body coupling as a self-organizing process with non-linear, chaotic, interaction-dominant dynamics. Interestingly, the discovery of the temporarily shifting dynamics within the chaotic pattern of subtle body movements during the states of cognitive distress is similar to the temporary decoupling states in the brain when switching from cognitive to motor activity reported by Rodriguez et al (1999) and Varela (1995).

Emotions could then be the transitional states of a system along the heteroclinic channel, when it's outside of the attractors typical for cognitive balance states (Rabinovich & Muezzinoglu 2010), and the observed white noise is the signal of the temporarily decoupled system looking for a new equilibrium. In this context it may be interesting to think of emotion as well as intense conscious activity as the two different ways of achieving the same task of breaking the cognitive-emotive balance and breaking out of the strange attractor towards the new metastable states.

This stunning correlation between the brain and the body dynamics supports the notion that cognition is an embodied process and that consciousness is not limited exclusively to the brain (Thompson & Varela 2001). The importance of the body as a vehicle for knowledge production has been exemplified in the work of Shusterman (2008), where he proposed a new discipline of inquiry called "somaesthetics" or "the critical, meliorative study of the experience and use of one's body as a locus of sensory-aesthetic appreciation and creative self-fashioning". The importance of body and mind for cognition was emphasized by Dewey (1938/1997) as well as the numerous studies in both cognitive and sociological sciences (Johnson 2008; Chemero 2010; Law 1992; Latour 2011).

It has been shown in the previous sections how complex cognitive tasks can be traced back to synchronization of different neural patterns within the brain. There is, however, a major rift between the representationalist and the dynamic stance on whether the resulting network assemblies are actually the representations of the outside world, or merely an integral component of the larger body-mind-environment system. We present the both points of view briefly below.

Representational theory of mind postulates that there are states of mind that encode the states of the world (Fodor & Pylyshyn 1988). In other words, mind is a mirror of nature, it stores internal interrelated "representations" of things that get activated by external impulses - input - to produce certain behaviors - output (Fodor 1981; Johnson 2008). The actual act of thinking, then, is the manipulation of the mental representations or "mental gymnastics" (Chemero 2009), and the mind is a computational device, which evaluates the external conditions according to the internal representations to produce the most relevant responses.

Representationalism is quite ubiquitous because it has strong connections to the philosophical traditions of Kant, Descartes and the structuralist psychology of the early 20th century. It is also very closely related to so-called "folk psychology" or common-sense view of ourselves that the

Western world has practiced for centuries: that is, the existence of universal “beliefs” and “desires” that govern human behavior. Representationalism has also been a dominant model of thinking in cognitive science for years, enabling the creation of artificial computational devices, computers, that function according to similar principles. Specifically, computational theory of mind assumes that cognition is rule-governed manipulation of formal symbols that represent various possible states of reality (Haugeland 1985) and has become the prevalent theory in the field of artificial intelligence.

The current developments in cognitive science, however, suggest that representationalist explanation of cognition is superfluous. That is, many cognitive tasks and behaviors can be successfully described without using the notion of representation. Moreover, they are in fact best described using mathematical tools, such as the dynamic systems theory and differential calculus, which provide an exhaustive account of their behavior without any recurrence to representations (Chemero 2009; Sporns 2010; Johnson 2008). This latter approach is referred to as embodied (situated) cognitive science or the dynamic stance. It has the roots in eliminativist approach pioneered by American pragmatists (Dewey and James) and their descendants (Rorty). According to Dewey’s principle of continuity, the mind cannot be separated from the body and the environment. The process of learning is made possible through experience, where bodily movement, perception, and interaction with the environment play a pivotal role (Dewey 1938/1997). In other words, we learn and perceive the world not only through our mental faculties, but also through the body by actively engaging with our environment. Every experience we’ve had comes into relation with the current situation, becoming part of the connectivity held together by a certain specific quality. The environment, human body, past experiences, and present situation come together into dynamic interplay creating the possibilities for the production of meaning. What we call “concepts” are the discrete aspects of continuous situations (James 1890/2007), which are encoded by neural pathways acting as interfaces in sensorimotor behavior (Johnson 2008). Gallese (2003) has also shown how “concepts” can be the neural activation patterns that are “turned on” by some sensorial or motor event in our bodies (Johnson 2008). These neuronal electric patterns relate the change in environmental energy patterns to a certain activity, which, in turn, affects the environment and produces the activation of neuronal patterns again. Maturana and Varela (1992) have shown how single-cell organisms engage in sensorimotor activity without any recurrence to internal representation. This is achieved through the dynamic coupling between the sensory and motor surfaces of amoeba’s membrane through a network of neurons. That is, there are certain “neural maps” that define sensorimotor behavior, but they are dependent on the body constitution are actively shaped by the environment, and are not directly experienced by the organism (Johnson 2008). Brooks famously said that “The world is its own best model” and emphasized the importance of the body-mind-environment interaction for cognition.

Our sensory experience has the ability to expand beyond what can be immediately observed (Dewey 1934). When we perceive an object, we don’t only see the form, but also experience the possibilities for interaction that this object proposes. This statement is supported by the research (Kohler et al 2002), which found F5 audiovisual “mirror neurons” in monkey’s brain that are discharged during the execution of a certain action, but also when the same action is merely observed or heard. Thus, seeing a cup may partially activate the neural pathways associated with holding it or breaking it, depending on the experience we’ve had with the cup so far and the situation’s demands. Furthermore, Pfeifer & Bongard (2007) have also shown how morphological properties of the body (e.g. soft fingertips that enable a soft careful touch) take on the processing job that otherwise would have to be done by the brain.

According to Gibson’s (1979) ecological theory of visual perception, perception is direct and is primarily for the guidance of action. All information necessary for the guidance of adaptive behavior must be available in the environment to be perceived, therefore what we perceive are the affordances or the environmental opportunities for behavior (or the possibilities for interactions mentioned earlier). Gibson’s theory has its roots in phenomenology, particularly the writings of Merleau-Ponty, who claimed there’s no perceptual monopoly on being and that the objects always

display themselves partially having “many other witnesses beside me” (Merleau-Ponty 1964, pp 15-16, 170). Environmental opportunities or, as Turvey (1992) calls them, “dispositional properties of the environment”, are thus intricately linked to the presence of a “witness” who actualizes them (Turvey 1992) actively interacting with the environment. Later Chemero (2003) expanded on the notion of affordances proposing that they are relations between the abilities of animals and features of the environment. This way affordances are closely linked to perception and action. They can be described using dynamical system apparatus as the evolving relation between the abilities to perceive and act and the features of the environment over time (Chemero 2008). This point of view is already widely accepted in experimental and explanatory practices of ecological psychologists (Chemero 2009). Over time, the abilities of an organism form a niche of affordances: things that it's able to do, which, in turn, influence the further development of its abilities. At the same time, according to enactivist view (Thompson 2007; Thompson & Varela 2001) and taking into account the earlier discussion, sensorimotor abilities of an organism are also generated by the neural assemblies, which, in turn, are modulated by them. Therefore, as a result we get a dynamic brain-body-environment system (Figure 9), which includes neural dynamics, physical interactions with the world through the body, and the environmental opportunities or affordances, which all influence and interact with each other (Sporns 2009; Cosmelli et al 2006).

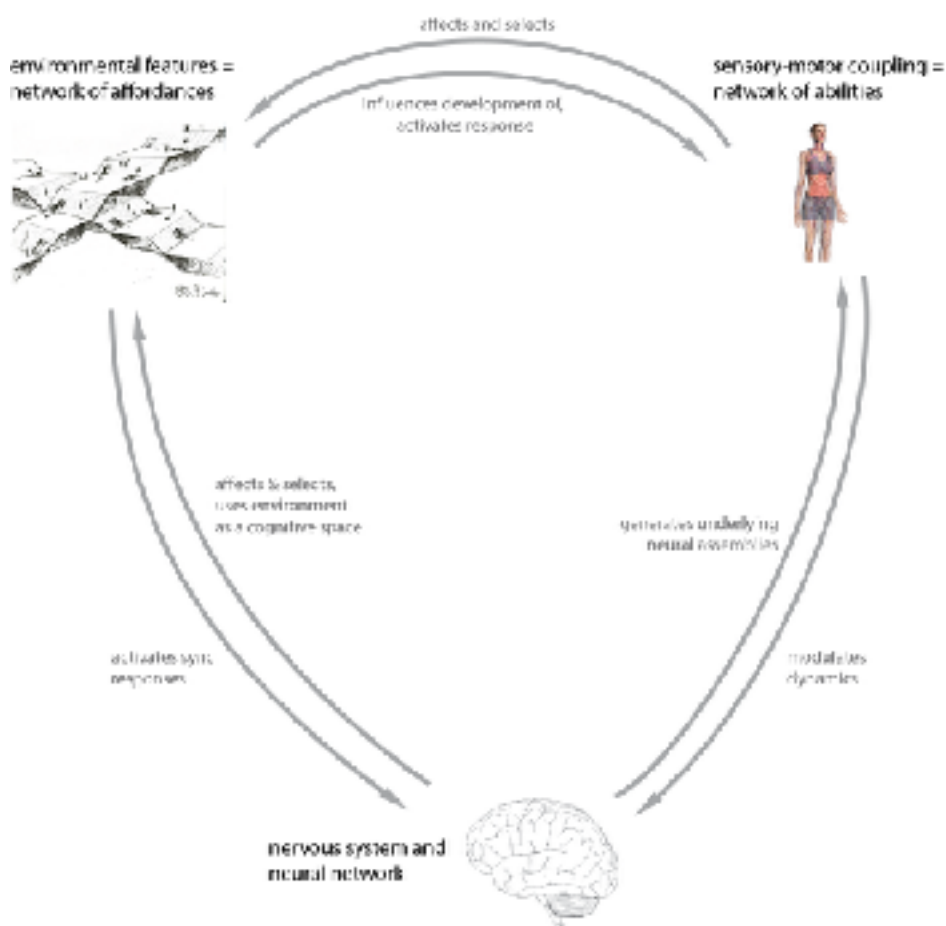


Figure 9: Autopoiesis of animal-environment system: affordances, abilities, neural assemblies

Adopted and modified from Chemero (2010).

Andy Clark (2008) has shown how "bodily actions [...] appear as among the means by which certain [...] computational and representational operations are implemented. The difference is just that operations are realized not in the neural system alone but in the whole embodied system located in the world." (Clark 2008). In other words, the mind extends beyond the brain, cognition is a process that utilizes the body and the environment (including the tools and the symbols). These

approaches lies at the basis of the extended mind thesis (EM), which asserts that some of the cognitive processes are composed of actions consisting of manipulating and exploiting of the environment (Clark 2008; Rowlands 2005). In other words, we think not only through our minds, but also through our environment and our bodies (as an interface).

Gregory Bateson in his famous collection of essays "Steps to an Ecology of Mind" has made the case for the fact that in order to understand our cognitive processes, we also need to understand the environment including the social relations that we are involved in (Bateson 1972; Hutchins 2010). His detailed analysis of the dynamics that leads to schismogenesis (continuous deviation from non-equilibrium stability in communities) is closely related to the dynamical accounts of mental states as a result of prey-predator competition discussed earlier in this paper (Rabinovich et al 2008; Rabinovich & Muezzinoglu 2010).

Social interactions, therefore, can also be seen as an integral part of cognition. According to Krueger (2010), "some of the expressive actions involved in the negotiation and management of we-space (gesture, touch, facial and whole-body expressions) drive basic processes of interpersonal understanding and thus do genuine social-cognitive work. Social interaction is a kind of extended social cognition, driven and at least partially constituted by environmental (non-neural) scaffolding."

The point of view expressed by American pragmatists as well as by the proponents of embodied cognition is closely related to the main posits of actor-network theory advocated by Latour and Law among others (although they are most often seen as the descendants from post-structuralist tradition and – specifically – Foucault's work on dispositif and biopolitics). Actor-network theory (ANT) claims that what we refer to as "social" is not exclusively confined to the sphere of human relations. Instead, it also includes the concepts and objects from the material world, which people use to communicate to each other. Each of these elements (or "actors") is a network (a person, an object, a concept), which actively comes together as a result of complex interrelations with the other elements of the network that they belong to (Law 1992; Latour 2011). These interrelations are similar to Gibson's affordances, or the environmental opportunities that define how such elements can be used, which, in turn, define the power and control mechanisms exerted by the network on its "actors". In this way, ANT and embodied cognitive science share a similar world view in their focus on interactions rather than concrete entities, using the framework of networks to model these ongoing processes. However, ANT is focused on the political and social implications of this activity, rather than mathematical description of the complex processes that shape it.

It follows directly that we are dealing with multiplicity of interacting components, which can be modeled as a network. This network is not limited only to the neural circuit activity inside the brain, it also includes the sensorimotor experience, and the environmental affordances of the organism, its social environment. Thus, the behavior of the organism in the environment over time can be explained using a system of differential equations, which describe the dynamics of such network (Chemero 2009).

Representational approach puts a huge load on the processing capabilities of an organism to perform even the most simple tasks, such as extending one's arm. The current and the desired positions, the speed, the velocity and the direction of the movement have to be represented internally and any deviation in the environment or the position would make it necessary to recalculate all these parameters. On the contrary, recent experiments in robotics and AI (e.g. Brooks 1991; Pfeifer & Bongard 2007) have shown how even more complex actions, such as walking, can be performed without using the notion of representations. Also, it has been shown that recurrent patterns of coordinated body movements can be understood as nonlinear coupled oscillators that produce dissipative structures or stable states far from equilibrium (Kugler et al 1980). Further research demonstrated that such coupling occurs in movement even on inter-personal level (Richardson et al 2007).

It can be said, therefore, that the brains and the bodies of autonomous agents form attractor states during their interactions with the environment, which then enable them to perform a variety of

actions without recurring to internal models describing external reality. The body-mind-environment system is seen as a network and the relation between the sensory inputs and the effectors (the points of action on the environment) can settle this network in multiple attractor states by the way of various perception-action cycles (Sporns & Lungarella 2006; Klyubin et al 2008), which then produce such activities as walking, running, etc. For instance, a certain activity in one module of the network can spur activity in another (sensor), which will then couple with another (effector), producing a certain change in the environment, which then spurs the cycle further. In this case the body and the environment become integral parts of the cognitive process by way of continuously activated circuits (or multiple attractor states) recurring at different parts of the body-mind-environment network. This activity on the environmental and social levels is closely related to synchronization and metastability occurring on the neural level, having more or less similar chaotic itinerancy and dynamics (Figure 10). It could therefore be interesting to shift the discussion about the effects of metastability on behavior from the theory of dynamic systems, networks, and embodied cognition towards sociology, philosophy, and psychology, proposing the new links between these disciplines.

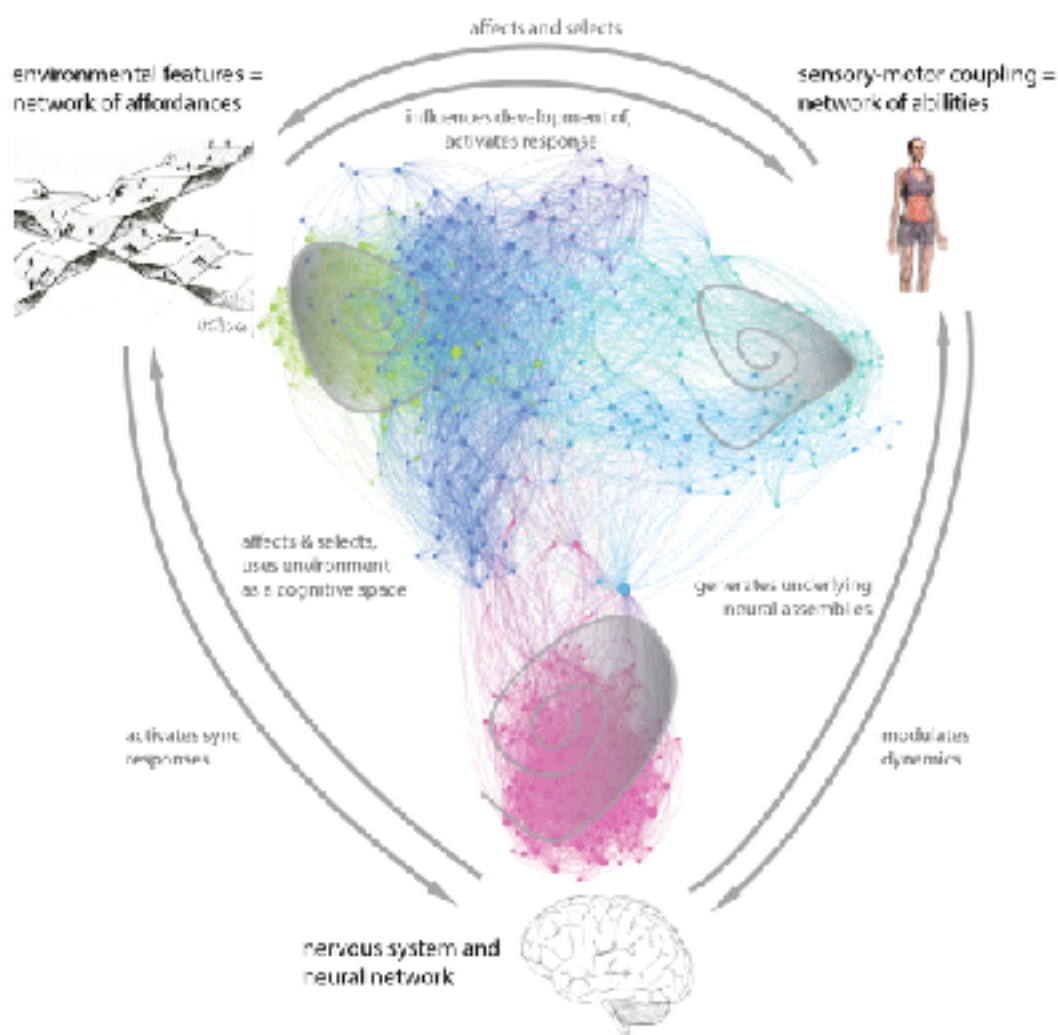


Figure 10: Body-mind-environment network

The interactions between neural assemblies, sensory-motor activities, and environmental features can be seen as a network. Various processes in each subnetwork generate attractor states (e.g. neural sync in the brain networks, coordinated motion and 1/f dynamics of swaying motion in the body, niches of affordances in the environment). On the large scale these processes interact and produce a global body-mind-environment network, which, in case of homeostasis, settles into a non-equilibrium stable attractor state.

6. Discussion: Metastability of the Social, the Body, and the Environment

In the previous section we focused on the notion of situated cognition. The networks of the brain modulate sensorimotor activities, which, in turn, influence the features of the environment that affect the organism's perception and abilities. Therefore, the dynamic body-mind-environment network is the infrastructure for the cognition that is embodied, which extends beyond the mind into the body and into the environment. Thus, to follow the posits of embodied cognition, enactivism, and actor-network theory, cognitive network includes not only neural assemblies, but also interactions with the environment (the niches of affordances), and social relations.

What is the structure of this body-mind-environment cognitive network? This question is important, because as we've shown above, the ongoing dynamic processes are often determined by the structural properties of the underlying network. If we know the structure of the extended cognitive network, we will know how robust, flexible, and stable it can be. We will also be able to tell how structural changes in this extended cognitive network might affect global connectivity, and, thus, the organism's behavior.

In order to answer this question, we need to look into the structure of underlying networks. That is, the neural networks that are related to sensorimotor activities, the networks of environmental opportunities (niches of affordances), and social networks.

Recent advances in the study of neural networks, which were discussed earlier in this paper, indicate that both functional and structural networks within the brain have small-world topology. Such networks have high clustering, high modularity, low average path, and high connectivity. These properties allow them to synchronize well while maintaining different distinct states – the condition referred to as metastability. Moreover, brain networks are in the constant state of activation and transformation, the segregated clusters of neurons are brought together into modules, while the existing modules are split into the smaller ones. These structural changes ensure that the neural networks are in the constant flux of evolution.

The discussion below will draw on theoretical and practical findings that we unfolded in previous sections and speculate on the various ways how the dynamics of metastability could be extended into one's social interactions, the body, and the environment. It may be seen as a proposition for further theoretical and experimental inquiries into the different ways how brain dynamics can inspire the social and personal change.

6.1 Metastability of the Social

Small-world structure is also typical for social networks, however, their connectivity is not as modular as that of the brain (Sporns 2010; Watts & Strogatz 1998; Newman et al 2006). It has been shown that our cognitive states are closely related to the social structures that we belong to (Krueger 2010). Many emotions, such as happiness, depression or loneliness, are social phenomena. Studies have indicated that such states spread dynamically through social networks and tend to be clusterized (Fowler & Christakis 2008; Rosenquist et al 2011; Cacioppo et al 2009). The more central individuals are more prone to feel happy (Fowler & Christakis 2008), while the individuals at the periphery (especially women) tend to experience loneliness more often (Cacioppo et al 2009).

Research in information propagation and viral marketing has shown that when a network has a highly modular structure the rumors (or temporary beliefs) tend to be endemically contained within distinct communities (Kuperman & Abramson 2001; Liu & Hu 2005; Yan et al 2008; Bragard 2007). When the randomness of connections increase, the network shifts towards high-amplitude

uncontrolled oscillations (Kuperman & Abramson 2001). When the connections are scarce, it loses the ability to integrate information globally (Keeling 1999; Zhou et al 2008). Therefore, our ability to maintain a certain belief or opinion is directly related to the social structure we are a part of. In other words, when one belongs to several distinct groups, the resulting small-world topology will make it easier for different beliefs, opinions, states to co-exist in the larger network that's comprised of all the different groups. When these groups are too disconnected, we'll often find ourselves unable to integrate all the differences efficiently into a coherent whole. When they are too well connected, the opinions within the group will be too homogeneous and susceptible to a quick global change (Figure 11).

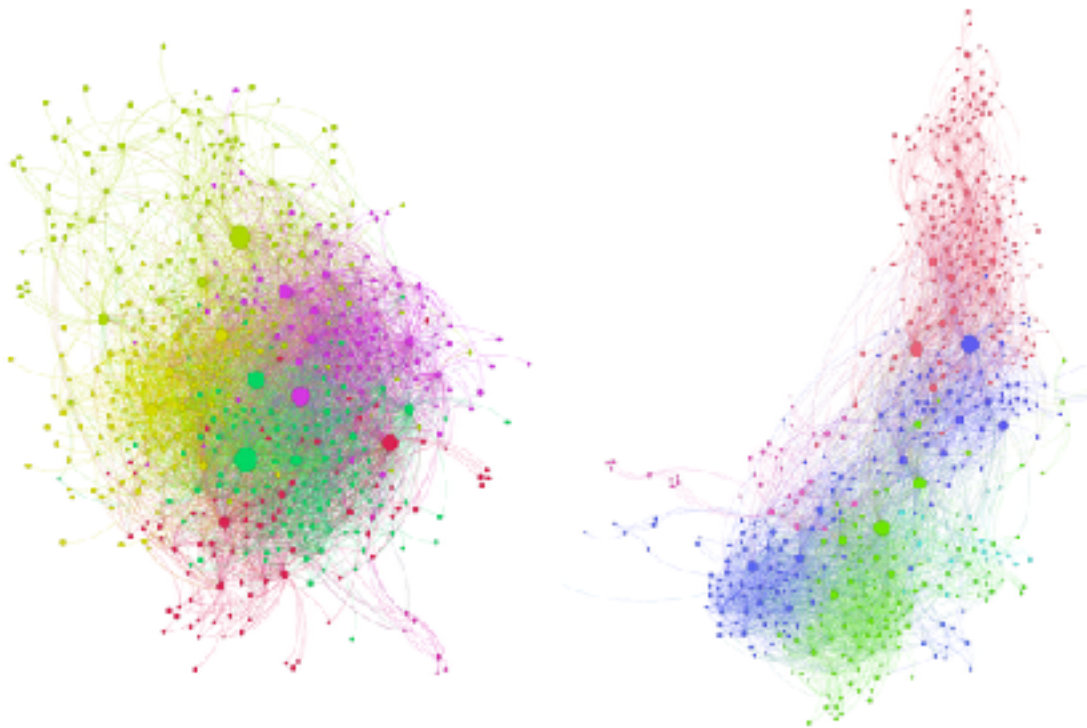


Figure 11: Social Networks

The network on the left has much less prominent community structure, the nodes are densely connected together. This network will tend to be quite homogeneous and can mobilize for a communal action (synchronize), but is also susceptible to quick fads and it's more difficult to retain information for longer time in this network.

The network on the right has prominent communities, which are more densely connected within than to one another. This network also can synchronize globally, but it's also more heterogeneous and can retain different trends at endemic levels in its distinct communities. Such structure is much more likely to produce metastable states than the more densely connected one.

Several studies of self-organized systems based on swarm populations (particles that act based on simple local behaviors to produce global sustained complex states) have also found that small-world topology was the most efficient structure to achieve globally optimal strategy (Matsushita & Nishio 2009; Kennedy 1999) when there are multiple possible solutions possible. A study of swarming populations tested the effect of neighborhood network topologies on the ability of particle swarm assemblies to find multiple optima of a multimodal function. It has been shown small-world network topology of swarm interactions leads to better performance on the landscape where several optimal solutions exist. Randomly connected assemblies performed relatively well on the functions with only one optimal solution. Also, it has been shown that when subpopulations are created that are isolated from the global focus, less optimal solutions are generated by the community (Kennedy 1999). Another study has shown that clustering procedure to identify niches

in the swarm helps produce different optima on the function landscape, instead of converging to a single one (Passaro & Starita 2008).

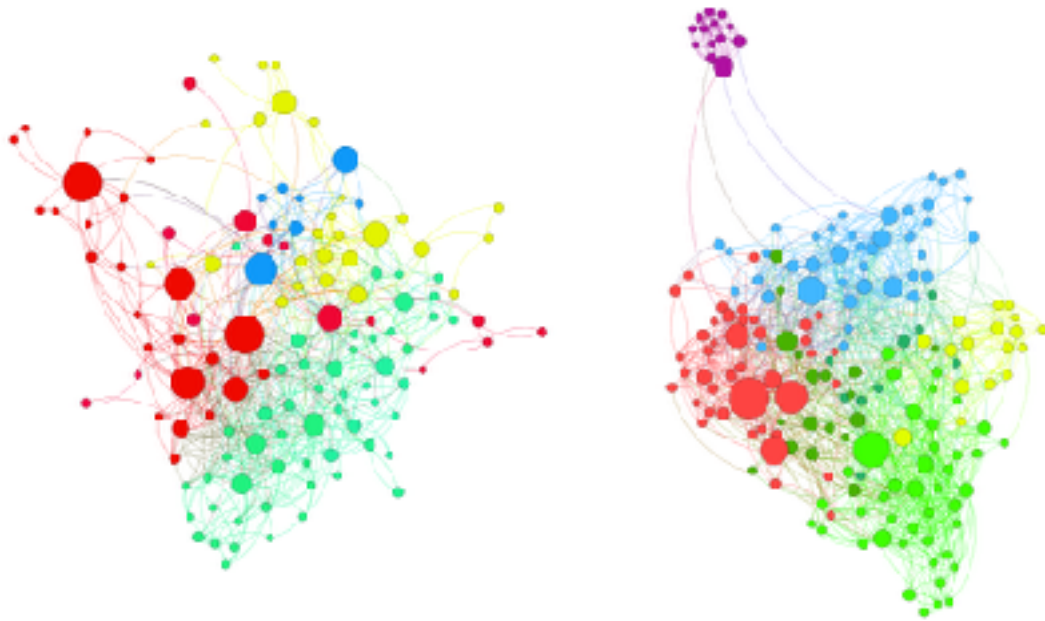
When interaction between elements is based on the small-world topology it may be not as fast in finding a solution, but it will definitely be robust and the prolonged exploration might help the swarm to find several optimal solutions. Randomly connected networks may reach the optimum earlier, but it may also be a premature convergence to a solution that is not globally optimal (Matsushita & Nishio 2009). In the context of social interactions these findings show the importance of small-world social network topology for maintaining several optimal solutions in the existence of cognitive local optima (Kennedy 2009).

Therefore, we can say that for the social network to have similar “metastable” abilities as the neural network, it should also have the dynamic small-world structure with a certain degree of randomness to allow for the global integration of the different distinct states. However, this network should not be too interconnected to allow for heterogeneity in order to retain its ability to maintain distinct endemic opinions and states. On the level of individual behavior this means that one should have sustained interaction with several distinct groups (work colleagues, friends, relatives, geographically dispersed communities). These groups should have connections to one another, but should not be too well-connected, in order to maintain their specificity. Local “hubs” could be introduced to one another to enable the possibility of global interaction.

One other important aspect is the constant reiteration of the network’s modularity, in order to ensure a certain level of constant evolution similar to the one happening in cortical networks over time with aging (Meunier et al 2009). That is, segregated clusters (probably, new communities or parts of the old ones) are integrated together to form the new groups, while the old ones are segregated into different parts (Figure 12). On the social level that would mean always searching for the new communities to enter, while also limiting one’s involvement into the already existing ones in order to ensure that there’s a constant social transformation that reflects one’s cognitive changes. This principle of “inclusive exclusivity” was shown to be beneficial for innovative and collaborative potential of social groups (Paranyushkin 2011).

Figure 12: “Healthy” evolution of a social network

The number of communities increases, while the nodes change the communities they belong to. The nodes at the periphery are integrated into the network and form the new centers, while the old centers are pushed towards the periphery to ensure constant renewal. The small-world topology is maintained to ensure the ability of the network to



A good example of successful implementation of this principle in the social sphere is described by Gregory Bateson in his account of the dynamics that he observed in polynesian tribes (Bateson 1972/2000). They were engaging in reciprocal activities, taking on the opposite sides of stereotypical social roles. On some occasions the children would be allowed to do everything they wanted and to tell adults what to do, on other occasions the adults would have the control again. Such dynamics, according to Bateson, ensured that the community at large held itself from the destructive extremes (schismogenesis) by constantly reiterating social roles between various segregated subgroups.

6.2 Metastability of the Body

We have shown above that the ability of the brain to settle into chaotic attractor states is made possible by its small-world network topology (Gross & Blasius 2007; Holme & Ghoshai 2006). Its modular structure and global connectivity allow for simultaneous existence of several globally interacting clusters, which can also integrate information on a global level – a condition referred to as metastability (Rabinovich 2008, Chemero 2009; Sporns 2010). This process extends beyond the brain, into the body and the environment (Thompson & Varela 2001). The body is an active participant in the cognitive process (Johnson 2008; Chemero 2009) and its morphological properties (such as soft fingertips, for example, which allow to handle objects carefully) take off the cognitive load for some sensorimotor tasks from the brain (Pfeifer & Bongard 2007). The disciplinary proposal of somaesthetics (Shusterman 2008) emphasizes the role of the body in the production of meaning. According to enactivist view of cognition the thinking process extends beyond our brain, into our body, and into the environment. We think when we move and the concepts can also be both constructed and construed through movement (Gallese 2003; Johnson 2008). Body gestures were shown to play an important part in the process of cognition, generating the new sets of affordances in relation to the environment (Krueger 2010).

Metastability on the level of the body would mean a dynamic organization of one's interaction with the environment following the small-world topology. Not only that, but also the ever-changing small-world topology, reflecting the constant reconfiguration that occurs in the human brain (Meunier et al 2009), allowing for the formation of the new centers and for the removal of the old ones.

Experiments show that this is already happening naturally: the chaotic involuntary swaying (Yamada 1995), movement coordination (Kugler et al 1980), or involuntary body-movements

having chaotic profile of $1/f$ pink noise (D'Mello et al 2011; Mandelbrot 1999). Healthy heart-beat was also shown to have chaotic variability (Bassingthwaight et al 1994), as well as the mood changes in mentally healthy individuals (Katerndahl et al 2007). Therefore, the body is already implementing the mechanisms that allow it to maintain metastability. Several experiments in robotics established that interactions with the environment that we engage in using our bodies are characterized by the emergence of strange attractors (Brooks 1991; Pfeifer & Bongard 2007). If we apply the principle of metastability there, we would ensure that there's also a certain chaotic variability between these strange attractors in order to maintain robustness and flexibility in our interactions with the environment (Kitano 2004; Rabinovich 2008). The best way to shift from one attractor into another is by changing the affordances, that is, one's abilities or the features of the environment. This may be achieved by changing the rhythm of the movement, its quality, the position in the environment. A small shift can already lead to reconfiguration of affordances and to the emergence of a new strange attractor, which is maintaining non-equilibrium stability but through a different kind of interaction.

Many body practices, such as Alexander technique or Noguchi Taiso (Kasai 1999; Noguchi 1979) ensure that the body is maintained in an open and sensitive state, making an emphasis on interconnections between the different parts. Any tension that exists in the body creates a block, which may influence its chaotic dynamics and decrease the scope of abilities and affordances available. Chaotic dynamics enables the body to be responsive to external impulses while maintaining internal stability (Yamada 1995). However, the cultural and social engagements are not always compatible with that naturally occurring rhythm. Prolonged periods of physical inactivity (such as sitting and reading) could be interrupted by another activity, which involves different muscle groups and provokes the body to shift its rhythm in order to maintain overall chaotic variability of one's physical motion, the heartbeat, and breathing. One's interactions with the environment, in terms of the affordances that are perceived, can also have the same variability in order to "refresh" the permanent niches. Instead, one can ensure that their point of view on the features of the environment and the abilities one possesses is constantly changing and that temporary niches of affordances are formed only to be replaced by the new ones, which might have some old elements, but still manage to offer the new possibilities for one's interaction with the environment.

Andy Clark said: "We do not just self-engineer better worlds to think in. We self-engineer ourselves to think and perform better in the worlds we find ourselves in." (Clark 2008)

6.3 Metastability of the Environment: Singularity vs. Polysingularity

Our interactions with the environment could also be modeled using the framework of networks. It's not such a far-fetched proposition given that such view is widely accepted in a variety of theoretical approaches from embodied cognition to actor-network theory (see Thompson 2007; Latour 2011). In this case, the networks that we engage with, that is, the semantic networks, the objects we interact with, the places that we travel to, the affordance niches that we create – will all contribute to the structure of the overall network that we are a part of.

Here we would like to discuss how the concept of metastability could be extended into the environment, including one's social interactions, environmental opportunities or affordances, as well as the emerging "network of things" made possible by the advance of ubiquitous computing.

Most of the real-world networks (that exist outside and often independently from our body) are known to be scale-free (Sole & Valverde 2004; Watts & Strogatz 1998; Newman et al 2006). Internet server networks, semantic networks, electronic circuits were all shown to have higher heterogeneity (scale-free degree distribution following power law), lower randomness, and lower modularity than cortical (brain) networks (Sole & Valverde 2004; Sporns 2010). Such networks can still be small world (in that they have a higher clustering than random networks with the same

connectivity), but the distribution of degree among the nodes varies much more. This leads to a less prominent community structure and lower capacity for global synchronization (Kuperman & Abramson 2001; Bragard et al 2007). Therefore, introducing a certain degree of randomness in their organization could increase the capacity of these networks to integrate information on the global level.

The relatively new field of ubiquitous computing is changing topology of our interactions with the environment. Its main proposition is to make networking so pervasive that everyday devices can sense their relationship to us and to each other (Vision et al 2002). The so-called “internet of things” proposes that every object gets their own IP address, creating the infrastructure that would allow for a more connected world, where things interact to one another and make rational choices, such as automatically choosing the right temperature for the laundry (Kranenburg 2006). The tech community seems to be very excited about these prospectives and fascination with the emerging field of singularity is proof of that (Kurzweil 2005). The proponents of singularity talk about the world where everything is connected to the extent that the new global consciousness emerges. But they seem to completely disregard the cognitive science research on what consciousness is. Somehow they think that when everything gets interconnected, consciousness will just pop up on its own. However, as we have seen above, the structural properties of this interconnectedness is the defining factor for the dynamics that can emerge from it. So far, singularity’s obsessive drive with interconnectedness is moving us to the scale-free network of things, mirroring the structure of the internet. That is, there’s a few, but significant number of hubs that have most of the connections, and most of the nodes have very few. This creates a modular structure that’s different than that of the brain’s small-world network. Communities depend much more on the hubs and lose their ability to maintain distinct states independent from the other regions of the global network that they belong to. At the same time, the ability of such network to synchronize is also reduced. Moreover, the filter bubble (Pariser 2011) which filters out information that doesn’t belong to one’s immediate surrounding, makes sure that those communities are densely connected together, but their access to each other is implemented only through hubs. This is the promise of singularity: severely isolated communities which are so densely connected within that there’s no space for heterogeneity of opinions inside. At the same time, these same communities can only interact through the hubs, which, in most cases, will be owned by the corporations implementing the digital infrastructure network that makes this “singularity” possible first place. A possible response to the advance of singularity could be polysingularity. The ubiquity of digital networks and the increasing density of connections could continue developing as there are many social and economical benefits to this process. However, polysingular approach would ensure this process advances with small-world network topology in mind. That is, the formation of distinct, interconnected communities, which allow for heterogeneity within, but can also engage into global interaction with one another. Polysingularity, thus, is the embrace of ubiquitous network advance, but with a certain limitation imposed for the sake of maintaining plurality of opinions and local idiosyncrasies (Figure 13).

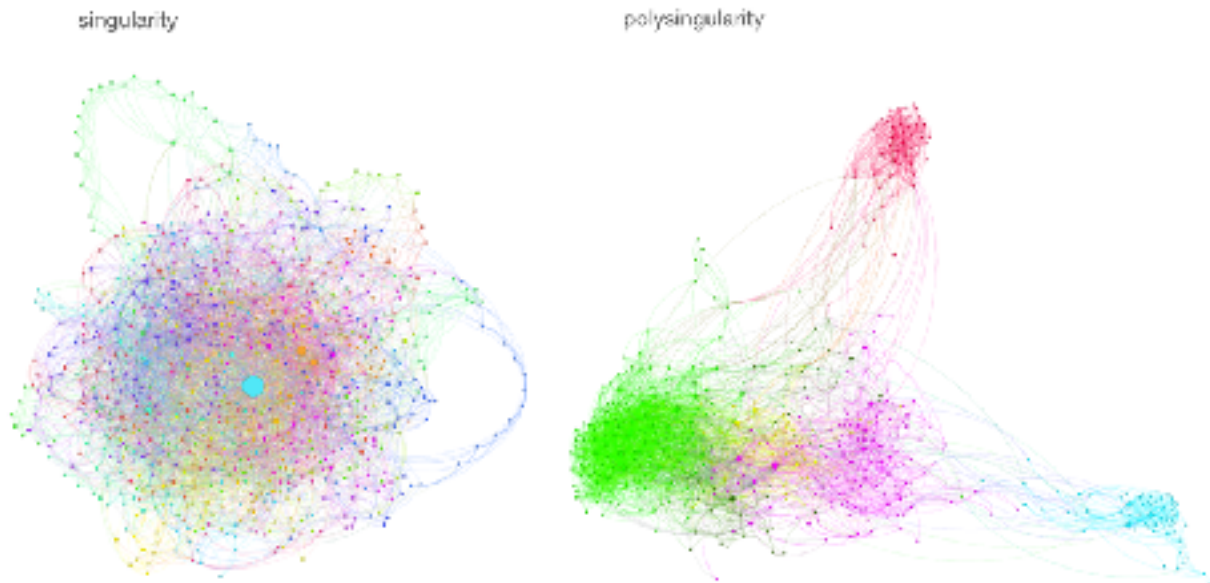


Figure 13: Singularity vs polysingularity

In singularity, networks are scale-free, the community structure is not very prominent, so they are relatively homogeneous. Such topology makes it difficult to maintain several distinct states and puts high importance on hubs for communication and global synchronization.

In polysingularity the networks have small-world properties, the community structure is more prominent, the networks are heterogeneous. Such topology makes it possible for the network to maintain several distinct states, which can synchronize globally using inter-community connections established both by peripheral and hub nodes.

The situation is such, that on the one hand, we have a very robust dynamic structure within the brain and the body defined by chaotic dynamics. On the other hand, there is the environment and the social networks, which are shifting towards a more interconnected topology. If we conceive of the cognitive network to include the social and environmental connectivities, then the fact that it's part of a more randomized structure might also affect its functioning and the ability to maintain metastability. We have shown above how certain mental diseases are a result of disturbed small-world topology, making it harder for distinct communities and modules to synchronize. Specifically, it has been shown above how Alzheimer disease and schizophrenia are characterized by lower clustering and higher connectivity in functional brain networks. If we extend the mind beyond the brain, we can see that exactly the same process is occurring in our environment. The incessant drive towards singularity is producing a cognitive network, which loses its small-world properties and, thus, its capacity to maintain metastable states. Further research is needed into the effects that external structures have on the psychological states of individuals, but on a larger scale the society and the environment are gradually shifting to the kind of connectivity, which is, in fact, schizophrenic. Gilles Deleuze gave a very interesting account of that tendency in his work "Capitalism and Schizophrenia" (Deleuze & Guittari 1983/2000). We've discussed in previous sections some effects that drugs have on neural networks. Specifically, MDMA was shown to increase high-frequency long-range synchronization across the different regions of the brain (Salomon et al 2011), while cannabis was shown to increase clustering, decrease global efficiency, and disrupt synchronization (Kim et al 2012). It could be interesting to explore whether drug use could be a response to the changing topology of the person's external networked involvements (e.g. their social network).

A possible resistance strategy to the advance of overall connectedness would be to retain a certain degree of disconnectedness in one's interactions with the environment. The easiest way to do that

is to make use of the spatial and physical limitations. Just like the brain network grows out randomly but is constrained by the space and energy limitations (Kaiser et al 2009; Kaiser & Hilgetag 2006; Sporns 2010), the humans could use the interface of their bodies to constrain the interconnectedness that emerges from ubiquitous computing. Practically that could mean taking a bike to see your friend instead of writing them on Facebook or refusing to use automated network assemblies that exclude human intelligence from making decision processes. This doesn't have to turn into some sort of neo-luddite practice of refusing technology. As we've shown above, a certain degree of randomness is very useful to ensure the capacity for global integration, but an occasional refusal to use the digital infrastructure that allows seamless sharing (Lohse 2003) and instead relying on one's own physical limitations, can play an important role in maintaining the capacity of our environment to be metastable.

7. Conclusion

The focal point of this paper has been the concept of metastability, or the ability of the brain to maintain several distinct states which can be globally integrated. Metastability emerges within human brain as a result of dynamic processes produced by the constantly evolving small-world neural network structure that underlies them. Brain networks have highly modular structure, synchronization within and between these modules ensures local and global integration. The structure of the brain is constantly evolving to maintain the capacity to integrate new information while retaining previous knowledge. The ongoing changes in synchronization patterns produce chaotic variability of different cognitive attractor states. These states are the patterns of non-equilibrium stability, which emerge as a result of interaction between different dynamic parameters (usually, groups of firing neurons that synchronize to form assemblies). The attractor states also engage sensorimotor activities, which produce movement, emotions, various perception modes and cognitive states. These states may have similar dynamics, such as chaotic swaying when standing still, or coordinated movement emerging through coupling between the different body parts.

We invoke the main posits of embodied cognition in order to demonstrate that cognitive network extends beyond the mind into the body and the environment. The key idea here is that of affordances, the relations between the physical and cognitive abilities of the body and the features of the environment. We then use the concept of extended cognitive network in order to propose a holistic view of the body-mind-environment system.

Finally, we ask how the concept of metastability, which is well-defined on the level of neural activity, can be extrapolated to the extended cognitive network that includes the body and the environment. We have shown how metastability plays an important role in maintaining robustness, adaptability, and flexibility of the neural network, as well as its ability to maintain distinct states and to integrate on a global level. We then assume it is equally important to explore the possibilities for the production of similar dynamics in the extended cognitive network that includes the body and the environment. In order to be able to perform this extrapolation we divide, following the posits of situated cognition and actor-network theory, the extended cognitive network into the social network, the network of affordances (or the relations between the abilities of the body and the features of the environment), and the network of things or objects around us. We then show the extent to which the structure of each of these networks is compatible to emergence of metastability.

Specifically, we find that while social networks have a tendency to self-organize so that small-world network topology emerges, there are also external forces that push social networks towards increased connectivity and reduced heterogeneity (the formation of so-called “filter bubbles”). The boundaries between the communities are effaced and those communities which cannot be merged are pushed further apart. This disturbs the ability of such networks to synchronize, and the increased homogeneity of connections makes them more prone to uncontrolled oscillations. The same structural changes in cortical neural networks lead to conditions such as schizophrenia and Alzheimer disorder. Therefore we also ask how much such change in the social structures can incur the advance of these psychological diseases among the affected individuals (it’s merely an assumption and a proposition for a possible thread for future research). We also propose various social strategies to maintain small-world structure within one’s social interactions. These include being part of several distinct groups, forging random links between the periphery members, ensuring the constant transformation of one’s social involvements. We provide references for empirical research that confirms that such social behaviors are more typical for diverse and healthy social environments.

We also ask how the concept of metastability could be introduced in one’s own relation to the body and the environment. It is a much more difficult question methodologically because of the difficulties encountered when attempting to model such interactions using the framework of

networks. However, we draw on the theory of affordances and ubiquitous computing (the internet of things) in order to offer some preliminary suggestions. We find that using the interface of the body in one's interactions with the environment ensures the emergence of metastability. Specifically, the current drive towards total interconnectedness proclaimed by the proponents of singularity (as well as the interested corporations) leads to scale-free organization of extended network topology, where connections are distributed according to Power law (winner takes all), hubs exert high influence on the network, and community structure becomes less prominent. We propose that actively using the body (and all its limitations in relation to space and energy) may ensure that the resulting network will shift towards the more prominent community structure characteristic of small-world topology (we refer to this process as polysingularity). This, in turn, ensures that metastable states can continue to emerge on the physical and environmental level, creating potential for diversity while still retaining the possibility for global integration. It has been shown that naturally the body has a tendency to fall into temporarily sustained non-equilibrium stable attractor states (e.g. chaotic swaying when still, coordinated coupling of the legs and swaying arms when moving, chaotic patterns of heartbeat). We show how various body practices can be used to ensure that these natural chaotic processes remain active in response to the limitations imposed by the activities produced by our cultural and social contexts.

Overall, methodological robustness is not the purpose of this introductory paper. We mainly attempt to show that an approach such as ours could be beneficial and feasible. Our proposition to explore how metastability can be maintained in one's extended cognitive network is a result of our inspiration with the brain's network dynamics. The latest advances in neuroscience reveal the processes behind inherent robustness and flexibility of the human brain. In this paper we want to propose the different ways how these processes could possibly be used to inform our interactions with our bodies, our environment, and with each other. And even though we are at the very beginning of this journey, we hope to open up some threads for the future research. We hope to demonstrate the potential that lies in multidisciplinary collaboration between the various fields we brought together in this paper: from the study of neural dynamics, to network science, to embodied cognitive science, psychology, and sociology.

References

- Arieli A, Shoham D, Hildesheim R, Grinvald A (1995) Coherent spatiotemporal patterns of ongoing activity revealed by real-time optical imaging coupled with single-unit recording in the cat visual cortex. *J Neurophysiol* 73:2072–2093.
- Arieli A, Sterkin A, Grinvald A, Aertsen A (1996) Dynamics of ongoing activity: explanation of the large variability in evoked cortical responses. *Science* 273:1868–1871.
- Baars, B. J., & Franklin, S. (2009). *Consciousness is computational: the lida model of global workspace theory*. Cycle.
- Barahona, M., & Pecora, L. M. (2002). Synchronization in Small-world systems. *Physical Review Letters*, 89(5), 54101. APS.
- Bassingthwaite, J. B., Liebovitch, L. S., & West, B. J. (1994). *Fractal physiology*. booksgooglecom (Vol. 11, pp. 40-46). Oxford University Press. doi:10.1109/51.139035
- Bateson, G (1972/2000). *Steps to an Ecology of Mind: Collected Essays in Anthropology, Psychiatry, Evolution and Epistemology*. University of Chicago Press.
- Bernardo, M., Garofalo, F., & Sorrentino, F. (2005). Synchronizability and synchronization dynamics of unweighed scale free networks with degree mixing. *IEEI*, 1-22.
- Bragard, J., Vidal, G., Mancini, H., Mendoza, C., & Boccaletti, S. (2007). Chaos suppression through asymmetric coupling. *Chaos (Woodbury, N.Y.)*, 17(4),
- Brassier, R. (2007). *Nihil Unbound: Enlightenment and Extinction*. Leonardo (Vol. 42). Palgrave McMillian. doi:10.1162/leon.2009.42.5.459
- Bullinaria, J. a. (2007). Understanding the emergence of modularity in neural systems. *Cognitive science*, 31(4), 673-95. doi:10.1080/15326900701399939
- Bystritsky, a, Nierenberg, a a, Feusner, J. D., & Rabinovich, M. (2012). Computational non-linear dynamical psychiatry: A new methodological paradigm for diagnosis and course of illness. *Journal of psychiatric research*, 46(4), 428-435. Elsevier Ltd. doi:10.1016/j.jpsychires.2011.10.013
- Cacioppo, J. T., Fowler, J. H., & Christakis, N. A. (2009). Alone in the crowd: the structure and spread of loneliness in a large social network. *Journal of Personality and Social Psychology*, 97(6), 977-991. NIH Public Access. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/19968414>
- Chemero, A. (2003). An Outline of a Theory of Affordances. *Ecological Psychology*, 15(2), 181-195. doi:10.1207/S15326969ECO1502_5
- Chemero, A. (2008). Self-Organization, Writ Large. *Ecological Psychology*, 20(3), 257-269. doi: 10.1080/10407410802189372
- Chemero, A. (2009). *Radical Embodied Cognitive Science*, p. 18. MIT Press.
- Cherkassky, V. L., Kana, R. K., Keller, T. a, & Just, M. A. (2006). Functional connectivity in a baseline resting-state network in autism. *Neuroreport*, 17(16), 1687-90. doi:10.1097/01.wnr.0000239956.45448.4c

- Chen, S.-S., Tu, P.-C., Su, T.-P., Hsieh, J.-C., Lin, Y.-C., & Chen, L.-F. (2008). Impaired frontal synchronization of spontaneous magnetoencephalographic activity in patients with bipolar disorder. *Neuroscience Letters*, 445(2), 174-8. doi:10.1016/j.neulet.2008.08.080
- Clark, A. (2008). *Supersizing the mind: Embodiment, Action, and Cognitive Extension*. *Consciousness and Cognition*. Oxford University Press. Retrieved from <http://philosophy-online.de/pdf/clark.pdf>
- Cosmelli, D., Lachaux, J.-philippe, & Thompson, E. (2006). *Neurodynamics of Consciousness*. *Dynamical Systems*.
- Damasio, H. & Damasio A.R. (1989). *Lesion Analysis in Neuropsychology*. Oxford University Press.
- Dewey, J (1934). *Art as Experience*.
- Dewey, J. (1938/1997). *Experience and education*. Macmillan.
- D'Mello, S., Dale, R., & Graesser, A. (2011). Disequilibrium in the mind, disharmony in the body. *Cognition & emotion*, 00(00), 1-13. doi:10.1080/02699931.2011.575767
- Dresler, M., Koch, S. P., Wehrle, R., Spoormaker, V. I., Holsboer, F., Steiger, A., Sämann, P. G., et al. (2011). Dreamed Movement Elicits Activation in the Sensorimotor Cortex. *Current Biology*, 21(Figure 1), 1-5. Elsevier. doi:10.1016/j.cub.2011.09.029
- Edelman, G. M., & Gally, J. a. (2001). Degeneracy and complexity in biological systems. *Proceedings of the National Academy of Sciences of the United States of America*, 98(24)
- Engel, a K., Fries, P., König, P., Brecht, M., & Singer, W. (1999). Temporal binding, binocular rivalry, and consciousness. *Consciousness and cognition*, 8(2), 128-51. doi:10.1006/ccog.1999.0389
- Fair, D. A., Cohen, A. L., Power, J. D., & Church, J. A. (2009). Functional brain networks develop from a “local to distributed” organization. *PLoS Computational Biology*.
- Fodor, J.A. (1981). *Representations*. Cambridge: MIT Press.
- Fodor, J. A., & Pylyshyn, Z. W. (1988). Connectionism and cognitive architecture: a critical analysis. *Cognition*, 28(1-2), 3-71. Elsevier. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/2450716>
- Fontanini, A., & Katz, D. B. (2008). Behavioral states, network states, and sensory response variability. *Journal of neurophysiology*, 100(3), 1160-8. doi:10.1152/jn.90592.2008
- Fowler, J. H., & Christakis, N. a. (2008). Dynamic spread of happiness in a large social network: longitudinal analysis over 20 years in the Framingham Heart Study. *British Medical Journal*, 337(dec04 2), a2338-a2338. doi:10.1136/bmj.a2338
- Frei, E., Gamma, a, Pascual-Marqui, R., Lehmann, D., Hell, D., & Vollenweider, F. X. (2001). Localization of MDMA-induced brain activity in healthy volunteers using low resolution brain electromagnetic tomography (LORETA). *Human brain mapping*, 14(3), 152-65. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/11559960>
- Gallese, V. (2003). A neuroscientific grasp of concepts: from control to representation. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 358(1435), 1231-40.

- Gibson, J. J. (1979). The ecological approach to visual perception. (C. University, Ed.) of Experimental Psychology Human Perception and (Vol. 39, p. 332). Houghton Mifflin. Retrieved from <http://books.google.com/books?id=SBF9AAAAMAAJ&pgis=1>
- Gross, T., & Blasius, B. (2008). Adaptive coevolutionary networks: a review. *Journal of the Royal Society, Interface / the Royal Society*, 5(20), 259-71. doi:10.1098/rsif.2007.1229
- Gomez-Gardenes, J., Moreno, Y., & Arenas, A. (2008). Paths to Synchronization on Complex Networks. *Network*, (3), 1-4.
- Haugeland, J. (1985). *Artificial Intelligence: The Very Idea*. Bradford Books (p. 287 p.). MIT Press. Retrieved from <http://www.amazon.com/dp/0262580950>
- Holme, P., & Ghoshai, G. (2006). Dynamics of Networking Agents Competing for High Centrality and Low Degree. *Physical Review Letters*.
- Hutchins, E. (2010). Cognitive Ecology. *Topics in Cognitive Science*, 2(4).
- James, W. (1890/2007). *Principles of Psychology*. Cosimo.
- Jensen, O., Bonnefond, M., & VanRullen, R. (2012). An oscillatory mechanism for prioritizing salient unattended stimuli. *Trends in cognitive sciences*, 16(4).
- Johnson, M. (2008). *The Meaning of the Body. Developmental perspectives on embodiment*. Chicago Univeristy Press.
- Just, M. A., & Varma, S. (2007). The organization of thinking : What functional brain imaging reveals about the neuroarchitecture of complex cognition The organization of thinking : What functional brain imaging reveals about the neuroarchitecture. *Cognitive, Affective, and Behavioral Neuroscience*.
- Kaiser, M., & Hilgetag, C. C. (2006). Development of multi-cluster cortical networks by time windows for spatial growth. *Neurocomputing*, 70(10-12), 1829-1832.
- Kaiser, M., Goerner, M., & Hilgetag, C. C. (2008). Criticality of spreading dynamics in hierarchical. *Computing*, 1-14.
- Kaiser, M., Hilgetag, C. C., & van Ooyen, A. (2009). A simple rule for axon outgrowth and synaptic competition generates realistic connection lengths and filling fractions. *Cerebral cortex (New York, N.Y. : 1991)*, 19(12), 3001-10. doi:10.1093/cercor/bhp071
- Kasai, T. (1999). A Butoh Dance Method for Psychosomatic Exploration. *Memoirs of the Kokkaido Institute of Technology*, (27).
- Kashtan, N., & Alon, U. (2005). Spontaneous evolution of modularity and network motifs. *Proceedings of the National Academy of Sciences of the United States of America*, 102(39), 13773-8. doi:10.1073/pnas.0503610102
- Keeling, M. J. (1999). The effects of local spatial structure on epidemiological invasions. *Proceedings. Biological sciences / The Royal Society*, 266(1421), 859-67. doi:10.1098/rspb.1999.0716
- Kennedy, J. (1999). Small Worlds and Mega-Minds: Effects of Neighborhood Topology on Particle Swarm Performance. *Proceedings of the 1999 Congress on Evolutionary Computation*, 3.

- Kennedy, J. (2009). Social Optimization in the Presence of Cognitive Local Optima: Effects of Social Network Topology and Interaction Mode. *Topics in Cognitive Science*, 1(3), 498-522. Blackwell Publishing Ltd. doi:10.1111/j.1756-8765.2009.01035.x
- Kim, D., Skosnik, P., Cheng, H., Pruce, B., Brumbaugh, M., Vollmer, M., Hetrick, W., et al. (2012). Structural Network Topology Revealed by White Matter Tractography in Cannabis Users: A Graph Theoretical Analysis. *Brain Connectivity*.
- Knyazev, G. (2007). Motivation, emotion, and their inhibitory control mirrored in brain oscillations. *Neuroscience & Biobehavioral Reviews*, 31(3), 377-395. Elsevier. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/17145079>
- Knyazev, G.; Slobodskoi-Plyusnin, Y.; Savost'yanov, E; Levin, A; Bocharov, A;. (2008). *Zhurnal Vysshei Nervnoi Deyatel'nosti imeni I. P. Pavlova*, Vol. 58, No. 5, pp. 576–583, September–October.
- Klyubin, A. S., Polani, D., & Nehaniv, C. L. (2008). Keep your options open: an information-based driving principle for sensorimotor systems. *PloS one*, 3(12), e4018.
- Kohler, E., Keysers, C., Umiltà, M. A., Fogassi, L., Gallese, V., & Rizzolatti, G. (2002). Hearing sounds, understanding actions: action representation in mirror neurons. *Science (New York, N.Y.)*, 297(5582), 846-8.
- Kranenburg, R. van. (2006). The Internet of things. (G. Lovink & S. Niederer, Eds.), 4(6), 20. Institute of Network Cultures. doi:10.1049/ce:20060603
- Krueger, J. (2011). Extended cognition and the space of social interaction. *Consciousness and cognition*, 20(3), 643-57. Elsevier Inc. doi:10.1016/j.concog.2010.09.022
- Kugler, P., Kelso, S., & Turvey, M. T. (1980). On the Concept of Coordinative Structures as Dissipative Structures. *Tutorials in Motor Behavior*.
- Kuperman, M., & Abramson, G. (2001). Small World Effect in an Epidemiological Model. *Physical Review Letters*, 86(13), 2909-2912. doi:10.1103/PhysRevLett.86.2909
- Kurzweil, R. (2005). *The Singularity Is Near: When Humans Transcend Biology*. book (Vol. 2011, p. 652). Viking. Retrieved from <http://www.amazon.com/Singularity-Near-Humans-Transcend-Biology/dp/0670033847>
- Latour, B. (2011). Networks, Societies, Spheres: Reflections of an Actor-Network Theorist. *Journal of Communication*, 5, 796-810.
- Law, J. (1992). Notes on the theory of the actor-network: ordering, strategy, and heterogeneity. *Systemic Practice and Action Research*, 5(1992).
- Leopold, D. A., Murayama, Y., Logothetis, N. K., & Planck, M. (2003). Very Slow Activity Fluctuations in Monkey Visual Cortex: Implications for Functional Brain Imaging. *Cerebral Cortex*, 422-433.
- Lima, M (2011). *Visual Complexity: Mapping Patterns of Information*. Princeton University Press.
- Liu, Z., & Hu, B. (2005). Epidemic spreading in community networks. *Europhysics Letters*, 72(2), 315-321. IOP Publishing. doi:10.1209/epl/i2004-10550-5

- Lipson, H., Pollack, J. B., & Suh, N. P. (2002). On the origin of modular variation. *Evolution: International Journal of Organic Evolution*, 56(8), 1549-1556. The Society for the Study of Evolution.
- Lohse, M. (2002). Dynamic Distributed Multimedia : Seamless Sharing and Reconfiguration of Multimedia Flow Graphs. *Architecture*, 89-95.
- Mandelbrot, B (1999). Multifractal systems and 1/f noise.
- Matsushita, H., & Nishio, Y. (2009). Network-Structured Particle Swarm Optimizer with Small-World Topology. *International Symposium on Nonlinear Theory and its Applications NOLTA'09*, Sapporo, Japan, October 18-21, 2009, 1, 372-375.
- Merleau-Ponty (1964). *Sings*. Northwestern University Press.
- Maturana R & Varela, F (1992). *The Tree of Knowledge: The Biological Roots of Human Understanding*. Shabhala Press.
- Meunier, D., Achard, S., Morcom, A., & Bullmore, E. (2009). Age-related changes in modular organization of human brain functional networks. *NeuroImage*, 44(3), 715-23. Elsevier B.V. doi: 10.1016/j.neuroimage.2008.09.062
- Micheloyannis, S., Pachou, E., Stam, C. J., Breakspear, M., Bitsios, P., Vourkas, M., Erimaki, S., et al. (2006). Small-world networks and disturbed functional connectivity in schizophrenia. *Schizophrenia research*, 87(1-3), 60-6. doi:10.1016/j.schres.2006.06.028
- Newman, M.; Strogatz, S.H.; Watts, D.J.; (2001). Random Graphs with Arbitrary Degree Distributions and Their Applications. In *Physical Review E*, Vol 64, 2
- Newman, M., Barabasi, A., Watts, D.J., (2006). *The Structure and Dynamics of Networks*. Princeton University Press
- Nir, Y., Hasson, U., Levy, I., Yeshurun, Y., & Malach, R. (2006). Widespread functional connectivity and fMRI fluctuations in human visual cortex in the absence of visual stimulation. *NeuroImage*, 30(4), 1313-24.
- Nishikawa, T., Motter, A. E., Lai, Y.-cheng, & Hoppensteadt, F. C. (2003). Heterogeneity in oscillator networks: Are smaller worlds easier to synchronize?, 014101, 1-5.
- Noguchi, M (1979). *Noguchi Taiso, Omosa ni Kiku. Noguchi physical exercise, ask the gravity*. Hakujuha
- Paranyushkin, D (2011). *Inclusive Exclusivity: How to Build Open and Innovative Cultural Networks*. Nodus Labs
- Pariser, E. (2011). *The Filter Bubble*. Penguin Press.
- Passaro, A., & Starita, A. (2008). Clustering particles for multimodal function. *Journal of Artificial Evolution and Applications*. Proceedings of the IEEE.
- Pfeifer, R., & Bongard, J. (2007). *How the body shapes the way we think*. MIT Press Cambridge MA. MIT Press.
- Price, C. J., Friston, K. J., & Price, C. J. (2002). Degeneracy and cognitive anatomy. *Trends in Cognitive Sciences*, 6(10), 416-421.

- Prill, R. J., Iglesias, P. a, & Levchenko, A. (2005). Dynamic properties of network motifs contribute to biological network organization. *PLoS biology*, 3(11), e343. doi:10.1371/journal.pbio.0030343
- Rabinovich, M. I., & Muezzinoglu, M. K. (2010). Nonlinear dynamics of the brain: emotion and cognition. *PhysicsUspekhi*, 53(4), 357-372. doi:10.3367/UFNe.0180.201004b.0371
- Richardson, M. J., Marsh, K. L., Isenhowe, R. W., Goodman, J. R. L., & Schmidt, R. C. (2007). Rocking together: dynamics of intentional and unintentional interpersonal coordination. *Human movement science*, 26(6), 867-91. doi:10.1016/j.humov.2007.07.002
- Rodriguez, E., & George, N. (1999). Perception's shadow : long-distance synchronization of human brain activity. *Nature*, 397 (February).
- Rosenquist, J. N., Fowler, J. H., & Christakis, N. A. (2011). Social network determinants of depression. *Molecular Psychiatry*, 16(3), 273-281. Nature Publishing Group. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/20231839>
- Rowlands, M. (2005). *Externalism: Putting Mind and World Back Together Again*. Australasian Journal of Philosophy, 83(1), 0. {McGill-Queen's University Press}.
- Rubinov, M., Knock, S. A., Stam, C. J., Micheloyannis, S., Harris, A. W. F., Williams, L. M., & Breakspear, M. (2009). Small-world properties of nonlinear brain activity in schizophrenia. *Human Brain Mapping*, 30(2), 403-416. Nature Publishing Group. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/18072237>
- Salomon, R. M., Karageorgiou, J., Dietrich, M. S., McLellan, J. Y., Charboneau, E. J., Blackford, J. U., & Cowan, R. L. (2011). MDMA (Ecstasy) association with impaired fMRI BOLD thalamic coherence and functional connectivity. *Drug and Alcohol Dependence*. Elsevier Ireland Ltd. doi: 10.1016/j.drugalcdep.2011.06.022
- Shusterman, R. (2008). *Somaesthetics: A Disciplinary Proposal*. The Journal of Aesthetics and Art Criticism, 57(3), 299-313.
- Smith, S. M., Fox, P. T., Miller, K. L., Glahn, D. C., Fox, P. M., Mackay, C. E., Filippini, N., et al. (2009). Correspondence of the brain 's functional architecture during activation and rest. *PNAS*.
- Soltesz, I. (2005). *Diversity in the Neuronal Machine: Order and Variability in Interneuronal Microcircuits*. University of Oxford Press. Chicago.
- Soltesz, I., & Staley, K. (2006). High times for memory: cannabis disrupts temporal coordination among hippocampal neurons. *Nature Neuroscience*, 9(12), 1461-1463. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/17128279>
- Sporns, O. (2006). Small-world connectivity, motif composition, and complexity of fractal neuronal connections. *Biosystems*, 85(1).
- Sporns, O. (2010). *Networks of the Brain*. MIT Press. Retrieved from <http://mitpress.mit.edu/catalog/item/default.asp?tttype=2&tid=12288>
- Stam, C. J., & Reijneveld, J. C. (2007). Graph theoretical analysis of complex networks in the brain. *Nonlinear biomedical physics*, 1(1), 3. doi:10.1186/1753-4631-1-3

- Thompson, E., & Varela, F. J. (2001). Radical embodiment: neural dynamics and consciousness. *Trends in cognitive sciences*, 5(10), 418-425. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/11707380>
- Thompson, E. (2007). *Mind in Life: Biology, Phenomenology, and Sciences of Mind*. Harvard University Press.
- Tsuda, I. (2001). Toward an interpretation of dynamic neural activity in terms of chaotic dynamical systems. *The Behavioral and brain sciences*, 24(5), 793-810; discussion 810-48. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/12239890>
- Turvey, M. (1992). Affordances and prospective control: An outline of the ontology. *Ecological Psychology*, 4(3).
- Varela F. (1995). Resonant cell assemblies: a new approach to cognitive functions and neuronal synchrony. *Biological Research*
- Varela, F., Lachaux, J.-philippe, Rodriguez, E., & Martinerie, J. (2001). The Brainweb: Phase Large-Scale Integration. *Neuroscience*, 2 (April).
- Variano, E. a., & Lipson, H. (2004). Networks, Dynamics, and Modularity. *Physical Review Letters*, 92(18), 1-4. doi:10.1103/PhysRevLett.92.188701
- Vision, R. W. S., Estrin, D., Culler, D., & Pister, K. (2002). Connecting the Physical World with Pervasive Networks. *Pervasive Computing IEEE*, 1(1), 59-69.
- Wagner, G. P., Pavlicev, M., & Cheverud, J. M. (2007). The road to modularity. *Nature reviews. Genetics*, 8(12), 921-31. doi:10.1038/nrg2267
- Wang, L., Zhu, C., He, Y., Zang, Y., Cao, Q., Zhang, H., Zhong, Q., et al. (2009). Altered small-world brain functional networks in children with attention-deficit/hyperactivity disorder. *Human brain mapping*, 30(2), 638-49. doi:10.1002/hbm.20530
- Watts, D. J., & Strogatz, S. H. (1998). Collective dynamics of "small-world" networks. *Nature*, 393(6684), 440-2. Nature Publishing Group.
- Watzlawick, P., Beavin, J. H., & Jackson, D. D. (1967). *Pragmatics of Human Communication*. (B. S, Ed.) *Dissertation Abstracts International*, 44(1-B), 356. W W Norton & Company. doi: 10.1177/003803856900300341
- Wills, T. J., Lever, C., Cacucci, F., Burgess, N., & Keefe, J. O. (2009). UKPMC Funders Group Attractor Dynamics in the Hippocampal Representation of the Local Environment, 308(5723), 873-876. doi:10.1126/science.1108905.Attractor
- Yamada, N. (1995). Posture as a Dynamic Stable State of a Body. *Research and Clinical Center for Child Development*.
- Yan, G., Fu, Z.-qian, Ren, J., & Wang, W.-xu. (2008). Collective Synchronization Induced by Epidemic Dynamics on Complex Networks with Communities. *Science And Technology*, 0, 3-7.
- Zhou, J., Liu, Z., & Li, B. (2007). Influence of network structure on rumor propagation. *Physics Letters A*, 368(6), 458-463. doi:10.1016/j.physleta.2007.01.094