

Raw cognition

Rhythms as dynamic constraints*

There is increasing evidence that the rhythmic interactions between intrinsic oscillators both in the body and in the brain play a constitutive role in cognition. However, the mechanisms and extent of these interactions are yet to be fully understood. In this article, I will contend that a notion of rhythm as an open entrainment can be useful for enactive approaches to different aspects of cognition. It allows us to think of the different oscillators that we find in the body, the brain, and the environment as nested dynamic constraints that through neuronal and non-neuronal interactions tie together the different domains while retaining their specific functions.

Keywords: Rhythm, Constraint, Entrainment, Dewey, Enactivism

1 Introduction

From an enactive point of view, cognition starts with an interaction. It does not matter whether we refer to the attunement between the actions of different subjects, to the engagement between an agent and its environment, or to the regulation between different aspects constitutive of cognition. Wherever we lay our eyes, we see oscillatory components interacting. However, the moment we isolate one of these temporal patterns and try to replicate the circumstances that have originated it, everything becomes more complicated. It is as if the particular pattern affects and is affected by the whole set. The enactivist position could be summed up as follows: the brain, body, and environment are dynamically combined into a system through physical relational processes in which significant changes in one part of the system cause changes in the other parts (Gallagher 2017, 8). Although enactivism is at the spearhead of this emphasis on dynamic aspects of cognition, cognitive science research in general points to a steady transition from a focus on stability to a focus on time-evolving interactions. In this paper, I will argue that a concept of rhythm based on entrainment rather than on order or repetition can be useful for enactive approaches to cognition, for it allows us to think of the different oscillators that we find in the body, brain, and environment as parts of nested dynamic constraints that nonlinearly modulate cognition¹. I will start by viewing this notion in relation to pre-

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¹The idea that the complexity of cognition can only be understood through nonlinear dynamics – i.e., the branch of physics that studies systems governed by equations more complex than the linear $aX+b$ form – has been widely accepted since the seminal works by Freeman (1992) and Port and van Gelder (1995).

Socratic and Deweyan understandings of rhythm. I will then identify some neuronal and non-neuronal oscillatory activity originating in the body, the brain, and the environment, and their interactions through entrainment. In the final section, I will lay the foundation for an enactive view of cognition based on rhythms as nested dynamic constraints.

2 Chasing rhythms

The earliest preserved account of the word ῥυθμός (*rhuthmós*) is found in a poem by Archilocus in which, according to Barletta (2020, 3), it denotes

a force that not only limits or constrains all humans [...] but one that also gives us form and meaning, pushing us always toward a mean between two forces.

This notion is related to the atomist idea of *rhuthmós* as “the form in the instant that it is assumed by what is moving, mobile and fluid, the form of that which does not have organic consistency” (Benveniste 1971, 285-286). In particular, the –θμός form indicates not the final state of a process, but the way it presents itself to the human eye as it takes place (Benveniste 1971, 285). *Rhuthmós* denotes the perceivable

pattern of a fluid element, or a letter arbitrarily shaped, of a robe which one arranges at one’s will, of a particular state or mood. It is the form as improvised, momentary, changeable. (Benveniste 1971, 286)

In its earliest use, *rhuthmós* meant a temporary interaction of forces. Nowadays the most widespread understanding of rhythm is as a regular temporal pattern of elements. We find iterations of this definition in dictionaries, papers, and scientific literature. The origins of this conceptualization can be traced back to Plato’s *Laws*, in which he defines rhythm as “order in movement” (665a). However, the debate on rhythm is far from settled.

In cognitive science rhythm is an important concept; however, there is no consensus on what rhythm is. In one paper aptly titled “What do we talk about when we talk about rhythm?”, Obleser, Henry and Lakatos (2017, 1) acknowledge that

we are still lacking a good working definition of rhythm. What does rhythm mean to a human or non-human brain, and to a perceiver more generally, and how variable does a sequence of events need to be so that our brains will cease to register it as rhythmic?

Leaving aside the cognitivism which transpires from the assumption that only the brain is implied in rhythmic perception and that this is a passive event which we just perceive or register, they highlight the most pressing question concerning the Platonic definitions of rhythm: how much variability can a rhythm display without ceasing to be a rhythm? This issue has given rise to an abundance of terms such as quasi-rhythm, pseudo-rhythm, and quasi-regular rhythm, which contribute to the lack of conceptual clarity. The tentative answer to the question provided by Obleser, Henry, and Lakatos (2017, 4) is:

regularity manipulations themselves need to be of sufficient magnitude and quality to modulate both percepts of rhythmicity and entrainment of a (neural or other) oscillator. Even then our beloved tools for dissecting rhythmic and non-rhythmic processes in the neural domain can be turned into rusty blades by notorious interpretational problems. This should encourage us to humbly spell out our predictions in those domains where rhythm truly resides: in perception and behavior.

That is, we have a rhythm as long as it simultaneously affects perceptual experience and its underlying entrainment. In my opinion, their definition is far too restrictive to be useful for enactive approaches to cognition: are higher cognitive processes devoid of rhythm? Is there no entrainment between brain oscillatory activity and bodily oscillatory activity? Nonetheless, I wish to draw attention to this notion of entrainment. Lakatos, Gross and Thut (2019, 890) define entrainment as “phase locking resulting from (predominantly) unidirectional coupling”. From their point of view, entrainment denotes the mechanisms by which periodic or almost periodic events from the environment – e.g., music, speech, movements, day-night cycles – drive the oscillatory activity in the perceiver’s brain, leading to the alignment – phase-locking in neuroscientific jargon – of their frequencies. I regard this to be a strong version of entrainment. However, there are weaker versions of it too. Many studies consider entrainment to mean not just perfect phase-locking, but also the general tendency toward this state (Pikovsky, Rosenblum, Kurths 2001). And they view it not as an exclusively unidirectional process,

but as one involving two or more self-sustained oscillators (Rimmele et al. 2018). I believe that assuming these two conditions implies a weaker but more open version of entrainment, which is the one that I will support in this paper². From my point of view, when Trost and Vuilleumier (2013) speak of perceptual, autonomic physiological, motor and social types of entrainment, they also back a weaker understanding of entrainment. And although the regulation between these different levels of entrainment is still open to discussion, Trost, Labbé, and Grandjean (2017, 105) suggest that these different types of entrainment are part of the same phenomenon.

Coming back to philosophy, I think that John Dewey is among the few thinkers to have developed an idea of rhythm that resonates with aspects of the pre-Socratic notion of *rhuthmós*. Dewey maintains that nature is ripe with different types of temporal patterns, and that rhythm is the kind of pattern which has the capacity to build up energy, as in the case of

a pond moving in ripples, forked lightning, the waving of branches in the wind, the beating of a bird's wing, the whorl of sepals and petals, changing shadows of clouds on a meadow. (Dewey 1980, 161)

That is, while remaining faithful to the temporal aspect of rhythm, he goes off the beaten track when he decides to base his idea of rhythm on variations of intensity or speed rather than repetition (Dewey 1980, 160). Dewey (1980, 179) believes that experience is rhythmic too, as long as it carries within itself

a summing up and each step forward is at the same time a summing up and fulfillment of what precedes, and every consummation carries expectations tensely forward.

² Despite this weaker understanding, entrainment still differs from other close concepts such as resonance. Rimmele et al. 2018 define resonance as “a passive phenomenon where neuronal responses reflect the stimulation frequency. This is generally distinguished from oscillatory phenomena, where neurons oscillate at a preferred frequency in the absence of stimulation and can entrain to an external stimulation” (872). Another important difference is that episodes of resonance only last while there is an oscillatory interaction and that they only take place as long as the frequencies of the oscillating elements are the same or nearly the same. On the contrary, once there has been an influence in the phase between two entrained oscillations, if we separate them, entrainment will not immediately disappear, but will last for some time after the interaction (Pikovsky, Rosenblum, Kurths 2001).

For Dewey, rhythm is a form of energy rearrangement, common to nature and certain instances of experience, characterized by accumulation and unity; it is not a measurable quantity, but the form of an event:

an operation through which material effects its own culmination in experience. (Dewey 1980, 152)

I have presented elsewhere (Author 2020, 88) a notion of rhythm as “an evolving pattern of oscillations able to entrain other oscillations”. With this definition, I intended to highlight the fact that the necessary condition for a rhythm is its capacity to influence and be influenced by other oscillations and that, when this occurs, these oscillations become part of the rhythm. This conceptualization does not neglect the temporal character of rhythms – it is encapsulated in the word ‘evolving’ – but makes continuity and pervasiveness their main feature. By this notion of rhythm I am trying to bring together some aspects already present in the ancient notion of *rhuthmós* – i.e., its nature as an emergent force that constrains us – and Dewey’s idea of rhythm as a common feature of nature and experience. This definition aims to make rhythm an extremely relational concept. Rhythm not as a fixed property, but a pattern that emerges from the interaction of (at least) two oscillatory elements. It is almost a fractal phenomenon. Speaking of human beings, we can focus on the emergent rhythm of the contraction of the heart – originating with the interaction of electric impulses generated by cells of the sinoatrial node – but this rhythm can also be regarded as part of a bigger rhythm, along with other mechanical rhythms related to respiration and gastric activity that are reciprocally regulated. And this resultant bodily rhythm can be considered an element belonging to a much more complex rhythm, together with brain and environmental oscillations, all of which enact a dynamic constraint that affects the whole through entrainment.

The idea of rhythms as dynamic constraints stems from the three mutually constraining dimensions of embodiment defined by Thompson and Varela (2001):

Three kinds of cycles need to be distinguished for higher primates:

- (1) cycles of organismic regulation of the entire body.
- (2) cycles of sensorimotor coupling between organism and environment.

(3) cycles of intersubjective interaction, involving the recognition of the intentional meaning of actions and linguistic communication (in humans) (424)

They argued that these cycles are reciprocal relationships between neural events and conscious activity (2001, 425). I consider that this idea, in light of recent research, can be expanded and become useful for non-neural rhythmic oscillations insofar as it incorporates a notion of rhythm based on entrainment. In doing so, we can look at the micro level – the interaction of individual oscillators – or at the macro level – the interaction between elements that already behave individually as rhythms – and we will find nested dynamic constraints that affect both specific and general aspects of cognition. Therefore, a definition of rhythm as evolving entrainment is not subject to formal problems of variability and repetition, since we can verify the existence or non-existence of entrainment. I thus believe it is possible to speak of a general cognitive rhythm that works as a dynamic constraint on cognition. Nonetheless, this does not mean that we can register a unitary, constant oscillation along the body. It means that different oscillations originating in places as different as our intestine, the thalamus, or the person we are looking at are connected in such a way that variation in one of these local rhythms affects the whole rhythmicity. Although, theoretically, we could assess the strength of a particular constraint – the correlation or anticorrelation in the changes between particular oscillations mediated by entrainment – it would be ill-advised to try and isolate the individual components of the different constraints, given the nonlinearity of cognition; therefore, an idea of nested constraints, although much more complex, would bring us closer to the understanding of the role of these constraints in cognition. The fact that constraints shape cognition does not mean that they only restrict our perceptions and actions. I share the definition of constraints offered by Juarrero (2015), who defines them as “any event, mechanism, or condition that alters a system’s probability space” (514). This conceptualization makes room for the possibility of enabling constraints, those that expand a system’s probability space.

From this point of view, rhythm emerges as the form through which ongoing oscillatory processes in the body, brain, and environment enact dynamic constraints on cognition that interact through the nonlinear dynamics of entrainment.

3 The oscillations behind rhythm

The most pressing problem with my understanding of rhythm is that it requires the existence of oscillators in the environment, body, and brain able to mutually interact through entrainment. All these regions have to present some intrinsic or self-sustained oscillators able to entrain and be entrained by oscillators originating in the other regions and to contribute measurably to a globally enacted cognitive rhythm. In order to address this need, I will successively discuss (1) bodily, (2) brain, and (3) environmental oscillatory activity with the potential to entrain and be entrained into a global cognitive rhythm.

3.1 Bodily rhythms and cognition

Both the heart and the gastrointestinal tract are known to be able to initiate mechanical contractions even if severed from the rest of the body and the brain. Of course, in normal circumstances, these populations of oscillators are under autonomic and hormonal control. However, the relevant fact is that both the cells of the sinoatrial node in the heart and the interstitial cells of Cajal in the gastrointestinal tract generate a rhythm, while other organs such as the lungs require brain inputs to generate oscillatory activity. Beyond organ-specific functions – pumping blood, gut contractions –

both the heart and the GI tract can be considered as intrinsic oscillators that continuously send information to the brain. Visceral signals can thus be considered as stimuli that influence spontaneous brain activity. (Azzalini, Rebollo, Tallon-Baudry 2019: 488)

That is, activity in the brain is conditioned by the frequency of bodily oscillators. For example, Richter et al. (2017) contend that gastric oscillatory activity causes up to 8% of the variance of one of the most important rhythms of the brain in spontaneous activity: the alpha wave. Another experiment (Lechinger et al. 2015) has shown a correlation between heart rate and the peak frequency of this very same brain wave. It could be argued that there is no such a thing as a visceral rhythm, and that the aforementioned examples are just information conveyed through nerves running from the viscera to the brain and only then integrated as bodily states. While I agree that neuronal information is essential for bodily influence on cognition, I maintain that the body is able to modulate brain-originated aspects of cognition through non-neuronal activity. Wagshul, Eide, Madsen (2011, 18) argue that

the fact that everything within the cranial cavity pulsates with cardiac periodicity has been well established and studied.

This, certainly has consequences on the physiology of the brain which in turn shapes the oscillatory activity typical of the brain. Chen et al. (2020) claim that “slow changes in systemic brain physiology can elicit large fluctuations in fMRI” (1), and that the

spatial heterogeneity of these physiological responses (i.e., respiratory and cardiac) [...] can give rise to correlated signals across diverse brain regions that resemble well-known large-scale brain networks. (12)

That is, bodily oscillatory activity constrains brain activity heterogeneously but not randomly. The fact that different brain networks present a particular respiratory and cardiac activity might support the idea that bodily oscillations actively constitute cognition. In other words,

spontaneous fluctuations in neurovisceral cycles (including heart-rate variability) influence information processing and behavior. (Allen 2019, 25)

The body thus arguably influences cognitive processes not only through neuronal connections, but also through non-neuronal oscillatory activity. However, in order to argue for the existence of an enacted reciprocal rhythm, we first need to prove that entrainment takes place within bodily oscillators, and between them and brain oscillators. Entrainment takes place mainly through phase-phase coupling – i.e., the phase of a frequency m drives the phase of another frequency n – which requires a close to harmonic ratio between the frequencies. That is, an oscillatory pattern is more likely to entrain another one that resonates at integer multiples. The fact that several precise frequencies originating in different parts of the body seem to exhibit doubling/halving relationships – the breathing dominant frequencies 0.07 Hz, 0.15 Hz, and 0.30 Hz; muscle activity supporting breathing at 0.60 Hz, a heart rate of 1.25 Hz – and that this geometrical relation expands toward some the most relevant brain waves – Delta 2.5 Hz, Theta 5 Hz, Alpha 10 Hz, Beta 20 Hz – has led Wolfgang Klimesch (2018) to conclude that brain and body oscillations form a single hierarchy that follows a mathematical law, whereby their frequencies do not vary randomly or arbitrarily (2448).

That is, we can register activity at different parts of the body, but most of these oscillations align into a geometrical relation. I believe that this circumstance favors the emergence of processes of entrainment between the gastric, cardiac, and respiratory rhythms, which shape cognition through neural and non-neural mechanisms. One interesting consequence is the fact that breathing at a frequency of 0.1 Hz – 6 breaths/min – induces high amplitude oscillations in heart rate (Vaschillo et al. 2002), and according to Mather and Thayer (2018) this bodily entrainment have a relevant role in cognition, for “heart rate oscillations can enhance emotion by entraining brain rhythms in ways that enhance regulatory brain networks” (6).

In a recent review on the role of neuronal entrainment (2019), Lakatos, Gross, and Thut concede that

we know relatively little about how these body rhythms interact with brain rhythms but there is some evidence for body-brain entrainment. (894)

Indeed, we do not know the precise mechanisms behind this body-brain entrainment, but we do know that everything within the cranial cavity pulsates in correlation with cardiorespiratory activity. And we also know that spontaneous rhythms – but ones which are subject to entrainment – such as breathing, are not only linked to involuntary respiratory-related movements, but also impact voluntary actions by modulating the readiness potential (Park et al. 2020), which supports enactive interpretations (Gallagher 2017, 139-142) of the classical Libet experiments. That is, bodily rhythms of non-neuronal activity not only modulate themselves reciprocally, but constrain the functioning of spatially distant parts of the brain belonging to functional networks, by entraining them through nonlinear dynamics.

3.2 Brain rhythms and cognition

Since Hans Berger recorded the first brain wave with an electroencephalography (EEG) in 1924, almost a century of research has aimed to understand what these electric current flows generated by groups of neurons really mean. Nowadays, there is overwhelming evidence that they play an essential role in the timing and coordination of all kinds of cognitive processes. The presence of certain rhythms in a particular region is indicative of a cognitive state; however, this is not to say that they are process-specific. In other words, the same rhythm serves different ends in different regions. This has led some researchers to argue that brain rhythms provide a kind of ‘neural syntax’ (Buzsáki 2010),

whose fundamental units would be cell assemblies. The various nested rhythms present in each cell assembly at a certain time would constrain the activity of the assembly – e.g., faster gamma brain waves nested within slower theta ones have been found in many areas of the brain and thus considered an essential element of this neural syntax. It is important to note, though, that

the individual neurons that compose an assembly may reside in widely separated brain areas but act as a single functional unit through coordinated network activity. (Canolty et al. 2010: 17356)

We are speaking here of assemblies bonded by strong reciprocal connections. Consequently, the activation of a small subset suffices for the ignition of the whole set. These cell assemblies integrate into large-scale brain networks, such as the default mode, the dorsal attention, the ventral attention, the fronto-parietal, the lateral visual, and the salience network. However, the precise number and borders of each network are subject to debate, owing to potential extensive overlapping between them; they are not stable and isolated entities. Najafi et al. (2016) argue that the existence of dense overlapping between the networks is what provides the flexibility to adapt to different tasks and situations. Beyond bodily oscillations, slow brain oscillations, such as alpha or theta waves, seem to play a significant role in constraining the functioning of different areas scattered throughout the brain by affecting their excitability. These processes have been studied in relation to specific cognitive tasks, such as attentional selection (Lakatos et al. 2008), spatial memory tasks (Jones and Wilson 2005), or speech discrimination (Luo and Poppel 2007). However, even more importantly

low-frequency brain rhythms are often entrained by external sensory and motor events as well as internal cognitive processes associated with decision making, motivation, and memory. That is, low-frequency phase entrainment combined with phase-amplitude CFC provides a plausible mechanism to coordinate fast, spike-based computation and communication with slower external and internal state events guiding perception, cognition, and action. (Canolty and Knight 2010: 2)

In other words, sensorimotor and internally generated cognitive processes entrain slow brain oscillations that play a role in the coordination of faster local oscillations within cell assemblies. This

fact points to the potential role of slow brain oscillations in the integration and segregation of the activity of the different regions composing the large-scale brain networks. Therefore, switching between brain networks in spontaneous (Fox et al. 2009) and task-driven situations (Fox et al. 2005) may be another instance of low-frequency oscillations modulating cognition. Now we have a thread connecting action, perception, oscillatory activity, entrainment, and cognition. Nonetheless, the cognitive picture is arguably even more rhythmic.

In recent years, there has been an increasing interest in so-called traveling waves, or traveling oscillations: emergent and transient oscillatory events that traverse the brain in different directions and at different speeds, and which are believed to constitute another rhythmic layer in the coordination and integration of cognitive processes by modulating neuronal excitability and shaping responses to external inputs. For example, Muller et al. (2016) have found circular patterns that repeat over hours as we sleep, in the form of transient rotating waves at 11-15 Hz originating in the thalamus. These traveling waves synchronize activity in the cortex and arguably play a role in memory consolidation. Another circumstance in which they are involved is sensorimotor coordination. In a study with primates, Zanos et al. (2015) concluded that the waves originated by saccadic eye movements reorganize neural patterns “prioritizing the processing of behaviorally relevant stimuli” (615). It is tempting to relate traveling waves with the enactment of time-extended cognitive processes. That is, while stationary brain waves are more fit to bind aspects of cognition with precise temporal extensions, traveling waves could integrate different levels of temporality into a unitary experience, entraining assemblies of neurons at different levels as they pass. This is supported by Zhang et al. (2018)’s research, which shows that theta and alpha brain waves often become traveling waves with a potential role in memory tasks. They have also found that

different subjects exhibited widely varying types of traveling waves even in the same anatomical region. (1278)

These intersubjective differences suggest that traveling waves – or brain waves behaving as traveling waves – are able to reflect individual cognitive variations. The researchers have concluded that their findings

emphasize that human cognition is supported by complex, large-scale neural patterns that are exquisitely organized across both time and space. (1279)

Faster oscillations entrained by slower oscillations of stationary and traveling nature seem to be the essential rhythmic scaffolding of the brain.

3.3 Environmental rhythms and cognition

Even those researchers who hold stronger views on what entrainment is, such as Lakatos, concede that different sensory modalities are entrained by periodic activity whose phase is close to the appropriate sensory frequency. For example Spaak, de Lange, and Jensen (2014) demonstrated that 10 Hz rhythmic visual stimulation induced alpha-band rhythmicity in neuronal activity, whose effects outlasted the stimulation, affecting the subject's perceptual ability (3542). However, oscillatory activity does not even have to reach the level of conscious awareness to affect cognition. Experiments conducted by Schurger et al. 2017 have shown that undetected auditory regularities entrain voluntary movement. These and related phenomena appear to be part of a shared mechanism: the rhythmic entrainment of slow cortical oscillations to the temporal structure of a stream of stimuli (Schroeder and Lakatos 2009). However, what happens when there is no clear periodicity? Rimmele et al. (2018) have offered a theory according to which

neural oscillations primarily constitute an intrinsic processing constraint rather than a dedicated temporal prediction mechanism. (875)

The authors suggest that the entrainment of neural oscillations in processing constraints is present when facing periodic stimuli, but that it is especially important when facing 'aperiodic temporal predictions', as is the case with language and certain types of music³. According to Rimmele et al. (2018), periodic stimuli are a bottom-up process in which entrainment is driven by the frequency of the stimuli, while certain aperiodic stimuli require a top-down processing, whereby higher cognitive

³Rimmele et al. (2018: 872) explain what these 'aperiodic temporal predictions' are as follows: "temporal predictions inferred from heterochronous streams of events, symbolic cues ('memory-based' predictions; e.g., a yellow traffic light that indicates a switch to red in a few seconds), or hazard functions ('probability-based' predictions; e.g., the increasing conditional probability over time that an event will occur given that it has not already occurred). For example, aperiodic temporal predictions occur in language (cf final section) and in music, where many musical traditions employ a non-isochronous (aperiodic) meter which builds up temporal expectations and can be embodied in dance".

processes and motor activity align the phase of neural oscillations with an expected event, to facilitate the potential entrainment. Stretching this theory, sensorimotor engagement with periodic oscillatory activity from the environment would be a process of attunement to a similar frequencies, able to drive other resonant frequencies in the brain and body of the agent, by generating a unitary and precise oscillatory constraint that focuses on a specific frequency. An example of this effortless constraint would be the spontaneous entrainment of running cadence to music with a predominant tempo (Van Dyck et al. 2015). However, in the case of aperiodic stimuli, there is a bigger implication of other cognitive processes that enact more complex constraints. These constraints entrain a particular ‘doing’ that makes us ready to act according to past experiences or preceding moments of the ongoing experience.

Intersubjective reciprocal entrainment is an extremely important phenomenon in most animals and particularly in humans. We constantly and effortlessly attune to one another during social interactions, and we enact shared rhythmic constraints just by walking together. In this case, we participate in the constraint by producing and reacting to the sensorimotor cues produced by those we are interacting with. However, even these interactions are far from being automatic or simple processes, for they are modulated by affective aspects of which we are not necessarily aware. In a recent review Hoehl, Fairhurst, and Schirmer (2020, 8) summarize the current state of research in interactional synchrony as follows:

temporal perception is enabled by cortical neuron assemblies and the integration of their signals by striato-cortical loops acting as a central timer or perhaps more generally as a regularity detector. Alignment value depends on socio-emotional computations and informs temporal processes via communication between the temporal and the social brain.

In a series of experiments, Golland, Arzouan, and Levit-Binnun (2015) found that emotional movies induced similar emotional responses in the participants, but – more importantly – that those who watched the films together presented a tighter coupling in their cardiovascular and electrodermal activity, even in the absence of direct communication between them (participants were asked to refrain from talking and making movements throughout the experiment). The authors suggest that this is the result of

recursive interpersonal influences, during which individual differences in the intensity and the dynamics of the emotional events were propagated across the co-present viewers, leading to shared emotional experiences. (10)

As potential channels of this emotional attunement, they point to “subtle peripheral cues (e.g. facial and postural emotional signals)” and “chemosignals, which do not necessitate conscious allocation of attention” (10). Although the mechanisms are yet unknown, these results support the enactment of intersubjective shared constraints mediated by oscillatory activity. The fact that there was a relevantly higher alignment in cardiovascular and electrodermal activity between individuals sharing the experience reveals the role of these oscillations in social bonding. These results support the idea that just sharing an experience, with no further direct interaction, causes the progressive enactment of a nested rhythmic constraint with the participation of brain and bodily oscillations that favor entrainment between those who partake of the experience.

3 Cognitive rhythm and nested dynamic constraints

An enactive approach should be able to account for embodied, embedded, socially situated, dynamic, action-oriented process aspects of cognition. In the previous section, I have identified different rhythmic constraints enacted between body, brain, and environment that I consider to be likely participants of a cognitive rhythm that constraints cognition. In the case of embodiment, the beating of the heart, breathing, the digestive movements, and other potential bodily oscillation not only serve their specific functions but enact an ongoing set of bodily rhythmic constraints constitutive of cognition. Bodily oscillations must necessarily happen. That is, their continued activity is necessary for life, but also for the modulation of brain oscillations, organizing them and potentially contributing to their temporal binding. For this reason, a slightly faulty bodily rhythm will not only have physiological consequences, but will also affect cognition. Such is the case of a decreased heart rate variability, which is considered to be a biomarker of mental disorders as depression and anxiety (Gorman, Sloan 2000). Bodily rhythms are relatively stable, but they have to be flexible enough to accommodate variation, novelty, and the unexpected. Accordingly, Rassi et al. (2019) have found that the coupling between heart rate and breathing frequency is stronger during sleep and when we have our eyes closed while awake than when we are awake and carrying out a memory task. These results are not only consistent with the idea that an overly-rigid bodily rhythm would increase the

stiffness of the constraint, which in turn would enslave other brain and bodily rhythms, limiting our capacity for sensorimotor entrainment with the environment, but also with engagement with the environment being able to entrain bodily oscillations. According to what we have seen, an instance of situated cognition such as partaking of a common experience with others, even in the absence of direct interactions, arguably causes the enactment of a shared rhythmic constraint that goes all the way down to bodily rhythms while being also constrained by brain oscillations.

Brain oscillations, unlike those originated at the body, are not continuous: certain processes of inhibition modulate the probability of the triggering and frequency of a particular rhythm. That is, certain neuronal assemblies or brain networks will present different oscillations or no clearly defined oscillatory pattern influenced by the different constraints to which they are subject. While bodily oscillations may be considered the basso continuo of cognition, brain oscillations are transient and more varied melodies that appear, affect the whole rhythm, evolve, and disappear. Among the different types, slower brain oscillations emerge as particularly important, owing to their apparent role at the crossroads between bodily, environmental, and faster brain oscillations. Specifically, I would argue that the particular dynamics of traveling waves point to a significant relevance in the integration and modulation of the different rhythms and thus in the enactment of the complex nonlinear dynamics required for cognition. They can be regarded as dynamic constraints that traverse the brain in different directions and patterns, and at different speeds, generating variable windows of excitability in neuronal assemblies and brain networks. The mere movement of the traveling waves suggests a constraining and genetic aspect, as they organize the regions that they traverse spatially and temporally. The substantial differences between subjects and the widely varying types registered in the same anatomical region (Zhang et al. 2018) make these patterns both incredibly difficult to identify and hugely interesting, for they constitute a particular brain-print with cognitive implications. Varela (1999) has argued that different components of temporality require a frame of integration that corresponds to the duration of the lived present (1999, 271). These frames would shape cognition, including our actions, and at the same time would be modulated by them in an endless loop. Accordingly, Gallagher (2020) argues:

At the same stroke, my action incorporates the situation that has been shaped by *past* actions, and by the projected *future* toward which it is moving, in the *present* circumstances that can both limit and enable it. (40-41)

An expanded version of Rimmele et al. (2018)'s theory of neuronal oscillations as processing constraints comes in handy to address this action-oriented aspect of cognition. By taking together Park et al. (2020)'s results suggesting that respiratory-related movements, impact voluntary actions by modulating the readiness potential and the well-known fact that respiration entrains the brain rhythms involved in stimulus sampling (Zelano et al. 2016), it is possible to view nested rhythmic oscillations that go all the way from the environment to the body as cognitive constraints that influence the organizing and shaping of our sensorimotor engagement with the world. In other words, when we speak of rhythmic constraints the differences between perception and action become blurred. In his seminal paper "The Reflex Arc Concept in Psychology", Dewey (1896), claimed that the

so-called response is not merely *to* the stimulus; it is *into* it [...] they are always inside a coordination and have their significance purely from the part played in maintaining or reconstituting the coordination. (359-360)

In my opinion, this coordination is the rhythmic constraint. As we actively explore the world through saccades and more complex involuntary and voluntary movements, traveling waves nested within slower bodily oscillations traverse the brain. What we do and what we perceive are just different names given to the same underlying process. Actions and perceptions are rhythmically connected outcomes generated by the same constraint. If we look at a traveling wave crossing the cortex there is no way of telling its boundaries. As Archilochus said two thousand and six hundred years ago, rhythms hold us all together.

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