Cognition through the lens of a body-brain dynamic system

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Opinion

Cognition through the lens of a body–brain dynamic system

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Continuous interactions between physiological body–brain rhythms influence how individuals act, perceive, and evaluate their environment. Despite increasing interest, the intricate interface between breathing, cardiac, neural rhythms, and cognitive function remains poorly understood. By evaluating current theoretical and empirical implications, we derive an integrative framework of a 'body–brain dynamic system' that combines a hidden hierarchical structure with dynamical state transitions. We propose that body–brain signals can interchangeably drive state- and task-specific coupling mechanisms which influence cognitive functions. The dynamical nature of this framework parallels the intrinsic variability of human behavior, and ultimately aims at better understanding how individuals act in and adapt to a dynamically changing environment.

Highlights

Although physiological activity from the body and the brain are often studied in isolation, accumulating evidence shows that body signals (e.g., respiratory and heart rhythms) modulate neural activity and influence cognitive functions.

We propose to look at continuous and bidirectional body–brain interactions through the lens of a dynamic system, with a hierarchical but flexible functional organization, and the scope to optimize adaptation in a dynamic environment.

After defining possible body–brain states in action, re-action, and perception, we provide empirical examples to address the causal role of body–brain dynamics in behavior and put forward implications for its clinical translation.

Reciprocal influence of body and brain rhythms on behavior?

The question whether there is any systematic relationship between the body and the brain (or the 'mind') represents a longstanding debate, dating back to Hippocrates. In the Platonic dialogues we also read:

> …the great error of our day in the treatment of the human body, … [is] that physicians separate the mind from the body.

Stepping back from Descartes' and Newton's reductionist principles, recent research confirms that multiple physiological activities of the body and the brain share a cyclic (quasi-)periodic [1] nature and display systematic patterns of (a)synchronous oscillatory dynamics and/or mutual dependencies.

Although the most evident body rhythms such as respiration and heart rate (HR) are considerably slower (roughly 0.25 Hz and 1.25 Hz, respectively) than the most frequently studied neural rhythms (1–50 Hz; Figure 1A,B, Key figure) and quite variable across the lifespan [2], empirical evidence confirms their tight link to neural and cognitive functions. Body rhythms might directly influence neural spiking and oscillatory activity and thereby modulate information processing [3,4], perception, action, cognition, and emotion regulation [5–12]. Stimulated by these recent developments, we propose that the combined assessment of rhythmic body–brain signals is critical to advance a holistic understanding of how individuals solve the fundamental task of continuously evaluating, reacting, and adapting to a dynamically changing environment [13,14].

Bridging the gap between current empirical research and existing theoretical propositions, we propose an integrative framework to holistically examine the body–brain–behavior interface. The central tenet of this body–brain dynamic system (BBDS) is to regard the body and the brain as partially independent subsystems that dynamically transition from decoupled to coupled states in a context-specific manner. We propose that an emergent hidden non-static hierarchical

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organization (see section 'An integrative framework') modulates neurocognitive function, continuously supporting the optimization of adaptive behavior. In contrast to static hierarchical conceptions, we reason that body–brain coupling instantiates a transient state that is interchangeably driven by either the body or the brain according to environmental contingencies.

The first challenge for this framework is that, while appealing, observed links between body–brain rhythms and behavior are mostly correlational in nature, and thus do not provide causal evidence. Second, research has primarily focused on the isolated influence of respiratory or cardiac rhythms on brain activity or behavior, precluding a more inclusive stance on the body–brain-behavior interface. Existing holistic perspectives, instead, tend to focus on (self-)consciousness, but not overt behavior [3,15]. With a broader perspective, the 'binary hierarchy body brain oscillation theory' [1] was among the first to propose the existence of a body–brain frequency architecture governed by binary (sub)harmonic relationships (frequency coupling and **cross-frequency coupling**, see Glossary). This theory accounts for inter-individual variability in body–brain rhythms (e.g., HR and spontaneous alpha band activity) and subjective rate preferences in overt behavior (e.g., spontaneous walking rate), and has stimulated key questions that define the starting point for the proposed BBDS framework:

(i) Are body–brain rhythms continuously coupled over time?
(ii) If body–brain coupling is not a constant phenomenon, which rhythm(s) drive it?
(iii) Do psychophysiological states (e.g., resting vs. active states) dynamically influence body–brain rhythms or are these constrained by static harmonic relationships?
(iv) Is cognition (e.g., the allocation of attention over time) influenced by body–brain rhythms and vice versa? If so, how?
(v) Finally, what exactly is the functional role of body–brain interactions?

Guided by these questions and bridging the gap between current theory and empirical findings, the goal of the BBDS is to provide a dynamic perspective on the body–brain interface, focusing on breathing and cardiac rhythms to explain how such intricate interactions enable individuals to efficiently act in and adapt to a dynamically changing environment. Rather than a formal description of system dynamics, the BBDS develops a framework and motivates future research to implement and test model predictions (see Outstanding questions). To this end, the BBDS embraces the natural variability of human behavior across multiple cognitive functions and promotes a holistic approach to the study of both neurotypical individuals and neurological disorders (see Box 1).

Brain rhythms

Neurophysiological activity is characterized by periodic fluctuations in the excitability of neuronal populations [16]. Rhythmic oscillatory activity is usually clustered (with some flexibility in the bandwidths) in multiple frequency bands, ranging from delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–25 Hz) and gamma (from 25 Hz onwards). These oscillations and their relation to cognitive function have been extensively studied in the domains of attention [17], sensorimotor behavior [18], speech [19], and music [20], while aberrant neural oscillatory activity is linked to dysfunction thereof [21]. Current evidence suggests that neural rhythms adhere to a specific spatio-temporal organization whereby **functional coupling** across space, time, and frequency is associated with local cytoarchitectonic structure, specific anatomical connectivity, as well as with cognitive function [22]. For example, the coordination of excitability changes across neuronal populations might render perception an essentially rhythmic function (see **perceptual cycles**), which at least partially depends on the phase and rate of the respective oscillations [23–25]. However, little is known about the joint influence of other physiological oscillations, such

Glossary

Brain readiness potential: in the context of EEG measurements, the brain readiness potential is a metric associated with motor preparation.

Cross-frequency coupling: cross-frequency coupling is a concept that describes the co-variation in the dynamics of two or more neural signals oscillating at different frequency bands (e.g., delta-beta coupling).

Cycle: when referring to periodic signals (neural oscillations, respiration, heart activity), a full cycle includes a repeated pattern in time. In the case of a sinusoidal wave, both the high- and low-excitability phases describe a full cycle, which is periodically repeated in time.

Directional causality: in the analysis of brain activity, directional causality measures the influence exerted by one signal on one or more other signals which are functionally coupled. It can be estimated by Granger causality and/or other metrics relying on the information theory framework.

Entrainment: in physics, entrainment refers to a mechanism of active alignment of two oscillators, whereby the signals are independently oscillating at their individual rates before and after a transient moment of alignment.

Functional coupling: in the context of EEG measurements, functional coupling describes the co-variation in the dynamics of two or more signals (e.g., from two brain regions) and can be obtained through various metrics of amplitude or phase changes.

Heartbeat evoked potential (HEP): an event-related EEG response reflecting body–brain interaction.

Hierarchical functional organization: this term refers to the presence of a structured pattern of functional coupling that can be mathematically quantified. Thus, elements at higher levels of the hierarchy interact with signals at lower levels and vice versa. Note that correlational evidence might suffice for this organization to take place. However, the model can be extended by means of measures of directional causality.

Perceptual cycles: given that oscillatory brain activity is characterized by alternating instances of high- and low-excitability phases, cognition might be a cyclic process with (sub-) optimal moments for information processing and perception.

as respiratory and cardiac rhythms on cognitive function. Thus, the question arises: is human behavior modulated by the interaction of body–brain rhythms? And if so, how?

Respiratory rhythms and their influence on brain dynamics and behavior

Two main control systems regulate respiratory muscles [26]. One exerts unconscious, autonomic, and continuous control of respiration meeting the body's metabolic demands. This pathway comprises the brainstem, reticular formation, pons, and medulla. The other system, comprising sensorimotor and limbic forebrain structures [27], facilitates the top-down control of respiration, allowing among other functions to coordinate speech and complex motor acts.

A widespread cortico-limbic network actively tracks human breathing [28]. Activation of olfactory and limbic regions, including the amygdala and hippocampus, aligns with the inspiration phase (see **phase-locking**) of the respiratory **cycle** [29]. Voluntary control of breathing engages primary sensory and motor cortices, the supplementary motor area, cerebellum, thalamus, caudate nucleus, and globus pallidum, bilaterally, as well as the medulla [30]. Notably, breathing is also modulated by covert motor behavior, for instance during imagery [31] and listening to music [32]. People tend to align their breathing with a perceived musical rhythm [33] as a form of respiratory **entrainment**. Consequently, the phase-alignment with external stimuli influences visuo-spatial [10,34] and memory performance [8,29]. Conversely, psychophysical states can modulate breathing. For instance, states of anxiety, depression, anger, stress, and other negative or positive emotions are linked to specific respiratory patters [35] and conscious control of breathing, for example, slowing, can induce changes in HR variability ([36,37]) and in brain activity [38]. This evidence points to an active interface of psychophysical states, breathing, and cognitive function. However, which mechanisms govern these intricate relationships, and what defines breathing–cognition coupling functionally? Moreover, what does cardiac activity add to the equation?

Cardiac rhythms and their influence on brain dynamics and behavior

The alternation of systole (ventricular contraction) and diastole (ventricular relaxation) gives rise to the cardiac cycle and the heart rhythm. The heartbeat (HB) does not display the regularity of a metronome but rather acts more like a dynamic pacemaker [39] driven by both sympathetic (acceleration) and parasympathetic (vagus) nerves.

> when the heart is affected, it reacts on the brain; and the state of the brain again reacts […] on the heart; so that under any excitement there will be much mutual action and reaction between these– Charles Darwin [40].

Research shows that noradrenergic neurons in the locus coeruleus may influence neurovascular coupling and cerebral blood flow [41], from health to pathology [42]. Similarly, HR modulates thalamic activity, resulting in global brain and cognitive effects ranging from emotion regulation [43] to attention and working memory performance [44]. Evidence further highlights a specific phase relationship between the cardiac cycle and information processing. Hence, visual perception is modulated by HB-locked neural responses [4], the so-called **heartbeat-evoked potential (HEP)**. Consequently, reaction times in response to auditory [45] and visual [46] stimuli increase around the **R-peak**. In turn, HEP modulated both early (P50) and later (N100, P300) event-related potentials (ERPs) of the EEG in response to somatosensory stimuli [47]. Hence, somatosensory stimuli are likely better detected during diastole than systole [48], and detection is inversely related to the amplitude of the preceding HEP, similarly to what has been observed for visual stimuli [47,49]. However, this link is likely bi-directional, as cognitive functions such as attention, emotional processing, and social cognition, as well as the underlying brain activity, similarly impact interoception and HEP [49–51].

Phase-locking: when examining neural oscillations, phase-locking describes a precise relationship between the phase of a signal with another signal or event. For instance, brain activity in the beta-frequency band can be phase-locked to the occurrence of an acoustic event.
Predictive coding theory: this view postulates the inherent predictive nature of neural activity. Hence, the brain constantly generates predictions about events in the (internal and external) environment and a continuous process of learning updates current knowledge via prediction error signals [signaling the (mis-)match between expected and actual outcomes].
R-peak: the R-peak corresponds to the maximal deflection observed in the periodic electrocardiogram signal.

Key figure

A framework for the body–brain dynamic system

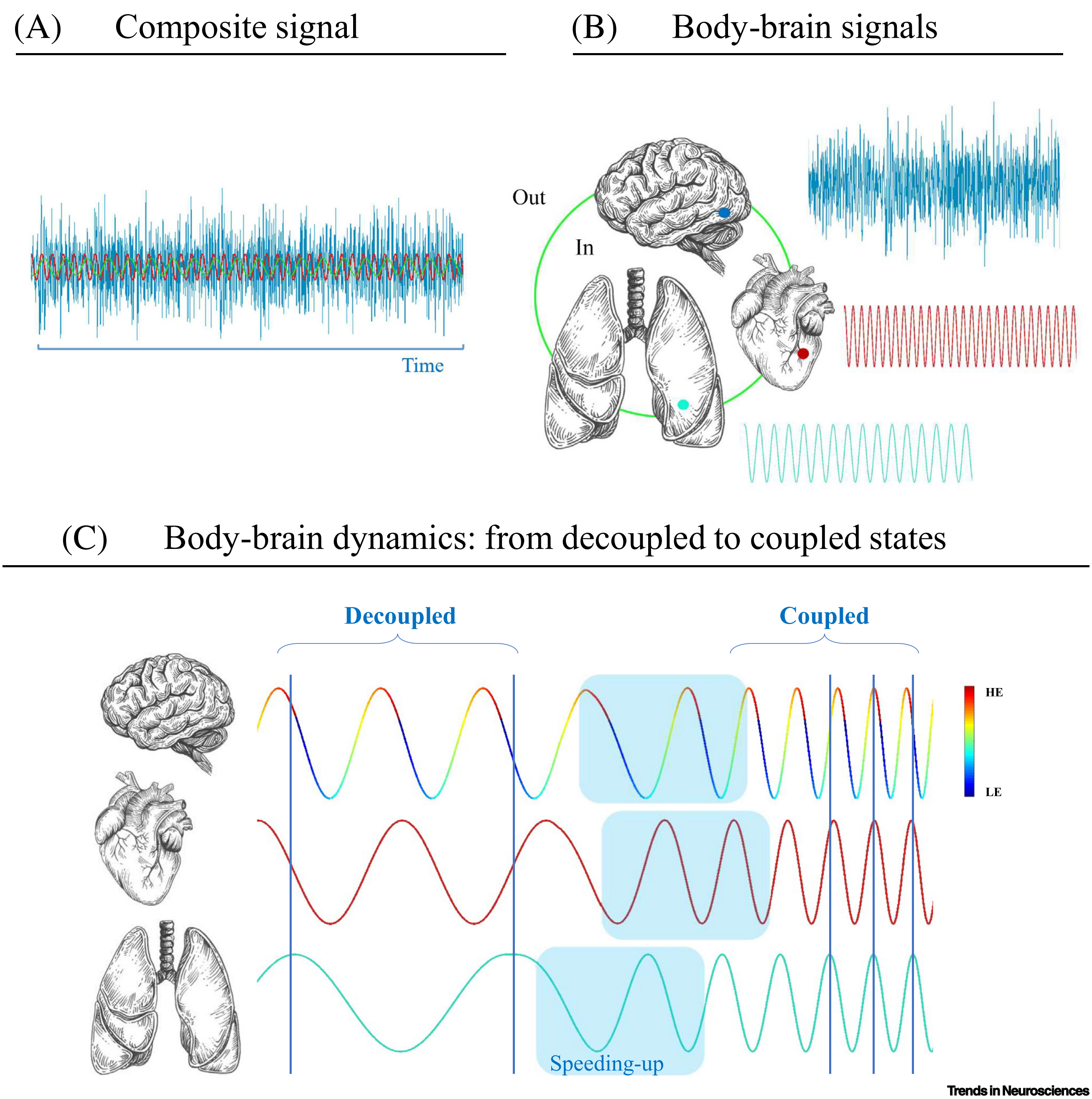

Figure 1. (A) A composite signal including brain (blue), heart (red), and respiratory (light blue) activity. (B) Brain–heart–lungs are partially independent subsystems, and a boundary (the physical extent of the body) separates them from the outside (Out). Like an open system, the three subsystems share and exchange information with the external environment (input) and jointly deliver output (perception and action) via transformation processes (e.g., information processing). (C) Body–brain signals might

(Figure legend continued at the bottom of the next page.)

The influential **predictive coding theory** [52] offers a potential explanation to these findings, suggesting that the brain predicts and attenuates responses to rhythmically regular signals to optimize resource allocation to non-predicted sensory input [53]. Consequently, the perception of sensory input oscillates at the HR, leading to the suppression of activity in response to events that fall on the low-excitability phase in the heart cycle [4,47]. Alternatively, the 'neural subjective frame' suggests that (pre-attentive) updating of internal body states modulates self-awareness and sensation [15]. Accordingly, the brain might switch attention from interoceptive to exteroceptive signals, and this transition parallels HEP modulations [54,55]. Supporting this notion, oscillations during interoception (35–110 Hz) differ markedly from those during exteroception (1–35 Hz) in the insula, amygdala, somatosensory cortex, and inferior frontal gyrus [54]. Interestingly, exacerbated HEP modulations are observed in disease and are associated with dysregulated behavior, impaired cognition, and atypicalities in brain volume and connectivity of allostatic networks [56–58].

Taken together, these findings highlight bidirectional influences between heart activity, brain function, and behavior. However, how do HB and respiration relate to each other? Generally, the HB accelerates during inspiration [respiration rate (RR) decreases] and slows down during expiration (RR increases). These fluctuations of HB in relation to the breathing cycle are part of the phenomenon known as HR variability and are influenced, among other factors, by the baroreflex and the sympathetic nervous system. The HR depends on breathing rhythms and tidal volume (depth of ventilation) and relates to breathing cycles approximately with a 4:1 ratio (four HBs within one respiration cycle) [39,59,60]. Yet, little is known about how respiratory–cardiac coupling influences brain activity and cognition. Similarly, conceptual frameworks for the dynamics of such a comprehensive body–brain system are largely lacking. In other words, how can the interactions between respiratory, cardiac, and brain activity, and their consequences for behavior, be characterized and explained?

An integrative framework

Earlier work has reviewed and discussed evidence of how visceral input modulates brain activity and subjective experiences of (self-) consciousness, as in the cases of intero- and exteroception [12,15,61]. Similarly, others have discussed the modulatory influence of breathing on brain activity, perception, and action [10,11,13].

Bridging the gap between current empirical research and existing theoretical propositions, the BBDS provides a dynamic perspective on body–brain interactions and describes how such an interface enables individuals to efficiently act in and adapt to a continuously changing environment. This integrative framework promotes a holistic approach to the study of the body–brain–behavior interface and motivates future research for its formal implementations (see Outstanding questions). The focus of the BBDS is on respiratory and cardiac rhythms alongside with brain activity and behavior. For simplicity, we disregard in the current discussion other bodily (or visceral) signals, but conceivably, integrating such signals into the framework may follow the same principles [12] (Figure 2).

A dynamic body–brain system

The proposed framework is inspired by systems theory and considers interactive body–brain rhythms within a dynamic system.

switch from decoupled to coupled states to optimize behavior. We hypothesize that changes in breathing rates (e.g., speeding-up) might drive state transitions and induce changes in the rate and phase of the other signals. Signal dynamics can then be quantified by circular statistic tests (e.g., phase-locking values). Thus, phase-locking might be highly variable in decoupled states, while coupled states might show a preferential clustering. Of note, some variability in the coupling patterns might still be present, but a prominent phase-angle optimizes behavior. Brain activity is plotted with a color-code ranging from low-excitability (LE) to high-excitability (HE). This refers to the concept of perceptual cycles, namely that there are (sub-)optimal windows for information processing that depend on the excitability phase in which signals are presented. The traces in the figure are based on data simulated for illustrative purposes using MATLAB.

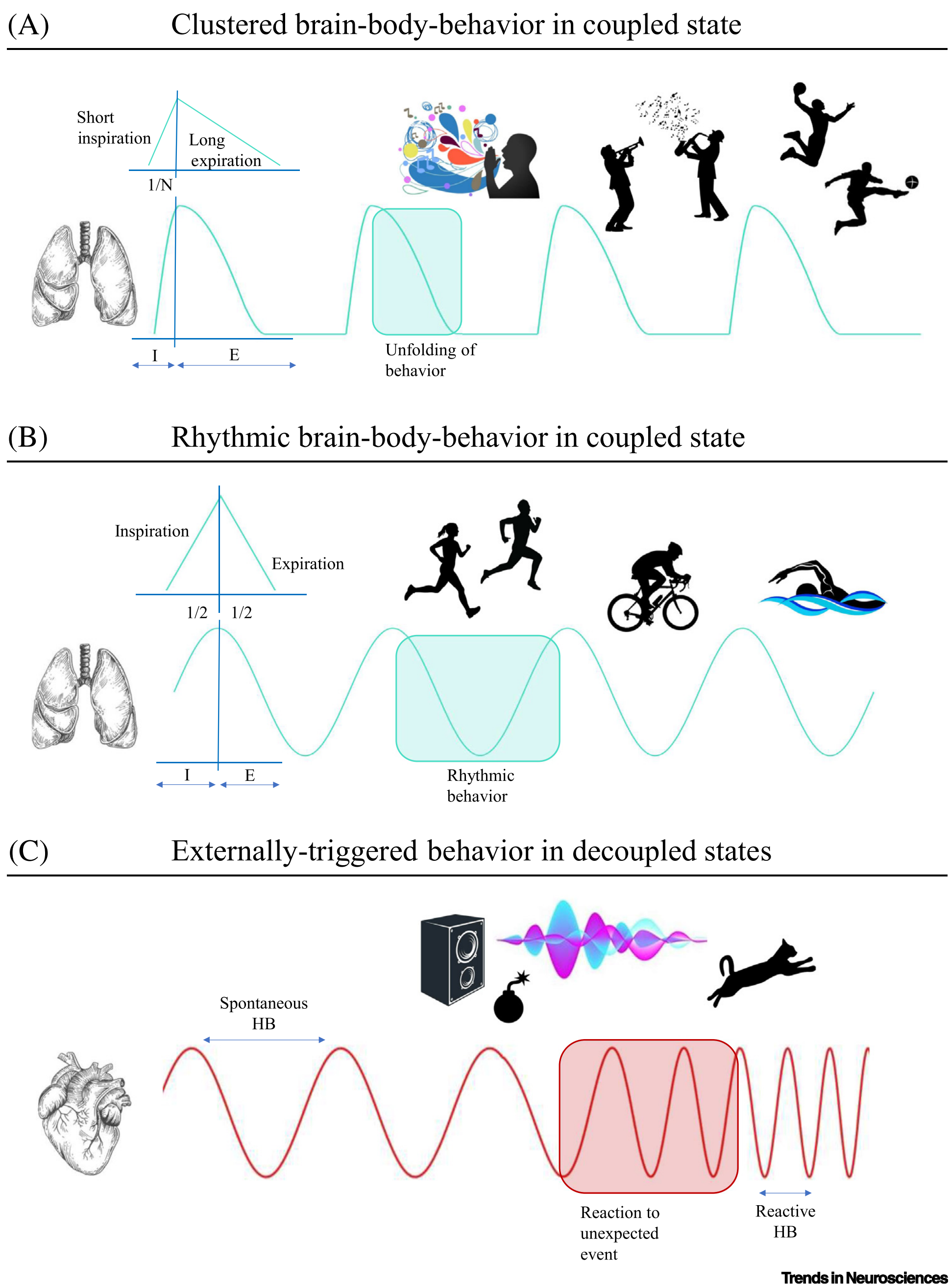

Figure 2. Body–brain–behavior relationship in coupled and decoupled states. (A) In clustered body–brain–behaviors, motor acts such as speaking, laughing, singing, playing a wind instrument, or shooting a ball would tend to unfold during the long-lasting expiration phase of the breathing cycle. Here, the phase-relationship between body–brain–behavior is not regular but would depend on the motor act performed and physiological needs (e.g., need of oxygen). (B) In rhythmic body–brain–behaviors, motor acts such as running, cycling, or swimming tend to establish a clear phase-relationship with the breathing cycle. The unfolding of behavior relative to body–brain rhythms is more precise as compared with clustered body–brain–behaviors. (C) Externally triggered behaviors allow body–brain rhythms to transition from decoupled to coupled states. In this case, the heart signal is the driver of body–brain coupling via speeding-up its pace. The traces in the figure are based on data simulated for illustrative purposes using MATLAB. Abbreviation: HB, heartbeat.

Box 1. Translational aspects of body–brain research

An interesting aspect of the body–brain integrative approach lies in the potential characterization of individual capacities as a prerequisite for personalized training or interventions. Clinicians and therapists have long asked how to improve standard protocols [70] as treatment outcomes vary significantly [71]. Specification of individual capacities, including behavioral and cognitive measures together with brain, respiratory, and cardiac activity, may reveal a pivotal link between cognitive dysfunctions (e.g., attention deficits, dysfluent speech) and altered body–brain coupling. Thus, a better understanding of the causal relationships between body–brain–behavior could factor into early diagnosis and the development of individualized training. For example, breathing control techniques, along with metronome-timed speech training [72], are found to improve speech fluency in people who stutter. In these scenarios, the processing of external (music) rhythms and the volitional control of respiration may superimpose a temporal pattern through which behavior can unfold efficiently (Figure 2). Through this mechanism, external rhythms provide a means to temporally (re-)structure altered body–brain–behavior. For instance, the speech production rate may align with the rate of externally presented rhythms. Alternatively, volitional control of breathing may facilitate sensorimotor coordination for speech production. Similar mechanisms may underlie the beneficial effects of rhythm training in dyslexia [73], gait performance, time perception, and sensorimotor timing abilities in Parkinson's disease [74,75]. Interestingly, the known modulatory effects of musical rhythm on blood pressure and cardiac activity [32,76] might foster post-stroke interventions [77].

Overall, these observations lead to the critical consideration that many clinical settings could benefit from an integrative body–brain–behavior approach. However, this requires a better understanding of the underlying functional and causal mechanisms linking body–brain physiology to behavior and general cognition.

The BBDS focuses on three key elements: the brain, the lungs, and the heart, which constitute interconnected but partially independent subsystems. A boundary (the physical extent of the body) separates this system from the external environment (Figure 1B). Like any open system, the three subsystems share and exchange information with the external environment (input) and jointly deliver output (perception, action) via transformation processes (e.g., information processing). The BBDS generates unique testable predictions: it is characterized by at least two states, a coupled and a decoupled state (Figure 1C). In neurotypical behavior, the functional coupling of the body and the brain is not invariantly maintained but can be dynamically and adaptively achieved whenever contingencies demand it. Thus, in wakeful states and in the absence of overt behavior, a largely decoupled system state is considered the default. In this scenario, autonomic centers regulating breathing and local cardiovascular centers modulating HB, dominate. When (re)acting, attending, and sensing the environment, the system can transition into a coupled state, influenced by top-down regulatory centers. This transition is achieved through changes in the rate and phase of internal signals, which tend towards preferred phase-coupling to optimize behavior (Figure 1C). Although body–brain coupling is not a constant feature of the system, the endogenous predisposition to achieve phase-alignment unveils a hidden non-static hierarchical organization. Thus, a directional organization is established that drives dynamic state transitions, which can be initiated by multiple physiological rhythms interchangeably (i.e., respiration or cardiac) in specific contexts. Methodologically, the assessment of body–brain interfaces resembles current state-of-the-art analyses of neural entrainment. Hence, transient changes in coupling strength can be analogously quantified by circular statistics [62] (Figure 1C) on a trial-by-trial basis. Consequently, variability in body–brain signals is the key mechanism for the dynamical aspect of the system, supporting the flexible interaction between the three sub-systems (lungs, heart, brain) and rapid adaptation to environmental contingencies, ranging from predictable to unpredicted events. Critically, this concept of flexible and adaptive interactions is supported by empirical evidence, showing that HB is prone to variability in healthy participants [63], neural oscillatory signals can display state and task-specific timely responses [64] and that respiration control modulates neural network activity and behavior [11,28]. Thus, the proposed functional implication of the body–brain interface is to prepare the organism to dynamically allocate metabolic and cognitive resources required for behavioral contingencies. To do so, predictive processes allow exploiting prior knowledge and inform how to prepare the organism to better (re-)act in the environment. Thus, breathing and HR are dynamically modulated to optimize perceptual, behavioral [43], and memory performance [8,29].

This perspective can be exemplified by scenarios in which successful behavior demands timely body–brain adaptation. We differentiate between at least two types of behavior that are characterized by strictly rhythmic or clustered body–brain–behavior relations in a coupled state (Figure 2). Motor acts like speaking, laughing, singing, playing a wind instrument, or shooting a ball are all preceded by a short preparatory inspiration, and behavior preferentially unfolds during the longer lasting and progressive expiration phase (Figure 2A). These actions can be characterized by a clustered body–brain–behavior relationship: signal coupling is not achieved by a 1:1 phase relationship, but by 1:N phase clustering. Hence, the sequela of motor acts unfolds in one expiration phase, accompanied by variability in HB and brain activity. This idea translates to the ***brain readiness potential***, which displays preferential phase-locking at the end of the inspiration phase, while behavior tends to cluster at the expiration phase [65]. Notably, respiration–action coupling is absent in unpredicted externally triggered actions [65], where action planning is missing (decoupled state). Conversely, more stable rhythms are generated during continuous actions such as walking, running, or cycling. Here, the body–brain–behavior relationship reveals a highly regular pattern, characterized by stable intervals between inspiration–expiration phases (Figure 2B). Likewise, motor movements and HB tend to phase-synchronize with breathing, establishing a rhythmic body–brain cycle.

In this view, breathing seems to emerge as the driver of body–brain coupling in both rhythmic and clustered behaviors. Indeed, motor planning cannot preclude breathing control, and the organism exploits these body–brain dynamics to improve motor coordination, attention, and perception. Empirical evidence further supports this role as breathing modulates heart activity and induces brain–breathing coherence in a widely distributed brain network [11,28]. Top-down regulatory effects are likely achieved by synchronizing activity within cell assemblies and coordinating network interactions, ultimately regulating cortical excitability, and shaping sensory encoding, memory, and behavior [6,66–68]. We further propose that coupled states are reinforced by sensorimotor feedback loops to reduce noise (variability) in body–brain–behavior phase-locking.

However, the BBDS is not assumed to rely on a single driver, which would imply a strict **functional hierarchy**. Indeed, unpredicted events and externally triggered actions may engage cardiac rhythms as the primary driver (Figure 2C). For instance, a loud and unpredictable sound may drive a sudden increase in HB. Such alerting signals may initiate a cascade of physiological processes, aiming at raising alertness and preparing the body for action. Consequently, body–brain coupling would aim to optimize a timely behavioral response and is achieved via a dynamic interplay between subcortical (autonomic) and cortical (top-down control) brain centers.

We have discussed so far how body–brain dynamics determine how individuals successfully act in a dynamic environment and adapt to it. A critical pending question, though, concerns how perception and other cognitive functions are influenced by body–brain dynamics.

In line with other neurocognitive accounts of multisensory perception [23–25], the BBDS considers that sensory processing, allocation of attention, and perception unfold continuously, but in discrete units. Thus, while sensing the environment, attention is dynamically and flexibly allocated to prioritize specific locations, features, and/or streams. In turn, the likelihood of perceiving a stimulus is modulated by the phase-relationship between the attended event and underlying neural activity, establishing so-called 'perceptual cycles' [69]. The high-excitability phase of neural activity represents an optimal window for processing information, while neural responses to events falling on the low-excitability phase are suppressed. The BBDS proposes to extend this principle beyond neural activity in isolation to incorporate bodily physiological signals as conjunct determinants of 'perceptual cycles'. It thus follows that body–brain rhythms establish high- and low-excitability cycles, influencing the likelihood of sensory processing and perception [4,10,12]. Supporting this view, neural activity time-locked to HB before stimulus onset predicts visual detection [4], and respiration-locked alpha modulations influence visuo-spatial processing [10]. Other cognitive functions may be similarly influenced by body–brain coupling, ranging from memory [8,29] to interoception [61] and emotional processing [35]. For instance, memory encoding and retention may be enhanced when stimuli are presented during the body–brain high-excitability cycle and performance may be worse elsewhere.

To conclude, the BBDS embraces the variability in human behavior and proposes that cognition necessitates intrinsically variable body–brain interactions to adapt to an ever-changing environment. A certain degree of variability in coupling states is well-documented in human EEG and respiratory signals and might support cross-domain generalization within such a framework. A static hierarchical model [1] might not sufficiently describe dynamic transitions from decoupled to coupled body–brain states, nor psychophysical changes observed from rest to motion. By contrast, the proposed differentiation of planned and externally triggered actions and of rhythmic and clustered body–brain coupled states suggests a flexible body–brain functional architecture, whose dynamics can be characterized by patterns of task- and state-specific evolution in body–brain phase-locking.

Concluding remarks and future directions

Bridging the gap between empirical evidence and theoretical perspectives, we propose a novel framework for a BBDS, which aims to integrate the dynamical nature of body–brain rhythms with the inherent variability of human behavior. The BBDS framework thus promotes the combined assessment of physiological body rhythms (respiratory and cardiac) and brain rhythms as valuable sources of information to explain how individuals act in and adapt to a dynamically changing environment. This quest promises to advance our understanding of human perception, action, and cognition in neurotypical individuals and in neurological disorders, but necessitates appropriate experimental paradigms and analytical tools (see Outstanding questions).

Outstanding questions

Are body–brain interactions steadily present over time or transient?

Which neuroimaging methods and experimental paradigms would enable testing the directionality and causal influence of body–brain signals on behavior?

Is signal synchronization (e.g., phase-locking or concurrent amplitude changes) the only pre-requisite for describing body–brain functional coupling? Would metrics of **directional causality** (e.g., Granger causality) deepen current understanding of the link between body–brain and behavior?

What are the generators of body–brain synchrony? What drives body–brain coupling and what is its functional role?

Is it possible to modulate the activity of body–brain oscillators to influence cognitive functions?

Is the influence of body–brain dynamics restricted to a specific sensory modality (e.g., vision or audition), cognitive function (e.g., speech processing) or can we rather speak of a cross-domain functional mechanism?

Can body–brain analyses enrich individual neurocognitive profiling along the spectrum from health to pathology? If so, would they inform prevention and intervention?

Which type of formal implementation (e.g., metastability, chaotic system, turbulence) would better describe body–brain interactions and predict their influence on cognitive functions?

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Declaration of interests

None to declare.

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