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Short Communication

Shared Intentionality Modulation at the Cell Level: Low-Frequency Oscillations for Temporal Coordination in Bioengineering Systems

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Abstract

The theoretical article aims to develop knowledge about the modulation of shared intentionality at the cellular level. A hypothesis about the neurobiological processes during shared intentionality argues that this pre-perceptual communication occurs through nonlocal neuronal coupling in an ecosystem that can be described as the mother-fetus communication model. The current theoretical study analyses literature to discuss recent findings on the effect of oscillations on neuronal temporal coordination to verify whether external low-frequency oscillations can only synchronize specific local neuronal networks from peripheral and central nervous subsystems for modulating shared intentionality. The review discusses 4 findings. First, gamma oscillations are associated with the temporal coordination of local ensembles of cells. Second, there is a relationship between low-frequency brain oscillations and the temporal coordination of peripheral and central nervous subsystems. Third, delta oscillations influence neuronal activity by modulating gamma activity. Fourth, external delta and gamma oscillations increase cortical excitability. The article concludes that delta oscillations can modulate gamma oscillations in the different subsystems of the nervous system, providing temporal network coordination. An external low-frequency oscillator can coordinate only relevant local neuronal networks in various subsystems already exhibiting gamma activity.

Keywords
Shared intentionality; bioengineering systems; brain waves; brain-computer interaction; delta waves; interpersonal dynamics; gamma waves; mother-fetus communication model; oscillatory synchronization; neuronal coordination

1. Introduction

1.1 Empirical Evidence of Shared Intentionality

This concise article focuses on the possible impact of external low-frequency oscillations on the synchronization of specific local neuronal networks from peripheral and central nervous subsystems, the self-contained piece of original research on shared intentionality. Our recent studies proposed assessing a cognitive development delay in preverbal children by measuring shared intentionality magnitude [1-5]. This computer-aided method emulated the mother-fetus communication model in a bioengineering system (children over 18 months) for modulating shared intentionality. Growing data from the neuroscience hyperscanning research [6-11] showed increased inter-brain synchrony in adult subjects performing similar cognitive tasks without interacting with sensory cues compared to solving these tasks alone. The psychophysiological [5, 12-16] research studies showed empirical evidence of shared intentionality in adult subjects performing similar cognitive tasks without communication. Our hypothesis about the neurobiological processes during shared intentionality argued that this pre-perceptual communication occurs through nonlocal neuronal coupling in an ecosystem that can be described as the mother-fetus communication model [17-19]. The theoretical studies outlined three features of this ecosystem consisting of at least a recipient-contributor pair: (i) social learning in a lack of meaningful sensory interaction between them; (ii) unintelligible stimuli to the recipient in a shared ecological context; (iii) a single low-frequency harmonic oscillator [17-19]. However, this is the only hypothesis of neurophysiological processes occurring during shared intentionality that links our knowledge from interpersonal dynamics to cellular interactions.

1.2 Electromagnetic Waves Join Maternal and Fetal Ecosystems

Regarding the mother-fetus communication model, it is essential to note that an ecosystem of any organism evolves in a cacophony of stimuli: electromagnetic waves, chemical interactions, and pressure fluctuations. The two ecosystems of the mother and fetus are not entirely the same. In defining two ecosystems of this pair, we need to consider two environments: the intrauterine environment of the fetus and the mother's external environment. While a significant share of exteroceptive stimuli (electromagnetic waves, chemical interactions, and pressure fluctuations) differ in these two environments and can activate different parts of nervous systems in these organisms through sensory receptors, a range of electromagnetic waves take part in both environments and impact the nervous systems of both organisms. From physics, we know that electromagnetic waves propagate in space depending on their frequency, intensity, and the medium's resistance. For instance, exteroceptive stimuli of the voice band's electromagnetic waves can reach the fetuses' sensory receptors. According to the received view in cognitive sciences, children begin social learning by assimilating first meanings to a large extent through hearing.

Empirical evidence shows voice recognition by fetuses. For review, see, e.g., [20-23]. They distinguish a change in the gender of a speaker [21-23] and can discriminate sounds [24], learning frequently heard sounds [24]. Neuroscience research studies revealed the underlying neuro-correlates of behavioral responses in response to language and voice stimuli [24]. At 33 weeks of gestation, activity increased in the fetal brain's left temporal lobe when exposed to an unfamiliar female voice compared with pure tones [19, 24, 25]. At 34 weeks of gestation, the lower bank of the temporal lobe was significantly more active during exposure to a maternal voice than to an unfamiliar female voice [19, 24, 25]. Exteroceptive stimuli of electromagnetic waves from the voice band take part in both ecosystems. This shared domain of their ecosystems provides social learning. From the perspective of social interaction in shared intentionality, the mother and fetus share the ecological context of the voice bands containing sensory stimuli that turn into meaningful cues during social learning. Unintelligible stimuli to the recipient in a shared environmental context, in the case of the mother-fetus dyad, are all social cues from outside the uterus that can reach the hearing of the fetus.

It is crucial for the current study that low-frequency waves also propagate in tissues [19]. In physics, particles with the same physical properties react similarly to the electromagnetic field with the same features, independent of the distance between these particles. Low-frequency oscillations may also again and directly impact neurons of both nervous systems, obeying the laws of physics. Empirical evidence shows long-term brain corticospinal excitability due to low-frequency oscillations [26]. Therefore, it does not matter where the low-frequency oscillator is - inside or outside the body. That is, low-frequency oscillations of the mother's heartbeats (the most potent source of the electromagnetic field in the body) can impact both nervous systems, considering the short distance between the mother's heart and the fetus's nervous system [17, 19].

1.3 Transition from Psychophysiological Processes to the Cellular Level

According to the hypothesis, interpersonal dynamics in organisms of the ecosystem matched the mother-fetus communication model launch the inherited mechanism of social entrainment of the recipient (fetus) to the contributor's (mother's) rhythm, synchronizing physiological processes in these organisms [17-19]. Meanwhile, interpersonal dynamics stimulate the emotional and sensorimotor embodied patterns [17-19]. Under these conditions, a harmonic oscillator (e.g., increased heartbeats of the contributor or the interference of the contributor and fetus heartbeats) affects the contributor with the same impact as the recipient; it synchronizes similar neuronal networks in both organisms. The synchronization causes the nonlocal coupling of neurons in peripheral and central nervous subsystems [17]. In such a manner, an intentional act of the contributor simultaneously becomes an appearance of subliminal perception in the recipient [17]. Therefore, nonlocal neuronal coupling provides shared intentionality between the contributor and recipient (the mother and fetus, respectively) [17].

The growing literature discusses the concept of nonlocal neuronal coupling from the quantum mechanics perspective (for review see, e.g. [27-29]), showing empirical evidence of this temporal coordination of neurons registered by the magnetic resonance imaging (MRI) techniques [29] (see limitations of the MRI in the subsection 5.4). Remarkably, this MRI neuroscience research also showed that the periods of signal bursts repeated at the same rate as the heartbeat in participants

asked to stay awake and stay still during brain screening [29]. However, the mechanisms for inducing quantum entanglement in specific neurons of particular neuronal assemblies are still unclear.

Recent research proposed other mechanisms of nonlocal coupling in the electromagnetic theory. At the cell level, they rely on two different assumptions (that can also be concomitant) about a cellular mechanism for modulating neuronal excitability during low-frequency oscillations for nonlocal neuronal coupling [17-19]. First, low-frequency electromagnetic changes can alter membrane ion channel function [17, 19]. According to Premi et al. [26], low-frequency electromagnetic oscillations act primarily at the synapse level, altering membrane ion channel function. It is proposed that Ca2+ and Na+ channel activity can be perturbed by magnetic fields, considering the diamagnetic anisotropic characteristics of membrane phospholipids [26].

Second, low-frequency oscillations can mediate an increase in A(2A) adenosine receptors. Low-frequency oscillations mediate a transient and significant increase in A(2A) adenosine receptors' neuronal communication [30]. Adenosine modifies cell functioning by operating G-protein-coupled receptors (GPCR; A(1), A(2A), A(2B), A(3)) that can enhance neuronal communication [30] since A(2A) has a vital role in the brain, regulating the release of other neurotransmitters such as dopamine and glutamate. Interactions between adenosine receptors and other G-protein-coupled receptors, ionotropic receptors, and receptors for neurotrophins also occur, contributing to a fine-tuning of neuronal function [30].

1.4 Two Opposing Kinds of Neuronal Plasticity

According to the received view in cognitive sciences, intentionality develops in ecological learning [16-18] due to experience-dependent neuronal plasticity, e.g., [31-34]. Neuronal plasticity refers to the capacity of the nervous system to modify itself, functionally and structurally, in response to experience and injury [35]. It is necessary not only for neuronal networks to acquire new functional properties but also for them to remain robust and stable [35]. There are two opposing kinds of plasticity: Hebbian progressively modification of network properties, such as Long-Term Potentiation (LTP) and Long-Term Depression (LTD), and homeostatic mechanisms that promote network stability by maintaining the set point of the network [36]. Homeostatic mechanisms include changes in synoptic strengths, changes in neuronal excitability, and regulation of the number of synapses [36]. LTP and LTD are also related to synaptic strengths since they result in associative changes in the strength of synaptic connections. Synaptic strength is the average amplitude of postsynaptic action potential evoked following a presynaptic action potential. Neuronal excitability is the ability to generate a significant, rapid change of membrane voltage in response to a stimulus.

1.5 Network Oscillatory Synchronization for Neuronal Interaction

According to Vinck et al. [37], four hypotheses on a mechanism of temporal coordination for neuronal interaction can be considered: (1) Oscillatory synchronization (communication-through-coherence) [38, 39]; (2) communication-through-resonance [40]; (3) nonlinear integration [41, 42]; and (4) linear signal transmission (coherence-through-communication) [43-45]. These hypotheses attempt to describe the temporal coordination of neuronal networks registered by numerous neuroscience research. Because large-scale neuronal integration cannot be explained only by linear integration due to synaptic interactions, an influential proposal is the idea of brain wave interactions

for network oscillatory synchronization [37, 46-50]. Oscillatory synchronization is the reasonable basis for the hypotheses on a mechanism of temporal coordination for neuronal interaction. Therefore, the current review considers processes occurring during oscillatory synchronization. According to the received view, most brain activities are associated with events in which large sets of neurons cooperate, displaying oscillations in four frequency orders, from the infra-low (<0.01 Hz) to ultra-fast (200 Hz) oscillations: delta (0.5-4 Hz), theta (4-8 Hz), alpha activity (8-13 Hz), beta (13-30 Hz), and gamma (30-200 Hz) frequency bands.

The article is outlined as follows. Section Research Problem shows why two ideas (noted in the Introduction) on the nonlocal coupling of neurons bear limitations to explain engaging specific neuronal networks in the mental process related to shared intentionality, i.e., engaging not any arbitrary neurons but the precise ones. Because low-frequency electromagnetic fields (e.g., the mother heartbeats) are pervasive in the whole tissue volume at an area related to its intensity without exceptions, the nature of the selective impact of the low-frequency oscillation should be clarified. Section Materials and Methods describes the literature selection for the research problem analysis. In the section Results, the article observes the literature on neuronal oscillations, pulsed electromagnetic fields, transcranial alternating current stimulation and brain mapping. It examines these data from the perspectives of the research problem. This section reveals four findings - four nonlocal neuron coupling constituent elements. The synthesis in the section Discussion postulates three inferences-propositions that constitute a frame of a provisional conjecture to guide further investigation toward an idea of a mechanism of nonlocal coupling at the cell level for providing shared intentionality. The section Limitation explains why inter-brain neuroscience techniques cannot observe neuronal activity in vivo at the cell level.

2. Research Problem

Although the above-noted assumptions explain plausibly how external low-frequency oscillations can modulate neuronal excitability, there is a limitation. Just as the conventional view defines any specific mental process, shared intentionality enables social learning if only specific neuronal networks are engaged, not arbitrary neurons from all parts of the brain (or not all nervous system neurons). However, low-frequency electromagnetic fields are pervasive in the whole tissue volume at an area related to its intensity without exceptions. Therefore, low-frequency oscillations should impact all brain neurons in the volume of their influence, not only neurons of the specific networks. Physics laws, specifically wave properties, challenge the proposed assumptions about the cellular mechanism for modulating neuronal excitability during low-frequency oscillations for nonlocal neuronal coupling. Why do the presented two cellular mechanisms - low-frequency oscillations a) for altering membrane ion channel function and b) for increasing in A(2A) adenosine receptors - only involve specific networks and do not excite others (or even all neurons of the nervous system)? Thus, to explain shared intentionality by the nonlocal coupling of neurons due to the electromagnetic field, the hypothesis needs to develop the proposed cellular mechanism of the nonlocal coordinated activity of neurons with the selective targeting signature. Alternatively, it needs to define the new mechanism, which can impact only specific neuronal networks necessary for the corresponding environmental learning, but not any ones, in a specific instance time frame.

3. Materials and Methods

The article aims to discuss recent findings on the effect of oscillations on temporal coordination to test whether external low-frequency oscillations can only synchronize specific local neuronal networks from peripheral and central nervous subsystems for modulating intentionality. If so, what can a mechanism of nonlocal neuronal coupling in electromagnetic field be? Observing temporal coordination "in vivo" during interpersonal dynamics, neuroscience research tools are limited to hyper-scanning techniques. However, these neuroscience inter-brain data only show indirect evidence of coordinated activity of neurons that we register by observing correlates (see more in section Limitations). Research data on the brain waves association with spike rate and synaptic strength are concerned with constraints conditioned by the mathematical models and experimental designs used in their measurements and calculations (which are out of the focus of the current article). Therefore, the recent review only accounts for research data showing the brain waves association with neuronal excitation and their temporal coordination. The present study analyses literature on neuronal oscillations, pulsed electromagnetic fields, transcranial alternating current stimulation and brain mapping. Articles for the review were found through a search in recent scientific conference proceedings and journals indexing in SCOPUS and Web of Science databases.

4. Results: Delta and Gamma Waves for Temporal Coordination

Finding 1: Gamma oscillations are associated with the temporal coordination of local ensembles of cells. Research reported that gamma oscillations are localized in time and space reflecting the synchronous activation of smaller ensembles of cells [51-53]. According to Buzsáki and Voroslakos [53], keeping neurons in an excitable state is most effectively achieved by fluctuating the membrane potential close to the action potential threshold [53]. Balanced excitatory and inhibitory inputs can cope with this duty by creating "noise." [53]. Gamma wave periods match the membrane time constant of pyramidal neurons, which explains why coalitions of neurons in this time frame are most effective in discharging their postsynaptic targets [53]. At the local level, this range of oscillations provides neuronal temporal coordination [53]. Gamma rhythms offer all the advantages of a noisy regime for individual neurons and allow the network to switch to synchrony [53] readily. Buzsáki and Voroslakos [53] argue that with their parallel feedforward inhibition, oscillatory excitatory inputs at the gamma range keep networks in an excitatory state [53]. They form neuronal coalitions by shared cycle phases across the population, resulting in relatively random baseline firing of principal cells yet synchronizing their actions when needed [53]. Meanwhile, gamma oscillations with excitatory and inhibitory dynamics are ubiquitous in all circuits, which allows local temporal coordination in all separated parts of the nervous system [53].

Finding 2: A relationship exists between low-frequency brain oscillations and the temporal coordination of peripheral and central nervous subsystems. The research observed global network synchronization across widespread neocortical areas and between the neocortex and the thalamus in a slow-wave band during natural sleep and anesthesia-induced [54-57]. The slow frequency could reflect the general excitability of the network [58], generating large, synchronous membrane-potential fluctuations in many neurons in brain-wide networks [53]. Low-frequency brain oscillations are associated with temporal coordination of peripheral and central nervous subsystem [59, 60]. The relative energy from low-frequency oscillations is proportionally more significant than that from gamma [61]; this quality allows low-frequency oscillations to penetrate all tissue

depending on the field's intensity. Together, these results show that slow waves could be involved in the temporal coordination of peripheral and central nervous subsystems. The following finding 3 shows that interference of delta and gamma oscillations (in physics, it is the combination of two waves that is the addition of the amplitudes of the individual waves at each point), i.e., delta nested gamma oscillations (in neuroscience), is crucial for temporal coordination and integrated neuronal processing.

Finding 3: Delta oscillations influence neuronal activity by modulating gamma activity. The different oscillations generated in cortical and subcortical networks show a hierarchical relationship via cross-frequency phase-amplitude coupling, meaning that the amplitude of the faster oscillation varies predictably as a function of the phase of the slower oscillator [53, 62, 63]. Numerous neuroscience research observed the low-frequency modulation of high-frequency oscillations, e.g. [64-68]. Study reported results of the relationship between increasing neuronal activity and the delta nested gamma oscillations [69, 70]. Delta oscillations influence local processing by modulating gamma activity within individual areas [64]. Even isolated alterations in gamma or low-frequency oscillations may impact the interactions of high and low-frequency bands involved in essential cognitive functions [61]. At the neuronal level, such nesting of multi-frequency oscillation (phase-amplitude coupling of low and high oscillations) shows how local processes are synchronized and reflects how distributed local processes are integrated into globally ordered states [53]. Again, low-frequency oscillations can travel farther than gamma waves because less energy is transferred to the medium and links remote brain areas [61].

Finding 4: External delta and gamma oscillations increase cortical excitability. According to Premi et al. [26], the low-frequency (1 Hz) nested theta (7 Hz) oscillations (in specific, external electromagnetic impulses 60 pulses per minute of magnetic field = 2 Tesla; intensity = 90 J; impulse frequency = 7 Hz) modulated long-term corticospinal excitability in healthy brains [26]. The research observed a persistent increase of more than 60% in corticospinal excitability (as an index of Long-Term Potentiation-Like Cortical Plasticity), recording the motor-evoked potential from the contralateral first dorsal interosseous muscle [26].

Again, gamma oscillations benefit synaptic potentiation among stimulated neurons by forming a unique network structure [31]. Growing evidence shows that transcranial alternating current stimulation (tACS) in the gamma range modulates cortical excitability and activity, e.g., [71-73]. Recent neuroscience research investigated the mechanism of tACS with a gamma frequency of 200 μA over the bilateral frontal lobe on 5 mice for 20 min over 2 weeks [74]. They found that the excitatory postsynaptic potential increased significantly under the tACS stimulation [74]. They argued that gamma oscillations could influence the long-lasting enhancement of neuronal synaptic transmission [74].

5. Discussion

5.1 Inference 1

Neurons show bidirectional relationships with oscillations. Delta oscillations can modulate gamma oscillations in different subsystems of the nervous system, providing network temporal coordination. Neuronal oscillations have a dual function in brain networks: they are influenced by spiking inputs and, in turn, affect the timing of spike outputs [53]. Recent studies (focused on plasticity between external inputs and receiving neurons) showed that gamma oscillations are

beneficial for coding input signals through plasticity, inducing synchrony (phase lock) of the post-neurons and the input signal [75] and finding 5 show that external delta and gamma oscillations increase excitability. From physics, we know that when incoherent waves are superimposed, the intensity of the resulting wave is equal to the sum of the powers of the superimposed waves. The energy of the resulting oscillations of each point of the medium is similar to the sum of the energies of its oscillations due to all incoherent waves. In neuroscience, this wave interference, the neurons' interconnection, where the phase of the underlying slow rhythm modulates the power of faster oscillations, is often called nested oscillations. These arguments mean neurons show bidirectional relationships with oscillations: neurons interact with other neurons' oscillations. Therefore, neurons are both generators and recipients of oscillations. Furthermore, it is likely that, due to the bidirectional quality of neuronal connections, the techniques of registering neuronal activity in inter-brain research show instead the interference patterns resulting from the superposition of all oscillations of neuron orchestra rather than networks born by linear neuronal connections. Given the above-noted findings, slow neuronal oscillations can provide a delta nested gamma band for coordinating and compressing neuronal activity in peripheral and central nervous subsystems.

5.2 Inference 2

Delta nested gamma oscillations can provide integrated neuronal processing for intentionality. Intentionality is crucial to developing cognitive functions like perception, attention, and memory. On the other hand, because intentional acts rely on previous ecological experience, intentionality seems to encompass and depend on attention, memory, perception, and spatial cognition.

Synchronization is one of the main features of neuronal activity in the brain that contribute to pattern formation [37, 46-50, 53, 76]. Network temporal coordination is crucial in interacting with different brain regions [37, 46-50, 77] that underpin cognition [78]. Structural connectivity interactions with temporal coordination are one of the fundamental functions of gamma-band synchronization, which subserves numerous higher cognitive functions [79]. However, gamma oscillations cannot transit large distances and are limited to local circuits [53]; it cannot provide network temporal coordination [61]. Gamma oscillations are associated with more minor changes in membrane potential in a limited number of cells synchronized only within a restricted neural volume [53].

Delta nested gamma oscillations are crucial for temporal coordination, contributing to cognition. Low-frequency oscillations are essential in engaging gamma rhythms and determining their behavioral consequence in attention [68, 80]. Cortical and hippocampal gamma oscillations have long been viewed as the neural correlate of active processing and memory recall [81-85]. The research observed nested delta and gamma oscillations as a correlate of active memory retrieval [81, 86, 87]. The nested hierarchy of delta and gamma arose during activation of memory patterns [81]. The research found that the delta and theta oscillations exhibited increased power in various brain areas during the mental arithmetic task [88]. According to Ertl et al. [89], low-frequency oscillations are modulated by vestibular stimulation [89].

The research observed delta and theta oscillations during navigation and found that spatial-related processing, along with speed and task variables, modulates delta and theta activity [90]. Research reported that coordinated sensory gamma oscillations modulate multisensory communication during a visual-tactile stimulus matching task [91]; multimodal integration is crucial

in perception. Therefore, delta nested gamma oscillations can consolidate locally fired neuronal networks in large-scale integration. This integrated neuronal processing can regulate processes like perception, attention, memory, and spatial cognition.

5.3 Inference 3

An external low-frequency oscillator can coordinate only relevant local neuronal networks in different subsystems already exhibiting gamma activity.

Findings 1-5 show that gamma oscillations can keep local networks excitatory. However, this increasing excitatory postsynaptic potential is limited to the local networks due to the limited propagation zone of gamma oscillations. It seems plausible that local neuronal networks of peripheral and central nervous subsystems excited due to interpersonal dynamics cannot enable relevant integrated neuronal processing for mental processes until synchronized with the relevant others. According to Findings 1-4, delta oscillations can modulate these already excited local gamma networks, uniting local neuronal networks from different brain zones in network temporal coordination. It sounds plausible that these coordinated local gamma rhythms of specific local networks can provide neuronal synaptic transmission in only these local networks being coordinated by delta temporal coordination.

From physics, we know that waves propagate depending on their frequency, intensity and the medium's resistance. Again, low-frequency waves propagate at a longer distance than high-frequency oscillations, they easily propagate in tissues [19]. As shown in the Introduction, low-frequency oscillations of the mother's heartbeats (the most potent source of the electromagnetic field in the body) can impact both nervous systems, considering the short distance between the mother's heart and the fetus's nervous system [17, 19].

Given the above-noted inferences, proposing the following mechanism of nonlocal coupling at the cell level is not too controversial for explaining shared intentionality. Shared intentionality emerges in the ecosystem of two or more organisms that match the mother-fetus communication model. In each independent organism of this ecosystem, gamma temporal coordination occurs in separate networks of different subsystems that are relevant to the interpersonal dynamics of these organisms in the specific ecological context [2, 3, 17]. The external low-frequency oscillator coordinates central and peripheral gamma temporal coordination in each organism by nesting gamma oscillations of local networks (due to delta and gamma wave interference). This integration of networks with gamma coordination provides integrated neuronal processing. Noticeably, external delta oscillations launch integrated neuronal processing in different organisms simultaneously, similarly modulating local gamma-temporal coordination in different brain zones of the other nervous systems. Because of the interpersonal dynamics, shared ecological context (at least in the low-frequency band), and the single external low-frequency oscillator, cells and even their networks in different nervous systems behave coordinately (nonlocal neuronal coupling), and the integrated neuronal processing in all organisms is similar. In these conditions, each intentional act of the contributor (the mother) becomes a template for the recipient's nervous system (the fetus) - the "instructions" about synaptic structural organization corresponding to a specific sensory stimulus. According to the received view in cognitive sciences, intentionality develops in ecological learning [17-19] due to experience-dependent neuronal plasticity, e.g., [31-34]. The structural organization of excitatory inputs supporting spike-timing-dependent plasticity remains unknown

[92]. It sounds plausible that the correct structural organization of the excitatory inputs that support spike-timing-dependent plasticity relating to a specific sensory stimulus can appear in the recipient due to these "instructions". Nonlocal neuronal coupling in the participants of this ecosystem coordinates neuronal processing in these organisms. Therefore, by coupling neurons of immature and mature nervous systems, shared intentionality yields the direct clue for the relevant stimulus, providing pre-perceptual communication. In the case of the mother-fetus communication system, in simple terms, the mother's heartbeats can synchronize brain gamma waves of already excited central and peripheral neuronal ensembles, similar in both organisms due to physiological entrainment being in the shared ecosystem, and, due to this physiological harmony, specific sensorimotor networks activation in the mother entrain those in the fetus; and because of the shared ecosystem, this engagement trains the young nervous system to respond correctly to certain sensory stimuli through statistical mechanisms based on numerous successful trials and errors (for review statistical learning in infants, e.g., [93, 94]). Again, recent neuroscience research has shown empirical evidence of the nonlocal temporal coordination of neurons registered by the magnetic resonance imaging (MRI) techniques [29] (see limitations of the MRI in subsection 5.4). It has also been shown that the periods of signal bursts repeated at the same rate as the heartbeat in participants asked to stay awake and stay still during brain screening [29].

This mechanism for nonlocal coupling at the cell level differs from the previously proposed by Val Danilov [2, 3, 17] because it explains nonlocal coupling where the external low-frequency oscillator only involves relevant neural networks. The external single low-frequency oscillator consolidates locally fired neuronal networks in a choir to shape harmony from a cacophony of distinct oscillations. In this mechanism, the external low-frequency oscillator does not excite new networks. However, it only unites those already involved in local gamma-temporal coordination due to interpersonal dynamics in the particular ecological context for the intentional act at a specific instant. In such a manner, low-frequency oscillations can substantially affect gamma oscillations in coordinating and compressing neuronal activity in different organisms indwelling in the same ecological context.

5.4 Limitations

The limitations of the hypothesis appear from the general rules of measurements of neuronal activity. The research tools for observing temporal coordination during interpersonal dynamics in vivo are limited to hyper-scanning conducted by five technologies. These neuroscience techniques register explicit correlates to assess the activation of neurons. The magnetic resonance imaging (MRI) technique can detect evolving spin polarization in Hydrogen atoms, mapping the location of water and fat in the body. Functional magnetic resonance imaging (fMRI) measures brain activity by detecting changes associated with the blood flow. These data show neural activity amplitude within individual voxels or regions in interactive dynamics. The electroencephalography (EEG) records the electrical activity on the scalp, which summarizes the macroscopic activity of the surface layer of the brain underneath. Spectral analysis is the crucial component of EEG analysis methods that fall into four categories: time domain, frequency domain, time-frequency domain, and nonlinear methods. The functional near-infrared spectroscopy (fNIRS) technique detects the near-infrared light of the cortical hemodynamic activity from regions near the cortical surface, which occurs in response to neural activity. The fNIRS analyses the temporal correlation between spatially

separated events by calculating functional connectivity through a topographical map of neural activation. The magnetoencephalography (MEG) records the magnetic fields produced by the brain's electrical currents. It is used to study local neural synchrony and cross-area synchronization by recording the magnitude of magnetic fields. In sum, neuroscience data only show indirect evidence of coordinated activity of neurons that we register observing correlates. Inter-brain neuroscience techniques cannot keep neuronal activity in vivo at the cell level. Most likely, these techniques show interference patterns resulting from the superposition of all oscillations of neuron orchestra.

The current literature analysis also found a dissonance in terms that constitute the grounds of main hypotheses on neuronal mechanisms for temporal coordination and their contributions to neuronal interaction. Neuroscience observes the physical features of neurons, accounting for connections of these physical objects in forming neuronal networks. The approach for studying mechanisms of temporal coordination for neuronal interaction is an interdisciplinary study requiring a unification of terms from different disciplines. Therefore, applying the physical terms - e.g., coherence and resonance - would be correct only to relevant processes. For instance, biological sources in Nature are not strictly monochromatic, consisting of many waves. Therefore, physical sources are mutually incoherent. The term synchronization regarding temporal coordination is also rather a literature hyperbole than a reflection of the biological process since the phase lock of neuronal activity is estimated under constraints conditioned by the circumstances as mentioned above. The above-noted measurement limitation and concerns about applying terms (e.g., coherence and resonance) do not enable discussing such concepts as neuronal coherence and resonance in interpreting neuroscience data of hyper-scanning. These data are still unobtainable. Without sophisticated math tools and advanced measurement methods, experimental data tells us about the coherence and resonance of neurons as much as looking at waves on the ocean surface tells us about ocean currents.

6. Conclusions

The theoretical study observed literature to discuss recent findings on the effect of oscillations on neuronal temporal coordination to verify whether external low-frequency oscillations could only synchronize specific local neuronal networks from peripheral and central nervous subsystems for modulating shared intentionality. The review revealed 4 experimental outcomes. 1) Gamma oscillations are associated with the temporal coordination of local ensembles of cells. 2) a relationship exists between low-frequency brain oscillations and the temporal coordination of peripheral and central nervous subsystems. 3) Delta oscillations influence neuronal activity by modulating gamma activity. 4) External delta and gamma oscillations increase cortical excitability. Given these empirical data, the article concluded that delta oscillations can modulate gamma oscillations in different subsystems of the nervous system, providing network temporal coordination. An external low-frequency oscillator can coordinate only relevant local neuronal networks in various subsystems already exhibiting gamma activity. This knowledge allows for the developing a computer-aided assessment method for diagnosing a cognitive development delay in preverbal children.

Author Contributions

The author did all the research work of this study.

Competing Interests

The author has declared that no competing interests exist.

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