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Short Communication

Theoretical Grounds of Shared Intentionality for Neuroscience in Developing Bioengineering Systems

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Abstract

The article discusses a definition of shared intentionality that reflects recent discoveries for inspiring further translational research in developing bioengineering systems based on human-computer interaction. The child's cognition begins through shared intentionality that occurs in child-caregiver interaction when communication via sensory cues is impossible. There needs to be more knowledge on how it appears. This article argues that shared intentionality is collaborative interactions in which participants share the essential sensory stimulus of the actual cognitive problem. This social bond enables ecological training of the immature organism, starting at the reflexes stage of development, for processing the organization, identification, and interpretation of sensory information in developing perception. In nature, shared intentionality appears in mother-child dyads in increasing interpersonal dynamics due to mechanisms of cell coupling that provide an ecological developmental template. Knowledge about neurophysiological processes occurring during pre-perceptual communication can contribute to advances in bioengineering systems.

Keywords

Shared intentionality; perception; social cognition; brain-computer interaction; bioengineering systems

1. Introduction

Over the recent three decades, the knowledge about shared intentionality (SI) has evolved, developing the definition of the concept. Initially, SI was defined as collaborative interactions in which participants share psychological states [1-3]. According to Tomasello and Rakoczy [4], one-year-old children's understanding of persons as intentional agents enables skills of cultural learning and shared intentionality. Then, Tomasello et al. [5] developed the SI hypothesis with new knowledge about SI's appearance period. They argued that SI typically emerges around the first birthday from the interaction of two developmental trajectories: a general primate line of development for understanding intentional action and perception and a uniquely human line of development for sharing psychological states with others [5]. Recently, Tomasello [6] introduced the hypothesis of gradually increasing social bonds between children and caregivers, referred to as time slices, beginning from emotion sharing from birth – newborns' basic motive force of SI.

This short communication employs a combination of psychophysiological, mathematical, and behavioral approaches to discuss the theoretical grounds of shared intentionality for proposing its actual definition. One of the purposes of definition development is to explain a proposed meaning by clarifying to the community of users that one intends, to attach a new proposed meaning [7]. The definition should reflect empirical data. Another reason is related to the essential role of the definition in establishing approaches to the study of the phenomenon it defines. Evidence from recent psychophysiological and neurophysiological studies challenges our knowledge of the processes underlying shared intentionality.

A research study shows that emotional contagion occurs among individuals without awareness of the emotional cues [8]. Increasing inter-brain research in neuroscience shows growing evidence of brain-to-brain synchronization. In 2020, the review by Valencia and Froese [9] observed 24 research studies that mentioned including EEG- and fNIRS-based hyper scanning methodologies. Among these hyper-scanning studies, four studies declared to observe inter-brain synchrony while people were cooperating without sensory cues between subjects. For instance, the research study by Fishburn et al. [10] communicated to observe shared intentionality without sensory cues between subjects, registering interpersonal neural synchronization in functional near-infrared spectroscopy (fNIRS). This neuroscience research reported coordination of cerebral hemodynamic activation in subject pairs when completing a puzzle together in contrast to a condition in which subjects completed identical but individual puzzles [10]. Astolfi et al. [11] observed strong estimated functional connectivity in subjectsof the same team but not in subjects of different teams. Another research study registered higher phase synchrony in subjects during joint attention than individual attention [12]. Hu et al. [13] found greater inter-brain synchrony when participants were believed to be interacting with a human than with a machine. In 2022, the systematic review of fNIRS hyper scanning studies observed thirteen studies with 890 human participants [14]. The meta-analysis revealed evidence of statistically significant inter-brain synchrony while people were cooperating, with large overall effect sizes in both frontal and temporoparietal areas [14]. Apart from these reviews [9, 14], another neuroscience study by Painter et al. [15] registered neuronal coordination in the inter-brain experiment during coordinated mental activity without sensory cues, placing subjects in different isolated locations. Even though these two reviews [9, 14] revealed significant inter-brain synchrony while people were cooperating, the data do not guide a conclusion about increased cooperative neuronal activity only due to interaction without sensory cues. From mentioned above research, only limited studies [10-13, 15] accounted for certain features of the mother-newborn model in their research designs: solving the shared cognitive problem without communication in the dyads. Other studies did not concern studying inter-brain activity in pairs without sensory cues aiming at another research problem. Even though the outcome of all this research can include an impact of shared intentionality, other variables may also affect increased inter-brain activity. We cannot distinguish pure shared intentionality from the outcome of inter-brain activity in studies that did not consider communication as a variable. Dissecting causal from correlational relationships is a central problem in neuroscience: merely observing that one variable precedes another is not sufficient to infer causality [16]. Obviously, any registered mirroring neuron activity needs a correct posed research design with specified variables to be interpreted. This problem concerns separating sensorimotor processes from emotional and cognitive ones from one side and, from the other, distinguishing inter-brain activity due to collaborative interactions without communication in which participants share the essential sensory stimulus for the actual problem while cooperating in solving it. Nevertheless, five research studies [10-13, 15] declared observed inter-brain activity under conditions without communication in pairs while subjects were solving the shared cognitive problem; and they registered an increased inter-brain activity in contrast to the condition when subjects solved a similar problem alone.

A growing body of the literature shows evidence of increased group performance in psychophysiological studies, as researchers have noted, due to shared intentionality. Atmaca et al., [17] in experiments with 86 subjects, Shteynberg and Galinsky [18] with 115 subjects, McClung et al. [19] with 138 subjects, Val Danilov et al. [20] with 51 subjects, Val Danilov and Mihailova [21] with 58 mother-child groups (68 children), and Tang et al. [22] with 33 subjects (11 groups of 3 subjects each) showed implicit coordination, greater cooperation and robust joint commitment under a condition when subjects were solving the shared problem without communication. A recent psychophysiological research study [23] assessed the differences in the SI magnitude in mother-child dyads with neurotypical (NT) children and neurodivergent (ND) children aged 3-6 years. These results presented empirical evidence of shared intentionality without sensory cues in the mother-child pairs. They also showed that ND children scored six times higher (on average) on SI tests than NT children [23]. The subsequent experiments [24], the continuation of the before-mentioned research study, proved the abilities of shared intentionality in ND and NT children without sensory cues. ND and NT children correctly solved unintelligible tasks in more items than predicted by probability, being with their caregivers who knew the correct answers. The study argued that this improved performance could mean the ability of bioengineering systems to encourage shared intentionality in human pairs by modeling the mother-newborn biological system [24].

This article discusses a new definition of shared intentionality that reflects recent discoveries for inspiring further translational research in developing bioengineering systems based on human-computer interaction. Semantics shows that two components of the term SI together yield quite a clear sense: "intentionality" – the directed property of certain mental states [2], and "shared" – owned, divided, felt, or experienced by more than one person [25]. The question of where this "property of certain mental states" is aimed has a reasonable answer. It is aimed at the common sensory cue that all participants can experience together simultaneously. As we know, only sensory cues can ensure simultaneous receptivity by two or more participants, which leads to synchronous changing of psychological states in these participants. Similar psychological states in different individuals may appear simultaneously without shared sensory cues only by chance. In this work, the term "cue" denotes a meaningful signal. It is a stimulus, event, or object that serves to guide behavior, such as a retrieval cue, or that signals the presence of another stimulus, event, or object, such as an unconditioned stimulus or reinforcement [26].

In contrast, the term "stimulus" is a meaningless change in physical energy that activates a sensory receptor; it is any agent, event, or situation that elicits a response from an organism [27]. At least one contributor should experience "intentionality" to share it with others. However, it is not clear how SI is divided with a newborn organism that cannot provide meaningful interaction. Infants can manifest pure reflexes during the first substage named 'reflexes' [28]. At this stage, the goal-directed behavior is pure reflexes [28]. What interaction modality promotes SI?

The article discusses this problem by reasoning how the blank mind can solve a vicious circle of the categorization-perception-intentionality trinity in the foundation of cognition. Section 2 shows that relevant stimulus cannot overcome the noise magnitude if it passes through the senses, posing the problem so-called Primary Data Entry (PDE) problem. The environment is uncategorized for the organism at this stage of development; the sensation is too limited by the noise to solve the cue problem. In Section 3, the article argues that even a dynamical approach cannot get around the cue to noise problem. It requires categorizing the environment, which appears due to (and only after) perception and intentionality. Section 4 poses arguments for why perception cannot appear on its own independently. Section 5 shows that intentionality is only evident by two months of age in infants. So, none from the categorization-perception-intentionality trinity alone allows for solving the PDE problem. While in the uncategorized environment, neither intentionality nor perception can develop, experimental data show early intentionality, which depends on interaction with caregivers and emerges around birth. Section 6 discusses the early intentionality features that correspond to the psychological construct of shared intentionality. It poses a hypothesis on solving the PDE problem, reasoning a possible mechanism of ecological training of the immature organism. The section presents a hypothesis on how neurons “know” the specific timing code of the synaptic strength in correspondence to a particular sensory stimulation. The new definition of shared intentionality appears here as the synthesis of previous arguments. Section 7 discusses possible applications to interventions, such as AI or prosthetic limb development. Even though the application might be premature given the theoretical nature of this article, this helps inspire further research.

2. The Cacophony of Stimuli Vs. Categorization

Two opposing views, externalism and internalism, define initial knowledge as the foundation of knowledge. It does not matter from what perspective to look at this issue. That is, whether knowing relies primarily on the discovery of relationships between previous knowledge and new information domains from outside. Or, knowing is mainly based on discovering new key links between cause and effect within initial (or previous) knowledge. Acquiring knowledge only begins if initial knowledge is already in place. This circumstance raises a problem. The blank mind cannot assimilate knowledge in communication. Communication is an exchange of mutually implied meanings. Meaningful interaction is inaccessible for neonates because only the "nine months revolution" opens a child the window to the world of objects as symbols [6]. So, the blank mind should already possess the knowledge to begin cognition.

The search for innate aspects of human cognition has not led to some very important insights [29]. For instance, the ontogenetic process of infants' understanding of objects in space—namely, the manual manipulation of objects—cannot be a crucial ingredient since infants understand objects in space before manipulating them manually [29-31]. The genetic code is no more than a rule of causal specificity based on the fact that cells use nucleic acids as templates for the primary structure of proteins. Yet, it is unacceptable to say that DNA contains the information for phenotypic design [32]. The epigenetic approach to human psychological development – that cascading phenotypic effects are not encoded directly in the genes – contrasts sharply with many so-called nativist approaches [6].

From an interaction perspective, two widely spread approaches to understanding the beginning of cognitive development – (i) Vygotsky's [33] internalization of external relations (actions) fixed in the meanings of these actions and even (ii) Piaget's [28] developmental stages overpassing through the interaction of innate capacities and environmental events – take into account a child's interaction with the environment. For them, meaningful interaction is a prerequisite to knowing and cognitive development. This article means knowledge in the sense of information because even in other senses of the word, the information sense of the word "know" is often implied. According to the mathematical communication theory, information is estimated by entropy quantity [34]. Sensory cues do not deliver meanings for the organism at the reflex substage of the sensorimotor stage of development. The actual sensory cue is one from a set of different stimuli. It acts on the receptors along with the noise – irrelevant stimuli from all sensory modalities. Two statistical processes define this interaction: the source (which produces sensory cues) and the noise. Therefore, all of the entropies (denoted E) of all sources should be assessed on a per-second basis:

$$\mathrm{E(am)} = \mathrm{E(s)} + \big(\mathrm{E(n1)} + \mathrm{E(n2)} + \cdots + \mathrm{E(ny)}\big) \tag{1}$$

A sum of the source entropy E(s) with the entropies E(n) of the noise (other "y" number of irrelevant stimuli) is the entropy magnitude of the actual message E(am). The equation shows that the noise magnitude significantly exceeds the source size because the number "y" of irrelevant stimuli is extensive. The noisy transmission does not let to reconstruct the original message [34]. None of the known sensory modalities can transfer information through sensory cues (ordinary stimuli for the organism) in a multi-stimuli environment, where all of them are equivalent or the relevant stimulus magnitude is below the noise [35]. The organism needs instructions for selecting a stimulus to begin cognition. However, even the clue on relevant stimulus cannot overcome the noise magnitude if it passes through sense [35].

A more powerful stimulus than noise does not solve the problem. Indeed, it needs to be clarified how the pure mind can distinguish sensory input caused by the body's movement from sensory input caused by stimuli from the outside world. Several authors have stressed the specific role of efference copy mechanisms on the origins of perception and consciousness [36-38]. According to this viewpoint, perception can be done by an efference copy mechanism, a carbon copy of the movement command that is routed to sensory structures [36-38]. However, it is still unclear how efference copy can give rise to the feelings that accompany and characterize our response to sensory stimulation [38]. In Section 3, this issue is reflected in more detail from the perspectives of the embodied dynamical system hypothesis.

The above considerations show that, at the reflex substage of the sensorimotor stage of development, the organism cannot distinguish relevant sensory stimuli independently. The environment is the cacophony of stimuli: electromagnetic waves, chemical interactions, and pressure fluctuations; it is uncategorized for the organism at this stage. Therefore, the organism cannot communicate with sensory cues and assimilate knowledge. Multisensory integration creates even more challenges for the blank mind, which we discuss in Section 4. The newborn is just capable of manifesting pure reflexes [28]. For beginning categorization, the blank mind should already possess knowledge about the environment for acquiring and understanding thoughts, experiences, and meanings. Contemporary theories do not support inherited knowledge or the explanation of acquired knowledge through sensations. This is a vicious circle – in the uncategorized environment; cognition requires initial knowledge about the environment that the blank mind cannot ensure or enable. In the uncategorized environment, no self-training mechanism succeeds. Even observational single-trial learning needs perception and intentionality, a problem for beginners. The categorization-perception-intentionality trinity poses a barrier to behavioral shaping, stimulus and response generalization processes. Self-training mechanisms need feedback whose cue cannot overcome noise in the uncategorized environment without perception and intentionality. Whether stimuli (related to reflexes) overcome the noise barrier. A selection process of neurons, differentially responsive to different sensory signals, can deal with the PDE problem. At the level of reflexes development, this neuron selection develops at the level of receptor responsiveness by making the individual neuron more or less depolarized or hyperpolarized. This process regards reflexes development as involuntary actions in response to stimuli but not the awareness of the automatic response. It does not contribute to activating the categorization-perception-intentionality trinity since it can act on stimuli before they reach the neuronal circuits responsible for perception and intentionality. So how does the blank mind receive initial knowledge at the very beginning for cognizing? The article calls this problem Primary Data Entry (PDE).

3. Does Embodied Dynamical System Solve the Problem?

According to embodied dynamic system theory – the most developed theory from the perspective of the PDE problem – the mind is an autonomous system by its self-organizing and self-controlling dynamics, which determines the cognitive domain in which it operates without inputs [32, 39, 40]. Dynamicists have grounded their approach on a dynamic system. However, their interpretation of the dynamical system is not complete.

At least two arguments challenge the embodied dynamic approach. First, the dynamical hypothesis in cognitive science [41] is based on a set of equations. It means that entering primary data is required to compute each particular situation. A description of the specific dynamical system may not evolve without entering initial conditions [42, 43]. Second, to be precise, van Gelder's [41] dynamical hypothesis in cognitive science nevertheless regards the initial conditions. Even though a dynamical system tracks primary data less than dynamic changes inside, according to the hypothesis, it still needs input [42, 43]. Even the dynamic system needs an input of initial knowledge of the specific community to trigger this system. Considering the above difficulties, embodied cognitivism tries to solve the PDE problem by dynamically embodied information. They believe that the sensorimotor motor network yields the pairing of the relevant stimulus (bearing a cue) with the particular symbol saved in the structures and processes that embody meaning (sense).

'Representational "vehicles" are temporally extended patterns of activity that can crisscross the brain-body-world boundaries, and the meanings or contents they embody are brought forth or enacted in the context of the system's structural coupling with its environment [32] (p.36).' In a multi-stimuli environment, the concrete stimulus link with specific neural "patterns of activity" is unpredictable due to the many irrelevant stimuli that can be randomly associated with this embodied meaning.

Moreover, this pairing is possible only when "the context of the system's structural coupling with its environment" is already grasped, which is a problem for the blank mind in the uncategorized environment (as shown above). Therefore, even embodied dynamical system with dynamically embodied information does not solve the PDE problem. Embodied dynamical system approach requires categorizing the environment, which appears due to (and only after) perception and intentionality. However, this is a vicious circle because perception and intentionality require initial knowledge of the environment to target (as shown below).

4. Whether Perception Emerges Itself?

According to the received view in cognitive sciences, perception enables a holistic representation of an object by the organization, identification, and interpretation of sensory information. Due to this quality, individuals can see the world around them as stable, even though the sensory information is typically incomplete and rapidly varying [44]. For solving the PDE problem at the onset of cognition, whether the perception is a primary characteristic of consciousness. Whether the perception is an active process of hypothesis testing that shapes itself; or whether realistic sensory information is rich enough to categorize the environment, making the perception unnecessary. This debate – of active perception vs. rich enough sensory information – is still in progress in theories of perception. Perception – as – direct – perception theory [45], perception-in-action theory [46], and many other approaches contribute to understanding perception by reasoning its purpose and processes. However, they leave a gap in knowledge on perception formation at the first step of cognition. In the beginning, what enables a holistic representation of an object before knowledge about the environment? As mentioned above, the organism cannot distinguish relevant stimuli independently at the reflex substage of the sensorimotor stage of development,. The environment is uncategorized for the organism at this stage of development. It is already a problem distinguishing sensory input caused by the body's movement from sensory input caused by stimuli from the outside world. It is even more challenging to recruit different modality stimuli in a holistic representation of an object by the organization, identification, and interpretation of sensory information.

The multisensory integration approach argues that we perceive a world of coherent perceptual entities [47] due to integrating different sensory modalities that interact with one another and alter each other's processing. Two issues challenge our knowledge about multisensory integration mechanisms in perception. First, according to Treisman [48], the binding problem – how animals generate a coherent perception of their environment from the cacophony of stimuli: electromagnetic waves, chemical interactions, and pressure fluctuations – can be dissected into three separable questions. (1) How are the relevant elements to bind as a single entity selected and segregated from those belonging to other objects, ideas, or events? (2) How is the binding encoded so it can be signaled to other brain systems and used? (3) How are the correct relations specified between the bound elements within a single object [48]? There are many different keys to these questions.

However, irrelevant to which of the proposed hypotheses is the most likely to be correct, the essential factor is the simultaneous coordination of receptors' different modalities. Indeed, a cacophony of stimuli of different continuance from the environment (a dynamical system) affects different parts of the nervous system in different ways every moment. Can an organism (also a dynamical system) distinguish them by combining the corresponding sensory stimuli of one or another moment from the time sequence? Different neural networks in the nervous system comprise thousands to hundreds of thousands of neurons with a whole axons length of hundreds and even thousands of meters. However, for stimuli that receptors detect simultaneously, the time difference impact on the nervous system of two simultaneous stimuli can become up to a second (even though nervous impulses can attain speeds up to 120 m/s). Different continuity of stimuli is a problem for the nervous system for multisensory integration, which in this case, can pair stimuli even from different time instants. Even ignoring different durations of incoming stimuli, different processing times of the stimuli also challenge their coupling. The stimuli cannot be recognized as simultaneous without a clue about the proper stimulus (while the clue cannot pass through the senses, as mentioned above). The latter feature (simultaneity) is crucial for multisensory integration. Multisensory integration is a complicated problem for immature organisms to complete independently.

Second, the facts from physiology show that newborns cannot interpret the environment the same as adults. Newborns' sense of the environment is limited due to physiological reasons. (i) The graduate development of children's eyes is well known. Neonates and infants cannot perceive the same picture of reality as adults; they cannot register the same magnitude of visual stimuli as mature organisms can get because of immature (underdeveloped) eyes [49-54]. (ii) Newborns' hearing is slightly worse than adults' [55]. To hear a sound clearly, newborns require that the sound be about 15 decibels louder than adults need. For instance, a typical conversation is about 60 decibels. Visual and auditory stimuli carry the main information (the most significant share) about social reality. As noted above, infants understand objects in space before manually manipulating them [29-31]. Newborns cannot sense the environmental stimuli from social phenomena to the same extent as adults. Even assuming that a newborn's brain somehow processes perception, can pure reason pick up similar to our interpretations of the percept independently using different sensory stimuli? So, the problem is not only the different durations of stimuli or the difference in stimuli processing time (see above the binding problem), but the outcomes of similar sensory stimuli processing in immature and mature organisms should also be different due to different sensory receptors' sensibility. Consequently, a corresponding holistic representation of the object in these organisms seems unlikely to occur (it must not occur). However, as we know from numerous research, young children gain the corresponding to adults the holistic representations of objects.

The above arguments show that perception cannot appear on its own independently. This is again the vicious circle – a newborn should gain a holistic representation of the environment before beginning perception for then successfully processing the organization, identification, and interpretation of sensory information. To our knowledge, sensation and perception appear due to relations between neurons uniting them in specific networks. Therefore, the question of perception emergence can be reduced to a challenge for neurons to “know” the specific timing code of the synaptic strength in correspondence to a particular sensory stimulation [43]. The structural organization of the excitatory inputs supporting spike-timing-dependent plasticity (STDP) remains unknown [56]. The article reflects this point in Section 6. In the categorization-perception-intentionality foundation of cognition, we discuss in Section 5 whether intentionality shapes other components of cognition.

5. Does Intentionality Solve the Problem?

According to Searle [2], intentionality is the directed property of certain mental states; it manifests both an individual's conscious and unaware targeting [57]. For instance, people cannot stop thinking about a traumatic life event; they think obsessively about the event to the point of distraction and an inability to function in their daily life [57]. From these perspectives, unlike intention, a newborn can manifest intentionality without awareness. What do empirical data reveal about intention and intentionality in neonates? The literature presents two research methods of detecting intentions in young infants "observational" and "experimental." The "observational" method studies self-directed behavior, verbal labeling behavior, and differential responses to different stimulus conditions of daily routine, all of which might indicate self-recognition [58]. The method shows that newborns do not actively interact with the mother in a natural environment (e.g., [33, 58-62]). Intention, even for simple acts, appears in infants no earlier than two months of age – starting to look at their hands [58]. The theory of cognitive development [28] and common knowledge from everyday life also support this fact [63]. On the contrary, the "experimental" research method detected more significant newborn achievements that seem intentional from birth. Neonates manifested numerous social actions in the first days and even the first hours of their life [64]. A growing body of research testified to newborn achievements such as a reaction to the crying of another newborn (e.g., [65-69]), early imitation (e.g., [70-73]), other-race effect (e.g., [74, 75]), recognizing faces by their parts [76], recognizing faces without their context in schematic pictures [77, 78], facial attractiveness [79], distinguishing mother and stranger (e.g., [80-83]), other-species effect, and others [64]. These results show that outcomes of "observational" and "experimental" research designs contradict each other. The difference is that in the "experimental" design, young infants exhibited an ability like intentionality in non-expectable cognitive achievements [63]. The article calls this ability "early intentionality" since immature organisms cannot manifest intentionality without categorizing the environment. Val Danilov and Mihailova [63] argued that unlike intention appearance at about two months, this newborn's ability ("early intentionality") depends on interaction with caregivers and emerges around birth. As the above statements are correct, early intentionality can solve the PDE problem, even in a developmental stage before perception.

6. Whether Early Intentionality is Shared Intentionality?

The noted above experimental data disclose that, in the reflex sensorimotor developmental stage [28], newborns manifest an ability "early intentionality" of unaware targeting. Immature organisms demonstrate this ability without perception and awareness of self-actions, indwelling in a group with caregivers. "Early intentionality" bears other features than intentionality; it even contradicts a definition of intentionality. Because in newborns, "early intentionality" cannot be the directed property of certain mental states. Being “directed” is impossible without a goal that requires the categorization of the environment. Being at the reflex substage of the sensorimotor stage of development, the organism cannot independently carry out categorization (as shown above). Again, newborns can show goal-directed behavior in primitive reflexes only. So, while intentionality is characteristic of consciousness in a mature organism, "early intentionality" is unaware interaction in which the immature recipient organism experiences the ability to select the only stimulus that the mature contributor organism is targeting. "Early intentionality" does not fit the features of intentionality, while "early intentionality" features are closely related to the definition of SI.

According to Tomasello [6], the intriguing question of what interaction modality promotes SI relies on emotional sharing. The mechanism of such emotional coordination is not clear. One could ponder that the hypothesis of universal emotional expressions proves emotional sharing in SI due to innate emotional patterns (together with understanding their meanings). However, many researchers disagree with the universality of emotional expressions. They believe it is formed by limited experimental methods since other research designs show the contrary inference [84-88]. There is no evidence of a genetic mechanism linking meaning in mind with specific social reality to apply an appropriate emotional pattern to a specific situation. Again, it is unacceptable to say that DNA contains the information for the behavioral phenotypic design. Furthermore, even imitation is a complex problem for organisms in the "reflexes" sensorimotor stage [89]. How a neonate can be aware enough of her movements and how these map onto the movements of others [90, 91], see also the above facts of newborns physiology. Anyway, even if a neonate could alone "read" the basic facial expressions of caregivers and recognize their context (the specific situation where it is applicable), the newborn does not have time for such a "training course" because, as we know, newborns demonstrate their behavioral achievements in experimental conditions already in the first hours of life [63, 64]. Finally, experimental data show SI ability in young children indwelling with caregivers of goal-directed behavior towards the common sensory cue they experience simultaneously. SI may not be inherited nor provided through parent-child sensory interaction. It appears around a birthday without newborns' awareness and even perception. The conditions of the mother-newborn model are (a) interpersonal dynamics of organisms (b) being in social entrainment and (c) solving the shared cognitive problem (d) without communication in the dyad.

Shared intentionality is an outcome of evolutionary development that facilitates the ability among social organisms to select only one shared sensory cue for the entire group instantly [43]. The empirical data and theoretical reflections allow us to discuss neurophysiological mechanisms of shared intentionality due to the neuron coupling of two nervous systems. Assuming that such a nonlocal connection of neurons is possible, it may provide a template for training immature nervous systems for multisensory integration. For example, this nonlocal connection might be both the sensory neurons coupling in two organisms and/or the coupled neurons in the modality-specific input gateways in the medial prefrontal cortex, precuneus, bilateral posterior superior temporal sulcus, and temporoparietal junctions [43]. From these perspectives, SI is pre-perceptual communication (via nonlocal neurons coupling) in which a recipient organism chooses one shared stimulus from many irrelevant stimuli due to a contributor organism's intentionality. Only after this, a child's perception can gain a holistic representation of an object in intentional acts by capturing statistical information from cascading interactions. If so, knowledge of SI changes our knowledge about children's cognitive development and our reality.

The pre-perceptual communication (nonlocal coupling mechanism) for shared intentionality does not seem bizarre in light of the idea of quantum principles for explaining consciousness that is already widely diffused. There is a commonly held view that quantum effects cannot be present only in mammalian brains and that quantum phenomena are quite common in biological systems [92]. The laws of quantum mechanics do not limit quantum processes to the boundaries of physical objects determined by classical physics, e.g., only inside the cerebral cortex or the nervous system. Quantum processes unite particles depending on their belongings to one quantum system rather than to a physical object. For instance, Val Danilov and Mihailova [43] supposed a quantum mechanism of the shared intentionality hypothesis – entangled protein molecules from neurons could engage neurons of different organisms in cooperative reactions to shared stimuli. However, this protein molecule hypothesis is only that, a hypothesis.

As noted above, it remains unknown how neurons “know” the specific timing code of the synaptic strength in correspondence to a particular sensory stimulation [56]. According to the hypothesis [43], coupled neurons of a newborn organism can learn the timing code to modulate a particular synaptic strength. A tetanic stimulation comprises a high-frequency sequence of individual stimulations of a neuron. The sign and magnitude of the change in the synaptic strength depend on the relative duration between the spikes of two connected neurons (the presynaptic and post-synaptic neurons) [56]. The synaptic strength triggers either Long-Term Potentiation (LTP) or Long-Term Depression (LTD). These outcomes correspond to the engagement of specific stimuli – the structural organization of the excitatory inputs supporting spike-timing-dependent plasticity (STDP) [56]. STDP involves pairing the presynaptic and post-synaptic action potentials (APs) in neurons [39]. The duration between the presynaptic and post-synaptic APs modulates the synaptic strength, thereby triggering either LTP or LTD [56]. The young neurons learn the structural organization of the excitatory inputs that support STDP about a complex comprising sensory stimuli and the activation of certain sensorimotor and/or emotional networks of the nervous system, coupled with mature organism's neurons [43].

The author believes this mechanism is a possible key to the problem of how neurons "know" the specific timing code of the synaptic strength in correspondence to a particular sensory stimulation in the shared environment with the mature organisms. Therefore even without sensory cues, shared intentionality yields the direct clue for the relevant stimulus by coupling neurons of immature and mature nervous systems. The specific ecological neuron pattern of a mature organism bears the categorization of reality for newborns, which contributes to mechanisms of efference copy and the establishment of perception. In such a way, shared intentionality ensures the assimilation of knowledge before categorizing the environment. During the first months of life (probably even before birth), cognition emerges in the immature organism by monitoring the statistical information available in the environment with caregiver clues through shared stimuli in the shared ecological context.

7. Forward-looking Outlook

Future inter-brain research provides more evidence of neurophysiological grounds for shared intentionality if they consider the new definition of shared intentionality. Definitions of brain functions should be carefully considered because the translational impact of basic neuroscience research relies on how we define these functions [93]. Even the neuroscience studies mentioned above [10-13, 15] declared to observe inter-brain activity under conditions without communication in pairs while subjects were solving the shared cognitive problem, they did not consider all necessary features of the mother-newborn model in the research design, e.g., pre-perceptual communication in dyads due to the non-local coupling of neurons. According to the new definition, a feasible way to detect shared intentionality in inter-brain research is by modeling subjects' conditions of the mother-neonate bio-system. This neuroscience research should be conducted within the conditions: of intentional/unintentional synchronization with/without communication between subjects. The 11 endogenous and exogenous factors should also be considered [24].

The quality must be preserved in an organism to some extent throughout its life if it appears at birth. The article argues that shared intentionality complements other interaction modalities during the life circle before communication with sensory cues. Recent studies discussed possibilities for assessing shared intentionality magnitude in bioengineering systems [23, 24, 63]. What can this assessment mean? What contribution does an understanding of shared intentionality make to bioengineering research? Apart from yielding a new latent construct for psychometrics, by assessing this quality, we can improve it. This knowledge is changing our understanding of social processes – sharing mental states with others is one of the fundamental elements of social interaction. Moreover, the ability to assess shared intentionality brings us closer to understanding the genesis of the mind. This may be correct because (i) the applied assessing method also proves the non-perceptual mechanism of this social interaction modality. (ii) Shared intentionality takes part in the mind ontogeny. This knowledge allows for discussing a broad range of topics. For instance, is shared intentionality the interpersonal sharing the necessary ingredient or is it superimposed on more primitive associational processes such that shared intentionality is just a more complex form of a more basic function of the development of neuronal associational processes which might be limited without the addition of the interpersonal context. Could the development of autism be a failure to graduate to this next higher level involving the interpersonal shared experience, a possible consequence of impaired prenatal patterns of connectivity? As the author believes, these complex issues can be studied by research on the mechanisms of the cell coupling quality for shaping embryos during development. How the shape of embryos emerges during development is a fundamental question that has intrigued scientists for centuries. Indeed, cell actions during an embryo formation, including shape changes, cell contact remodeling, cell migration, cell division, and cell extrusion, need control over cell mechanics [94]. This complex dynamical process is associated with protrusive, contractile, and adhesive forces and hydrostatic pressure, as well as material properties of cells that dictate how cells respond to active stresses [94]. Precise coordination of all cells seems to be a necessary condition. Moreover, such a complex dynamical process likely requires clear parameters of the final biological structure – the complete developmental program with a template for accomplishing it. Genes provide only the part of this program – a genetic code. Again, the genetic code is no more than a rule of causal specificity because cells use nucleic acids as templates for the primary structure of proteins [32]. The embryo's development program in the specific environment likely consists of a combination of the genetic code with ecological instructions obtained in interactions with the mother. Integration of the mother and embryo nervous systems could give the embryo complementary instructions for complementing the genetic code. However, their nervous systems are completely separated, so only the non-local coupling of cells can provide the embryonic development template. This issue requires a well-designed study, which, unfortunately, is beyond the limits of the current article.

Understanding neurophysiological processes occurring during shared intentionality reveals perspectives for different applications in bioengineering. In medicine, evaluation of shared intentionality magnitude in mother-child dyad can contribute to assessing children's cognitive development. An assessment of cognitive development would make possible early intervention in children to correct cognitive development trajectories [63].

The development of intelligent prosthetic limbs has taken a giant leap, although they lack the biological properties of actuation and sensing. In solving this problem, progress in knowledge of shared intentionality can contribute to learning artificial neural networks of intelligent prosthetic limbs and provide their management via a bond with the human sensorimotor network [95]. Artificial intelligence is a critical point in the fourth industrial revolution. The feasibility of integrating the human brain with a computer shows the way to a new stage in artificial intelligence design.

8. Conclusions

The article attempted to advance a theoretical foundation for the ontogenesis of a psychological construct of shared intentionality. It discussed recent psychophysiological and neuroscience research data that showed increased collaborative interactions when subjects completed similar mental tasks without communication. Based on recent empirical findings and theoretical reflections, the article proposed a definition of shared intentionality as collaborative interactions in which a recipient organism chooses one relevant stimulus from many irrelevant stimuli due to a contributor organism's intentionality. The recipient and contributor share the essential sensory stimulus of the actual cognitive problem. It is pre-perceptual communication via the nonlocal coupling of neurons. This social bond enables ecological training of the immature organism, starting at the reflexes stage of development, for processing the organization, identification, and interpretation of sensory information in developing perception. In nature, shared intentionality appears in mother-child dyads in increasing interpersonal dynamics due to mechanisms of cell coupling that provide an ecological developmental template.

The article argued that shared intentionality complements other interaction modalities during the life circle before interactions with sensory cues. Knowledge about shared intentionality mechanisms can contribute to advances in bioengineering systems employing human-computer interaction, such as assessing cognition in preverbal children and non-invasive brain-computer cooperation. This theoretical article encourages hyper-scanning research on shared intentionality, which would consider the mother-newborn model's conditions.

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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