Parallels between the Digital Twin Concept and Mathematical Phenomenology of Human Perception

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***Abstract*—This paper explores the conceptual relationship between Digital Twins (DTs) and proposed Cognitive Twins (CTs), showing that both share a similar five-dimensional structure in which upper-level components (virtual entities or qualia) govern lower-level physical components. While DTs arise in engineered, socio-technical contexts and CTs emerge from biological evolution, their structural parallels suggest the possibility of deeper, shared mechanisms. Additionally, we highlight the importance of an often-overlooked dimension in DTs: the data-processing component, analogous to the sensory unit in CTs. This mid-level bridge transforms bottom-up data into top-down information and may be effectively modeled using Hilbert space formalism to capture uncertainty and one-to-many mappings in decision-making based on high-level information.**

Keywords*—Digital Twin, Cognitive Twin; cyber-physical system; five-dimensional structure; information flow; decision-making; Hilbert space formalism

I. Introduction: Digital Twin Concept

Nowadays, the concept of the Digital Twin (DT), originally introduced by Grieves in 2003 (see [1] for details), plays a central role in the development and operation of Cyber-Physical Systems and the Internet of Things. It serves as a key enabler for the monitoring, optimization, and forecasting of real-world system behavior across various domains. Although multiple definitions of DT exist (e.g., [2], [3]), it is generally understood as a digital representation of a specific physical system that replicates the structure, context, and behavior of its real-world counterpart (see [4]-[7] for recent reviews). According to [8], [9], a typical DT is characterized by five dimensions: (1) a physical entity in the physical space; (2) a virtual entity in the virtual space; (3) data and information flows connecting the physical and virtual entities; (4) twin data that integrate all relevant information from both domains; and (5) services that enable the virtual entity to influence its physical counterpart, through either automated or human-mediated operations. These dimensions are manifested through distinct features within a unified cyber-physical space. It is important to emphasize that the term Digital Twin refers to the integrated (holistic) system comprising both the physical and virtual components, along with the data flows and services that connect them; it does not refer solely to the virtual model.

The multi-factorial correspondence between the physical (PE) and virtual (VE) components (entities) of a DT is a defining feature that captures the essence of the DT concept (e.g., [6]). On the one hand, the PE $\rightarrow$ VE mapping should ideally approximate a one-to-one relationship, wherein the virtual model accurately reflects the structural dimensions, physical properties, assembly relationships, and other relevant characteristics of the physical entity. On the other hand, in cyber-physical systems, the AI in the network layer—processing data received from both autonomous numeric detectors and human-based inputs—governs the operation of the physical system. Given the complexity of physical entities—which encompass industrial resources such as products, personnel, equipment, materials, processes, environments, and facilities—it is often practical to monitor only a core subset of elements. The remaining elements may be omitted without significantly compromising the operational efficiency of the virtual model. As a result, the VE$\rightarrow$PE mapping is better characterized as one-to-many. Consequently, the virtual entity of a DT is not a complete replica but rather a digital image of the physical component; its individual properties reflect, but are not reducible to, those of the physical entity. Within a DT, physical data are generated during the operation of the physical entity, whereas virtual data emerge from the functioning of the virtual entity. These data streams are fused and integrated through mutual conversion, making bidirectional data processing (PE $\rightleftarrows$ VE) a distinct and essential dimension of DTs [6, 10].

Although the literature on DTs is extensive, most existing studies focus primarily on their application during the design phase. In contrast, considerably less attention has been paid to their use in the operational phase, i.e., to the dynamic aspects of DTs [11]. These include updating data from physical counterparts, modifying virtual models throughout the system's lifecycle, and delivering various services, particularly those that support decision-making based on the current state of the corresponding cyber-physical system.

The concept of the Dynamic Digital Twin (DDT), as proposed in [11], may be regarded as a distinct scientific and engineering direction. Nevertheless, its key features underscore fundamental aspects that are also applicable to the general concept of the DT, including:

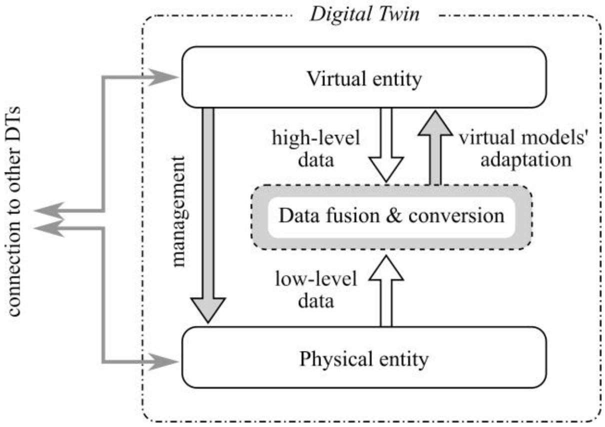

Fig. 1. Schematic illustration of the nature of the Digital Twin. Empty arrows represent passive data stream handling, while shaded arrows and region indicate that the corresponding data streams are fused, mutually converted, and used to modify the structure and behavior of the virtual and physical components of the Digital Twin.

- Automatic adaptation of virtual models, which must be continuously updated throughout the functioning of a DT;
- A flexible architecture capable of accommodating uncertainties and evolving requirements over the DT's lifecycle;
- A multi-level architecture that enables continuous processing of both high-level data (generated by the virtual entity) and low-level data (originating from the physical entity);
- The ability to monitor the state of the physical entity, continuously aggregate input data, adapt the structure of the virtual entity, and influence the behavior of the physical entity—all within the framework of predefined goals and policies;
- The capacity for integration into a network of diverse DDTs.

Nowadays, various mathematical formalisms are employed to describe the functioning of DTs, including Petri nets, graphs, ontologies, finite state automata, Markov processes, dynamical systems, and neural networks (e.g., [6, 11-15]). These approaches are generally grounded in the paradigm of Newtonian physics. Specifically, it is assumed that the current states of the physical and virtual entities can be represented as points (collections of numerical values) in corresponding multi-dimensional phase spaces. Within this framework, the uncertainty inherent in modeling DTs is typically treated as a random factor (noise).

Finally, it is worth noting that the concept of the (Dynamic) Digital Twin emphasizes that the physical and virtual entities, constitutive components of the DT, can be understood as parallel worlds [11], each with its own dynamics and properties, yet mutually complementing one another within the DT framework. These aspects are illustrated in Fig. 1.

The purpose of the present work is to draw attention to an alternative perspective in which the states of the virtual entity are described in terms of clouds (elements of a Hilbert space) that can be understood as nonlocal functions defined over the corresponding phase space. This approach is motivated by the conceptual parallels between the notion of the Digital Twin and the phenomenological description of human perception based on the formalism of space-time clouds [16-19]. It is also worth noting that the integration of characteristic human factors, such as motivation, stress, experience and skills, workload, intuitive bias, auditory and visual sensitivity, and emotional states, has emerged as a distinct research direction within the broader field of Digital Twins (e.g., [20, 21]).

II. Mathematical Phenomenology: Basic Elements

There are two distinct approaches to human consciousness whose conceptual "languages" are mutually untranslatable, as each relies on fundamentally different types of notions. These are:

- the *naturalistic* account, which holds that consciousness is grounded in the neural (physical) states of the brain;
- the *phenomenological* account, which considers the first-person data obtained through introspection fundamental elements to describing consciousness, e.g., [22], [23].

A synthesis of these views—without resorting to naturalistic reductionism—may be achieved by incorporating phenomenology of mind into natural sciences, a project often referred to as *naturalizing phenomenology*, e.g., [24-27]. This can be pursued through *formalizing phenomenology*, which aims to develop a mathematical formalism capable of bridging the two accounts [28, 29]. Concepts from dynamical systems theory and broadly understood self-organization processes may be particularly relevant in facilitating the transition from the natural to the phenomenological domain [30]. Notably, this approach to naturalizing phenomenology calls for the creation of a novel mathematical formalism, rather than the direct adoption of existing frameworks from physics [16, 27, 31, 32]. We refer to this intellectual project as *mathematical phenomenology*.

There are a number of concepts and theories developed in cognitive sciences that underlie mathematical phenomenology. Here, we briefly mention some of them to clarify our constructions (for details, see [19]):

- The concepts of *neural correlates of consciousness* [33, 34] and *second-order psychoneural isomorphism* [35], which posit a strong relationship between external stimuli and the structure and dynamics of brain activity patterns;
- The paradigms of *predictive coding* and *active inference* (e.g., [36-38]), which postulate the following. First, bottom-up signals from sensory modalities and top-down signals from mental images of the environment contribute equally to cognitive processes. Second, modification of mental images, learning, and behavioral adaptation are driven by *prediction errors*, i.e., discrepancies between changing sensory data during human activity and the neural signals generated by mental images;

- The modern division of processes responsible for sensory information analysis into three categories (actually following Freud): *subliminal*, *preconscious*, and *conscious* [39], [40]. Subliminal processes are assumed to occur when bottom-up neural activation is insufficient to engage large-scale networks in the brain—the *Global Neuronal Workspace* [41, 42]. A process becomes preconscious when it potentially carries enough activation to be broadcast within these networks and could, in principle, become accessible to the mind—yet remains outside conscious awareness due to factors such as the absence of top-down attentional amplification.
- The division of sensory information processing into three stages (e.g., [43]):
  - The first stage, based on bottom-up, low-level processes specific to individual sensory modalities;
  - The second stage—the mid-level bridge—involving the integration of outputs from the first stage and converting them into neural signals accessible to preconscious information processing;
  - The third stage—high-level processing—responsible for the preconscious integration of sensory information from various sources, including the mid-level processing outputs, to complete object recognition. This stage reflects both task-irrelevant properties and task-relevant target representations.
- A variety of theories of consciousness proposed to explore the relationship between neural network activity and conscious states, each emphasizing different aspects (see [44]-[47] for a review). Their relevance to our account of mathematical phenomenology is discussed in [19]. Here, we highlight the family of *Higher-Order Theories* of consciousness (e.g., [48, 49]. Broadly speaking, these theories maintain that the cognitive perception of an external stimulus substantially depends on the subject's awareness of what the stimulus could be.

Mathematical phenomenology is partly concerned with developing a formalism capable of describing phenomenal (P) consciousness and its specific manifestations—qualia—within the framework of Cognitive Twins to be constructed below. Leaping ahead, we note conceptual similarity of Cognitive and Digital Twins. P-consciousness can be characterized as the *what-it-is-like* property of mental states. In other words, it refers to the subjective experience of perceiving, feeling, or being aware of something [50]. Notably, phenomenal consciousness arises from preconscious information processing and is simply given to the mind, while the details of the underlying information processing remain outside conscious awareness. For further discussion of P-consciousness and qualia, see [51] and [52], respectively.

In the next two sections, we introduce the concept of the Cognitive Twin, which aims to describe a quale—a P-conscious image of an observed object—and justify the structural analogy between the Cognitive and Digital Twins.

III. Cognitive Twin: Constituent Components

Before proceeding to the description of the Cognitive Twin, let us briefly outline the characteristic features it must possess. As a pivot point, we note that through the accumulation of experience via trial-and-error learning, a certain coherence emerges between mental images and their corresponding physical objects. This coherence is inherently complex: mental images may, for example, evolve over time independently of the associated physical objects (as in bistable perception) or be shaped by contextual factors (as in optical illusions). Thus, similar to Digital Twins, mental images exhibit properties that are, on the one hand, irreducible to those of physical objects. On the other hand, humans ultimately develop the ability to estimate, with some degree of accuracy, the actual properties of observed objects based on sensory input. Accordingly, we propose that (*i*) mental (P-conscious) images, (*ii*) preconscious representations inheriting properties from the corresponding mental images, and (*iii*) the outputs of the mid-level bridge can be described mathematically within a unified framework using the mathematical language developed in physics. This constitutes the cornerstone of our account of mathematical phenomenology.

A. *Mathematical relationship between objects of physical reality and their mental images*

The notion of the mathematical eidos, introduced in [18], serves as a formal construct for capturing the fundamental spatio-temporal characteristics of mental images as they are situated within the space-time continuum. This concept is likewise employed in developing mathematical descriptions of the spatio-temporal properties of physical entities in the external world. A central issue concerns the precise correspondence between the eidoi associated with physical objects and those representing their mental counterparts. This relationship underpins the mapping of external physical reality onto qualia—the subjective domain of mental imagery. Within this framework, the relation between a physical object and its mental image is conceptually analogous to the pairing of physical and virtual components in a Digital Twin. Fig. 2 illustrates this analogy using the example of a material point and its corresponding space-time cloud, which represents its mental image.

The concept of a *space-time cloud*, rooted in first-person experiential perspective, fundamentally differs from a material point in terms of its characteristics [18]. Firstly, the phase space associated with a space-time cloud is broader than that of a material point. This expansion arises from the nuanced structure of the experiential present, which requires incorporating additional perceptible dimensions, namely, acceleration a and jerk $j = da / dt$. Both quantities can be directly sensed and thus must be accounted for in the cognitive model. Secondly, the mapping of an object into the mental space-time continuum lacks precision by nature. Even for simple physical entities like a material point, the resulting mental image takes the form of a blurred region, representing the perceptual vagueness inherent to human cognition. Lastly, the space-time cloud reflects a tripartite temporal structure, simultaneously encoding aspects of the recent past, the current moment, and the near future. This

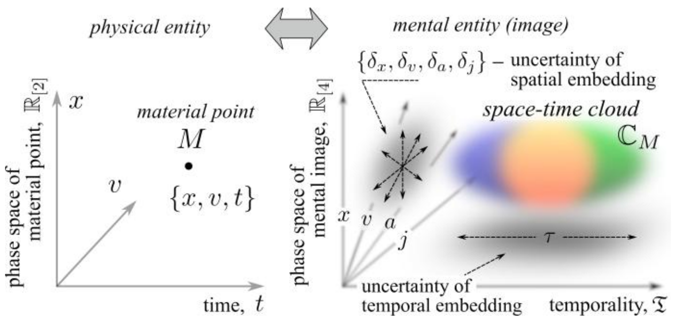

Fig. 2. Mathematical eidoi of a material point and its corresponding space-time cloud, both embedded within the space-time continuum. The axes of the mental continuum are depicted as blurred lines to indicate that its elements cannot be defined in terms of discrete spatial coordinates or temporal instants. Different colors are used to represent the temporal structure of the space-time cloud: blue indicates the immediate past, orange the present moment, and green the near future. Gray-shaded regions suggest the intrinsic uncertainty associated with perceiving the space-time position of the material point

makes it a spatial-temporal construct that is intrinsically non-local, distinguishing it as a mental phenomenon that transcends conventional physical representations.

Such a distinction between physical objects and their mental images enables us to conceptualize physical reality and qualia as two parallel worlds, each possessing individual properties that reflect but are irreducible to one another.

B. Preconscious representations of observed objects

Within the phenomenological framework, preconscious high-level representations exhibit the following characteristics:

- Each preconscious representation can be understood as an entity that inherits key features of its associated quale—such as the space-time cloud $\mathbb{C}_M$—with the exception of its temporal profile. Unlike qualia, these representations are defined at point-like time instants.
- The principal variables structuring preconscious representations, and thereby enabling potential access to consciousness, govern dynamics of the late-stage information processing. Consequently, the late-stage of processing can be fully described in terms of these variables.
- The mind is incapable of isolating specific time points involved in sensory information processing. Instead, P-consciousness integrates the temporal components of preconscious content—namely, (*i*) information retained in short-term memory, (*ii*) information currently being processed, and (*iii*) information predicted by internal models—into a unified experiential *now*, characterized by a tripartite temporal structure.

These assertions may be understood as a concrete instantiation of second-order psychoneural isomorphism, specifically linking the late stages of information processing to phenomenal consciousness. From the first-person perspective, this stage must be treated as a holistic process, since its internal temporal segmentation is inaccessible to conscious awareness.

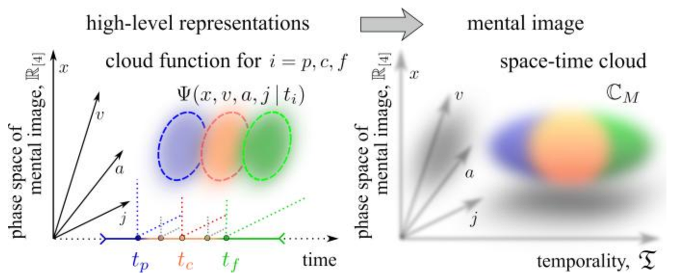

Fig. 3. The relationship between (*i*) the preconscious processing of sensory information—dynamics of the cloud function $\Psi(x, v, a, j \mid t_i)$—and (*ii*) the corresponding P-conscious image. The material point and its space-time cloud $\mathbb{C}_M$ are used as example. The temporal boundedness of the shown time interval (left panel) indicates that the late stage is a finite process with its own beginning and end. The other graphical details are the same as in Fig. 2.

Its mathematical modeling can adhere to the principles of physical science, while still accommodating top-down modulation from mental states. Such top-down influences can be conceptualized as boundary conditions externally imposed on the system, whereas its internal dynamics operate locally according to physical laws.

With regard to the material point, its preconscious representation at a specific time instant t is given by

$$\Psi(x, v, a, j|t) = \Psi_{[3]}(x, v, a|t) \times \Psi_{[1]}(j|t), \qquad (1)$$

where the arguments $\{x,v,a,j\}$ are defined over a domain with blurred boundaries in the four-dimensional phase space $\mathbb{R}_{[4]} = \{x, v, a, j\}$. This cloud function inherits its spatial structural features from the space-time cloud $\mathbb{C}_M$ (Fig. 3).

Using the pair consisting of the material point and its corresponding space-time cloud $\mathbb{C}_M$ as a representative example, it is important to emphasize that the phase space of such mental images comprises two types of phase variables—inner and control—which differ in both function and properties. In the case under consideration, the inner phase variables of the space-time cloud $\mathbb{C}_M$ are $\{x,v,a\}$, while the control phase variable is the jerk $j=da/dt$. Notably, within the *experiential now*, the control variable j may undergo sharp changes, whereas the inner variables $\{x,v,a\}$ tend to remain relatively stable over the same time scale. These inner variables are directly presented to the subject, who can modulate their evolution indirectly by selecting a strategy that governs the dynamics of the control variable j [18].

Therefore, to highlight key aspects of preconscious information processing, below our discussion will be confined to the j-dimension. Although the subject's goal-oriented actions, represented within the $\{x,v,a\}$-dimensions, constitute an individual-level problem, the analysis of preconscious processing of sensory input within the j-dimension reveals common features of these processes.

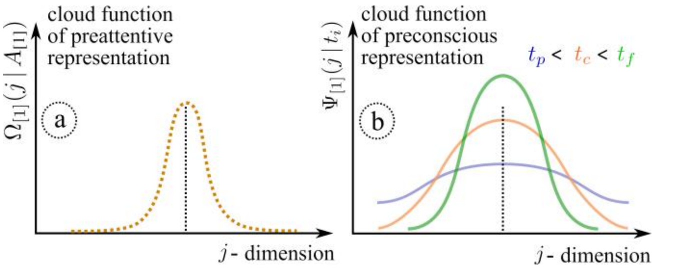

Fig. 4. Preconscious processing of sensory information in the *j*-dimension. Panel "a" presents the high-level output of the mid-level bridge, while panel "b" illustrates the temporal evolution of the preconscious representation of the jerk *j*. The temporal parts of this representation that jointly contribute to the P-conscious image are color-coded as specified in the Fig. 2 caption

C. *Dynamics of the cloud function*

Figure 4 illustrates the proposed framework for modeling the preconscious processing of sensory information related to the control variable *j*. Bottom-up low-level processes operating during the early and intermediate stages give rise to a preattentive representation $\Omega_{[1]}(j|t, A_{[1]})$, where $A_{[1]}$ denotes attention directed toward the *j*-dynamics. The preattentive representation becomes accessible through the Global Neuronal Workspace, which constitutes the high-level output of the mid-level bridge (Fig. 4, a). During the late stage of information processing, the preconscious representation, the cloud function $\Psi_{[1]}(j|t)$, progressively aligns with the preattentive representation $\Omega_{[1]}(j|t, A_{[1]})$ (Fig. 4, b). From the standpoint of dynamical systems theory, this alignment corresponds to the evolution of $\Psi_{[1]}(j|t)$ toward the attractor $\Omega_{[1]}(j|t, A_{[1]})$, which forms a "landscape" within the Global Workspace. When either the state of the perceived object or the focus of attention shifts, the preattentive representation $\Omega_{[1]}(j|t, A_{[1]})$ updates accordingly—almost instantaneously, relative to the temporal scales of the late stage.

A mathematical formalism capable of describing the preconscious processing of sensory information must accommodate the following features:

- Preconscious representations of perceived objects are holistic entities with internal integrity;
- These representations inherit properties from the corresponding qualia, with the exception of their temporal structure. Consequently, all such properties must be attributed to the cloud functions as unified wholes. Therefore, the dynamics of cloud functions cannot be reduced to the individual dynamics of their constituent parts taken in isolation;
- Due to the unconscious nature of preconscious processing, its dynamics can be described within the paradigm of physical systems. Specifically, the rate of temporal change in the cloud functions must be entirely determined by their current state and by the corresponding preattentive, high-level representations that constitute the landscape of the Global Workspace;
- The emergence of qualia—P-consciousness images of perceived objects in the mind—can be associated with the completion of preconscious processing of sensory information. This completion is marked by the cloud functions approaching a certain stationary (or quasi-stationary) state in their dynamics
- For similar objects perceived simultaneously, the cognitive comparison of their properties is possible only through comparison of the corresponding clouds, $\mathbb{C}_1$ and $\mathbb{C}_2$, as unified entities. Mathematically, this can be represented via their overlap, symbolically denoted as $\langle \mathbb{C}_1 | \mathbb{C}_2 \rangle$, which should be implemented through the overlapping of cloud functions:

$$\langle \mathbb{C}_1 | \mathbb{C}_2 \rangle \Leftarrow \langle \Psi_1 | \Psi_2 \rangle = \int_{-\infty}^{+\infty} dj \, \overline{\Psi_1(j,\mathrm{t})} \Psi_2(j,\mathrm{t}), \qquad (2)$$

where $\overline{\Psi_1(j,\mathrm{t})}$ denotes the complex conjugate of $\Psi_1(j,\mathrm{t})$ (included here for generality), and the symbol t indicates that the overlap of cloud functions may be averaged over time in a specific manner to accommodate the tripartite temporal structure of the corresponding qualia. Since any cloud coincides with itself, the following identity must hold:

$$\langle \mathbb{C} | \mathbb{C} \rangle = \langle \Psi | \Psi \rangle = \int_{-\infty}^{+\infty} dj |\Psi(j,t)|^2 = 1. \qquad (3)$$

- A perceived physical object is not directly accessible to the subject's mind as it exists in itself. Rather, the subject interacts with the object via its mental image. If the mental images of two similar objects are close, i.e., $\langle \mathbb{C}_1 | \mathbb{C}_2 \rangle \approx 1$, the subject may categorize these objects as equivalent. In this sense, within the qualia→reality mapping, the space-time cloud $\mathbb{C}$ represents the entire collection of its physical *instantiations*, treated as a unified entity rather than as a statistical ensemble. Put differently, during interactions with physical objects, the subject is unable to identify a specific instance of the reality→qualia mapping. Thus, the qualia→reality mapping must be understood as one-to-many.
- From the first-person perspective, the relationship between a mental image and its physical instantiations acquires probabilistic characteristics in the context of the subject's actions. Here, the term *instantiation* refers to the result of actions by the subject that are (*i*) induced by the perception of the observed object, and (*ii*) aimed at altering or maintaining the object's current state through active control. In

either case, the property of the object, here the jerk j, assumes a new value, $j \neq j_0$, which is not fully determined by the subject and thus cannot be predicted with certainty. This uncertainty in the subject's actions reflects the inherent uncertainty of human perception, and both are intrinsic features of human nature. Accordingly, we turn to the framework of probability theory and define the probability $P(j, t)$ of encountering a physical instantiation j associated with a given mental image $\mathbb{C}_j$ as

$$P(j,t) = \left|\Psi(j,t)\right|^2 . \tag{4}$$

The features listed above have led us [18], [19] to formulate the governing equation for the preconscious processing of sensory information as follows:

$$\tau \frac{\partial \Psi}{\partial t} = \mathcal{H}\Psi - \left\langle \Psi \,|\, \mathcal{H} \,|\, \Psi \right\rangle \Psi. \tag{5}$$

Here, the operator $\mathcal{H}$, referred to as the *Hamiltonian of information processing,* represents the underlying neural mechanisms of late-stage information processing, and $\tau \sim 1\,\mathrm{s}$ denotes the characteristic timescale of the experiential present (or "now"). The second term on the right-hand side of Eq. (5) arises from the strong nonlocality in the dynamics of the cloud function Ψ and ensures the conservation of normalization (3).

Moreover, Eq. (5) may be regarded as a generalization of the Schrödinger equation—extended to allow complex-valued time points—and combined with the Lotka-Volterra model to describe the behavior of cloud functions. Specifically, the Hamiltonian $\mathcal{H}$ can be written as

$$\mathcal{H} = \mathcal{H}_{GW}(\Psi) + \Omega, \tag{6}$$

where the first term in Eq. (6) corresponds to preconscious processing within the Global Workspace, including the self-interaction of the cloud function, while the second term represents the preattentive high-level output of the mid-level bridge.

IV. Cognitive Twing: The Concept

Figure 5 illustrates the proposed account of the Cognitive Twin, summarizing its constituent components as discussed in Sec. III. It comprises three fundamental entities:

- the perceived physical object—here, a material point whose motion is characterized by the current jerk value j_0;
- the sensory (or sensing) unit, hierarchically organized and incorporating sensory modalities along with the large-scale neural networks of the brain, which processes sensory information through low-level, intermediate-level, and high-level stages;
- the mind, which hosts a set of P-conscious images, or qualia.

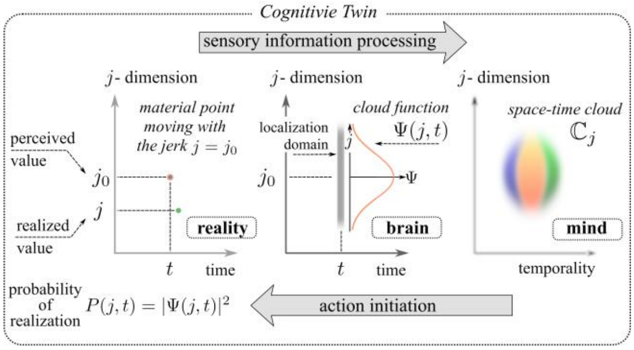

Fig. 5. Illustration of the Cognitive Twin, comprising: (*i*) a physical object (a material point moving with jerk j_0); (*ii*) the sensory unit responsible for information processing, where the dynamics of the cloud function $\Psi(j,t)$ plays a crucial role; and (*iii*) the subject's mind, in which the corresponding quale—the space-time cloud $\mathbb{C}_j$—emerges. The shaded arrows represent two additional dimensions: the stream of sensory information and the subject's actions aimed at reproducing the perceived jerk value at future moments

This tripartite system is accompanied by:

- the stream of information processing culminating in the emergence of mental images, represented in Fig. 5 by the space-time cloud $\mathbb{C}_j$, a nonlocal entity in the space-time continuum;
- the subject's actions aimed at controlling the state of the observed object, illustrated by the jerk value j acquired by the material point as a result of those actions.

These components and processes may be collectively categorized as the five dimensions of the Cognitive Twin.

Within the framework of the first-person perspective, the causal power of the Cognitive Twin should be attributed to the mind—primarily, to the subject's phenomenal consciousness. Based on the corresponding quale—here, the space-time cloud $\mathbb{C}_j$—the subject initiates actions with probabilistic outcomes, causing the material point to move with a certain jerk j. Owing to the intrinsic uncertainty of human cognition, the instantiated jerk value, j, is (*i*) reproduced each time only with limited accuracy, and (*ii*) this deviation goes unnoticed by the subject. Consequently, the subject perceives their actions as producing identical outcomes.

The sensory unit plays a crucial role in the functioning of the Cognitive Twin. Its operation is based on:

- Bottom-up, low-level processing of sensory information, culminating in the output of the mid-level bridge, which forms the preattentive representation serving as the landscape for the Global Neuronal Workspace;
- Preconscious processing of high-level representations within the Global Neuronal Workspace, influenced both by the bottom-up output of the mid-level bridge and by top-down modulation from the mind, for example, the conscious allocation of attentional resources.

The evolution of preconscious high-level representations, cloud functions, ultimately determines the dynamics of the subject's recognition processes, endowing them with complex behavior. Cloud functions, which inherit properties from the corresponding qualia, are also fundamentally nonlocal entities in space. For this reason, they must be treated as elements of a Hilbert space, and the mathematical formalism required to describe recognition dynamics shares much in common with the formalism of quantum mechanics.

V. Conclusion: Parallels between Digital and Cognitive Twins

The general results of the present paper can be considered from two perspectives.

First, we have demonstrated that the concept of the Digital Twin and the constructed concept of the Cognitive Twin exhibit potential parallels in their systemic architecture. Both are characterized by a similar five-dimensional structure, in which causal power is attributed to upper-level components in governing the lower-level components—the physical entity and the controlled object, respectively. In the case of Digital Twins, it is the virtual entity. In the case of Cognitive Twins, it is qualia, in line with views that endorse phenomenal consciousness as a source of action.

However, the domains in which Digital Twins and Cognitive Twins arise are fundamentally different, or at least treated as such from a contemporary standpoint. Digital Twins belong to cyber-physical systems; they are elements of the socio-technical domain and are products of deliberate, collective human effort. By contrast, Cognitive Twins should be regarded as elements of individual cognition, emerging from the long-term evolution of living beings. Nevertheless, their structural and functional similarities may point to the existence of deeper formal or organizational principles.

Second, the presented construction of the Cognitive Twin prompts us to draw attention to a specific dimension of the Digital Twin—namely, the component responsible for data processing—which, to date, has not been explicitly emphasized. In the case of the Cognitive Twin, this role is played by the sensory unit or the mid-level bridge. In the context of Digital Twins, it is important to emphasize the following points:

- This dimension should be recognized as a distinct constituent component, alongside the physical and virtual entities, possessing its own properties and functioning independently of the other two;
- Within this component—may be also referred to as the mid-level bridge—a bottom-up data stream is transformed into an information flow via top-down regularities that reflect the goals and policies associated with the virtual entity's operation;
- The format in which data are processed by the mid-level bridge can be also described using the formalism of Hilbert spaces, which captures two essential features: the one-to-many nature of the virtual-to-physical entity mapping, and the inherent uncertainty involved in decision-making based on data accumulated within the virtual entity.

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