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Review Article

Interpretation and modelling of the brain and the split-brain using the HLbC (Human Language based Consciousness) model

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Abstract

The HLbC model, as proposed by the author, has been utilized to interpret the varied behaviors manifested by individuals with split-brains. This paper initially provides a succinct overview of the function of the corpus callosum, pivotal to discussions concerning split-brains, along with the distinctive behaviors demonstrated by subjects with split-brains. Subsequently, it elucidates the application of the HLbC model in interpreting the behavior of such individuals. Comparative analyses with normal brain function are then conducted. Traditionally, thehavehavior of individuals with segregated brains has been predominantly discussed considering the disparate roles of the left and right hemispheres (Michael S. Gazzaniga, 1970). However, this paper reinforces the conventional argument by employing the HLbC model.

Keywords: Split-brain, HLbC model, Consciousness, Corpus Callosum

Introduction

The authors have pioneered a consciousness model rooted in Human Language [1] and have extended its applications to interpret illusions and the principles of behavioral economics, notably the Prospect Theory [2]. The foundational framework revolves around the following concepts: 1) Observation of events through the five senses, 2) Linguistic and imagistic representation of observed events, 3) Comparative analysis between existing multiple episodic memories (associations involving language or imagery combined with emotions relating to events), 4) Random selection of actions from a repository of multiple episodic memories concerning observed events, 5) Specific behavioral manifestations, 6) Encoding of behavioral outcomes into short-term memory, and 7) Verification of current actions derived from short-term memory - constituting the facets of consciousness. Based on this paradigm, for instance, within process (4), it has been theoretically demonstrated that the random selection process adheres to a pseudo Schrödinger equation. This paper aims to expand upon the proposed HLbC model by the authors, interpreting the phenomenon of split-brain and understanding the functions of our brain. Subsequently, we encapsulate the role of the corpus callosum in interlinking the left and right hemispheres and elucidate the hallmarks of split-brain phenomena. First, to provide an overview of existing research on split- brain phenomena.

Corballis et al. showed that subjects who underwent anterior commissure sectioning surgery were able to integrate information regarding position and motion between the visual hemispheres despite losing some visual information [3]. Following this surgery, the lack of information transfer in visual stimuli explained a major factor in classical disconnection syndromes, where voluntary attention integrates across hemispheres, but object-based attention and visual exploration can function simultaneously and independently across both hemispheres. This suggests the existence of two distinct visual systems, one specialized in form analysis and detailed exploration of visual scenes and another focusing on low-resolution processing of aspects like motion and position.

Funnell et al. investigated computational abilities in both hemispheres of split-brain patients [4]. The superiority of the left hemisphere in calculations was indicated, with the possibility suggested that even the right hemisphere could generate approximate solutions in addition and subtraction tasks. Moreover, higher accuracy was observed in the right hemisphere for problems involving small numbers, particularly in precise addition tasks. Additionally, while the left hemisphere demonstrated similar accuracy in both tasks, the right hemisphere showed higher accuracy in approximate addition, and differences related to operand size were observed in precise addition.

Miller demonstrated that presenting redundant stimuli to different cerebral hemispheres in individuals without the corpus callosum results in increased gain [5]. This implies the potential for both hemispheres to respond to stimuli, potentially accelerating their reactions. Unique and intriguing findings from split-brain studies revealed greater redundancy gain in individuals without the corpus callosum compared to existing models. New hypotheses and mathematical models were proposed concerning this phenomenon, showing alignment with experimental results. Redundancy gain is a phenomenon in which the simultaneous presentation of multiple similar pieces of information enhances perception and cognition, typically improving processing efficiency and increasing the certainty of information.

In split-brain patients, recognition and responses to objects within the visual field differ across hemispheres due to callosal sectioning. However, recent evidence suggests this interaction might not be absolute, as de Haan et al. observed the ability to detect stimuli and identify positions anywhere on the body after anterior commissure sectioning [6]. This suggests a less severe impact than anticipated from callosal sectioning.

While sustained attention is reported to decline due to brain damage, it may not always be specifically identified when evaluating the left and right hemispheres. Dimond suggested that vigilance is governed by specific brain regions and highlighted the potential role of the right hemisphere in sustaining attention [7]. While the right hemisphere might be involved in concentration, the left hemisphere is believed to be involved in selective attention.

Roser and Corballis, conducted tasks involving two different tasks focusing on red or green discs in four split-brain patients, two patients with agenesis of the corpus callosum, and 14 normal subjects [8]. In Experiment 1, responses to paired stimuli on both sides were faster than to a single stimulus, indicating redundancy gain. This gain was more significant in patients with agenesis of the corpus callosum, or split-brain patients compared to normal subjects, suggesting a neural summation beyond the competitive model. In Experiment 2, subjects were asked to respond only to specific colored stimuli, showing neural summation for target stimuli but not for non-target stimuli. These results indicate that neural summation in agenesis of the corpus callosum or split-brain conditions involves converging activations associated with responses.

While patients with right hemisphere damage or corpus callosum disconnection tend to neglect the left visual field, individual hemisphere testing does not always reveal this neglect phenomenon. Lausberg et al. compared split-brain and partially corpus callosum-disconnected patients with healthy individuals regarding neglect and spatial use during posture demonstration [9]. Results showed that split-brain patients ignored their left personal space during gesture demonstration with the right hand, suggesting this might not be due to right hemisphere inhibition but rather specialization in the left hemisphere.

Alzheimer's disease (AD) is considered to indicate breakdowns in cortical connectivity and is expected to exhibit overall impairment in interhemispheric transfer in AD patients. However, research results by Reuter-Lorenz and Mikels, with healthy young and older adults along with AD patients, challenge the applicability of the 'split-brain' model in visual processing areas [10]. These results suggest the possibility of breakdowns in both intra- and inter-hemispheric cortical connectivity in AD.

Ouimet et al. investigated manual asynchronous and crossed-uncrossed differences (CUD) in ten normal individuals, four front-split-brain patients, and four complete split-brain patients [11]. Results indicated deteriorated CUD and asynchrony in front-split-brain patients compared to normal subjects, and larger CUD and more asynchrony in complete split-brain patients compared to both normal and front-split-brain patients. This indicates different mechanisms for differences in CUD and asynchrony and implicates involvement of the anterior and posterior portions of the corpus callosum.

Studies on split visual fields in neurologically normal adults have indicated the left hemisphere's superiority in temporal judgments over the right hemisphere. However, Funnell et al. suggested a significant role for the right hemisphere in temporal judgments of visually presented stimuli based on two temporal judgment tasks in split-brain patients, where the right hemisphere's performance surpassed that of the left hemisphere [12].

There are studies using neuroimaging and lesion (damage) analysis to understand neural mechanisms related to numerical processing, but there is a lack of research simultaneously examining the roles of the right and left hemispheres. Addressing this issue, Colvin et al. investigated immediate recognition (subitizing) and magnitude comparison abilities in split- brain patients [13]. The results indicated similar performance by both hemispheres in the ability to compare numerical magnitudes.

Uddin et al. evaluated the functionality of both hemispheres by presenting self-face images to split-brain patients [14]. Results showed no differences between hemispheres in self-face recognition, while only the right hemisphere succeeded in recognizing other people's faces. This suggests that while both hemispheres possess self-recognition capabilities, there are different roles across hemispheres in recognizing others. Morphing is a digital image processing technique used to smoothly transition between two or more images and is utilized in movies and scientific experiments.

Pinto et al. discovered that the standard result of responding only with the left hand to stimuli in the left visual field and with the right hand or verbally to stimuli in the right visual field did not universally apply in their study of two split-brain patients [15]. Disconnecting the cerebral hemispheres may divide visual perception, but it does not create two independent conscious perceivers within one brain.

The corpus callosum plays a role in integrating perception and cognition between cerebral hemispheres, evaluated using Poffenberger and redundancy target paradigms. Westerhausen conducted a meta-analysis of data from patients with cerebral sectioning, performing 116 observations using the Poffenberger paradigm and 103 observations with redundancy gain [16]. Results indicated an average CUD of 60.6 ms in commissure sectioning patients, 43.5 ms in complete cerebral sectioning patients, and 8.8 ms in partial sectioning patients, significantly different from other groups. Similarly, the bRGmin average was 42.8 ms in complete cerebral sectioning patients, 30.8 ms in partial sectioning patients, significantly different from the control group. This study suggests both paradigms assess integration by the corpus callosum and test different brain hemisphere functions.

de Haan et al.'s review paper aims to summarize empirical commonalities, present diverse interpretations, and identify remaining questions [17]. While cerebral commissure sectioning disrupts functional integration, some processes remain integrated, leading to discussions about the mechanisms of this remaining integration. Issues regarding the integrative nature of consciousness related to the first-person perspective of split-brain patients are considered insufficiently addressed by current evidence, suggesting approaches for future research.

Downey claims that split-brain syndromes are best understood within an expanded framework of the mind, supporting an externalist explanation for conscious perception [18]. Providing an overview of experimental abnormal models of split-brain syndromes and their explanations, this focuses on the possibility of unifying conscious perceptual fields using external factors. The preference for externalist explanations over internalist competitors is suggested due to their ability to explain split-brain syndromes avoiding typical problems.

Thus, numerous studies are being conducted to elucidate the split-brain phenomenon. Next, firstly, the role of the corpus callosum in a typical brain will be explained, followed by illustrating a typical case of split-brain syndrome.

Role of the left brain, right brain, and corpus callosum

First, the functions of the left and right brain are described. The left brain takes input from the right eye and right ear and controls the behavior of the right limbs (**Figure 1**). The right brain is the opposite. The left brain is also responsible for language, while the right brain is responsible for imagery. Both brains have memory areas in the posterior part of the brain, especially the right brain, which can retain imagery memories [19]. Joining the two brains is the corpus callosum, which holds the left and right brains together structurally and is responsible for the exchange of information between the two brains. Corpus callosum is a major bundle of nerve fibers connecting the left and right cerebral hemispheres, comprising approximately 200 to 350 million nerve fibers. These fibers serve the role of transmitting information between corresponding or different brain regions. The corpus callosum is divided into four parts: R (rostrum), G (genu), B (body), and S (splenium). The rostrum, situated at the anterior end, interconnects the left and right prefrontal lobes, supporting cognitive functions. The body, located centrally, facilitates coordination between the left and right motor functions. Additionally, the splenium, positioned towards the posterior end, transmits visual information between hemispheres. The body further subdivides into AB (anterior body), AMB (anterior midbody), PMB (posterior midbody), and I (isthmus) regions.

When the corpus callosum is severed, potentially affecting balanced functionality. Particularly, symptoms associated with "higher brain functions" and "cognitive functions" are known to arise following corpus callosum disconnection.

The elucidation of the brain's entirety, comprising the distinctive roles of the right and left hemispheres interconnected by the corpus callosum, was initially posited through the pioneering research of Roger W. Sperry [20]. Regarding brain function, detailed accounts are provided by Gazzaniga, Geschwind, and Sperry [21-23]. Furthermore, the roles of the right and left hemispheres have been elaborately described by Kosslyn & Koenig, and Hellige [24,25]. Notably, the right and left hemispheres undertake divergent functions within cognitive processing. While the left hemisphere predominantly engages in language comprehension, logical reasoning, and mathematical processing, the right hemisphere specializes in spatial awareness, emotional processing, and creative ideation. The corpus callosum assumes a pivotal role as it facilitates the interhemispheric exchange of information, thereby enabling coordination and integration between the two hemispheres. Consequently, the presence of the corpus callosum fosters cohesive functionality, where both hemispheres synergistically operate as a unified cognitive entity. For instance, while the left hemisphere is engrossed in linguistic tasks, the right hemisphere concurrently processes visual stimuli or discerns emotional cues. Such interhemispheric collaboration underpins the intricate cognitive capabilities exhibited by humans.

Structurally, the corpus callosum represents a robust bundle of neural fibers linking the left and right cerebral hemispheres, thereby enabling seamless communication between them. This

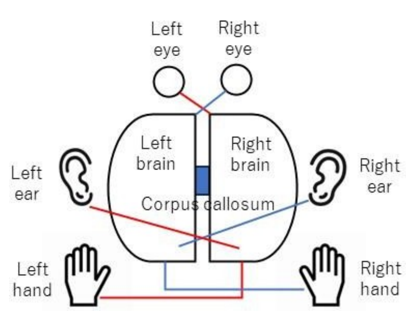


Figure 1. Relation of the left brain, right brain, and corpus callosum.

conduit serves as the conduit for diverse forms of information, including visual, auditory, motor, and affective signals, fostering their exchange and amalgamation across hemispheric boundaries. The corpus callosum not only facilitates the reciprocal sharing and integration of information but also ensures coordinated processing across hemispheres. For instance, visual stimuli originating from the left visual field are predominantly processed within the right hemisphere but are subsequently relayed to the left hemisphere via the corpus callosum. Such cross-hemispheric integration permits collaborative endeavors between hemispheres, enabling complex cognitive tasks such as the joint comprehension of linguistic and spatial information. Moreover, the corpus callosum's functionality extends beyond mere information transmission, as it plays a crucial role in mitigating the impact of unilateral brain damage by enabling compensatory functions from the unaffected hemisphere, thereby contributing to the brain's plasticity and reparative mechanisms.

In the realm of memory processing, discernible disparities exist between the right and left hemispheres. The right hemisphere demonstrates a proclivity for processing non-verbal and visual stimuli, facilitating the retention of visual imagery and spatial configurations. Conversely, the left hemisphere exhibits a predilection for processing language-based information and factual knowledge, thus favoring the retention of linguistic and factual memories. Memories consolidated within the right hemisphere often elude conscious access, contrasting with those formed in the left hemisphere, which are more readily accessible to conscious retrieval. Furthermore, the right hemisphere excels in grasping overarching patterns and holistic representations, thereby encoding memories within spatial frameworks, while the left hemisphere excels in processing detailed or sequentially structured information, typically encoding memories within linguistic frameworks.

Split-brain

In the 1960s, surgery was performed to remove the corpus callosum, connecting the left and right hemispheres of the brain, to control severe epileptic symptoms. This is the so-called split-brain phenomenon. Initially, it was believed that there would be no inconvenience in life, but some characteristic cases were identified in experiments conducted with subjects with split brains, with Gazzaniga conducting systematic experiments and obtaining many findings. Here are some examples [26].

Example 1 (Figure 2): First, a photograph of a snowy landscape was shown to the subject's left eye and a photograph of a chicken's foot to the right eye. They were then asked to select, with their left and right hands, one of several photographs that was closely related to the two left and right photographs they had seen earlier. As a result, the left hand selected a photo of a 'snow shovel' related to the snowy landscape, while the right hand selected a photo of a chicken related to the chicken's feet. As mentioned earlier, the left brain prompts the right hand to act on the signals seen by the right eye. The right brain does the opposite. Hence, the actions of the left hand (right brain) and the right hand (left brain) are correct. Then ask the subject, 'verbally', "Why did you choose the chicken and the snow shovel?" The subjects then responded that they chose the chicken because they saw the chicken's feet and the snow shovel because it could be used to clean the chicken coop. In the split brain, the action chosen by the right brain is not transmitted to the left brain, so the left brain, when asked a verbal question, creates the reason for its choice in retrospect.

Example 2: Next, the right brain is shown the word 'walk'. The right brain perceives it as an image and can walk. In response, the subject's right ear asks, "Why did you walk?" to which the subject replied, "Because I was thirsty and wanted to get a Coke". This is also thought to be an afterthought, a creation of a reason, as the left brain does not know why the right brain made him walk.

This paper endeavors to decipher such distinctive traits observed in split-brain cases and explore the potential of the HLbC model to interpret functions within an intact, non-split brain.

Summary of HLbC Model

To begin with, this paper presents an overview of applying the HLbC model to interpret split-brain phenomena. The HLbC model, conceived by the authors, stands as a mathematical construct of consciousness rooted in "Human Language." Below, the authors will provide a concise summary of this overview.

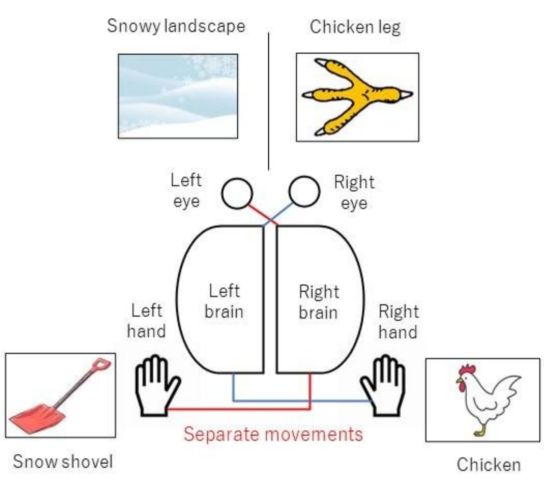


Figure 2. Example of behaviors exhibited by subjects with split-brains.

The role of language in consciousness and definition

In preceding research, the authors explored the potential for inverted qualia within consciousness using neural networks. While philosophical inquiries into consciousness have long been subject to debate, their inherently abstract nature often complicates arriving at definitive conclusions. However, through the utilization of neural networks that mimic the brain's neural circuits, it has become plausible to simulate and potentially draw conclusions on philosophical questions that were previously the domain of speculation. The authors directed their attention to the philosophical problem of inverted qualia, highlighting the possibility that observers A and B may perceive differing colors when observing the color "red." Consequently, if individual observers perceive distinct colors, the task of modeling consciousness solely based on qualia becomes challenging. Hence, notwithstanding potential variations in individual qualia, the authors opted to emphasize the pivotal role of "words" in communication. Regardless of how observers A and B perceive colors in their brains, they can standardize the colors they see by employing a shared "word," such as "red."

In consciousness or volition, it is posited that episodic memories derived from past experiences play a significant role. In the HLbC model targeted by this study, as elucidated later, episodic memory assumes a crucial role. Considering episodic memories stored in the brain in the form of logical sentences, "Human Language" also plays a critical role in episodic memory itself.

In summary, within human consciousness, "Human Language" is deemed indispensable both for interpersonal communication and as a fundamental element of episodic memory. Consequently, the authors have endeavored to articulate the mathematical definition of "Human Language" in terms of probability space as follows:

Consider, for instance, two observers, A and B, both gazing at the color 'red.' Curiously, within each other's minds, they perceive 'different colors.' Yet, neither can discern the exact sensation (qualia) the other experiences, and each believes the other 'must perceive the same color as they do.' Moreover, if they establish a convention where they both label the color they see as 'red' to one another, it poses no impediment to communication. This convention constitutes what we define as language. Regarding color perception, as we observe various hues, each of us maintains perceiving red for one shade, blue for another, and so forth. This signifies our ability to establish a probability space for the occurrence of color. Notably, these individual probability spaces can be defined. For instance, for observers A and B, the probability density function within each probability space defines the Kullback-Leibler divergence outlined below.

$$D_{KL} = \int p_A(x) \cdot log\left(\frac{p_A(x)}{p_B(x)}\right) dx$$

This is one expression of the distance between P_A and P_B and satisfies the following conditions:

a) $D_{P_A P_B} \geq 0$ for any $P_A(x)$, $P_B(x)$

b) $D_{KL} = 0$ and $(\forall x)$ $P_A(x) = P_B(x)$ are equivalent

c) Generally, $D_{KL}(P_A, P_B) \neq D_{KL}(P_B, P_A)$

If the distance is zero, the following holds:

a) Reflectance law: A~A

b) Symmetric law: A~B then B~A

c) A ~C if transitive laws A~B, B ~ C

where, "~" is a symbol denoting equivalence.

We establish the concept of "equivalence" between the outcomes experienced by observer A and observer B in each event. Throughout this paper, instances signifying this parity collectively embody what we term as "human language." Consequently, despite everyone's unique criterion for perceiving color—their distinct qualia—when observing color through a shared criterion, the resultant probabilities align. When computing the probability density function, the Kullback-Leibler divergence becomes null, thereby enabling the color observed by both A and B to be deemed synonymous—ultimately defining a language as a universal guideline for color perception. Furthermore, expressions formed from language take shape as the Cartesian product of probability spaces for each word. Both sentences and emotions find representation through the intersection of probability spaces. The authors conceptualize "sentence + emotion"—a fusion of language and emotions—as a facet of episodic memory. Consequently, in scenarios such as "a white dog running towards you," the accompanying emotions, like "fear" or "empathy," engender disparate interpretations. This paper constructs a consciousness model interwoven with language, emotions, and interconnected episodic memory. Thus, the proposed model of consciousness is delineated as the Human Language-based Consciousness (HLbC) Model, detailed further in the ensuing section.

Fundamental concept of HLbC model

The HLbC model proposed by the authors has been extensively discussed in previous publications [1]; thus, only a concise overview is provided here. The process of consciousness generation within the HLbC model unfolds in the following steps:

[STEP-1]: Observation of events through the five senses.

[STEP -2&3]: Selection of a similar past episode from memory corresponding to the observed event. These episodes stored in memory comprise multiple events, each encapsulating emotions and corresponding actions. Memory episodes consist of three essential elements: language or imagery, emotions, and actions undertaken at the time. Each element is defined within a probability space, and memory episodes are represented as the Cartesian product of these three probability spaces. Within the HLbC model, "similarity" denotes a state where the Kullback-Leibler divergence between the observed event and the probability density function of memory is minimal. The selection of multiple similar episodes from memory is postulated to occur randomly due to inherent physical noise, such as the brain network's state or neurotransmitter activity. In essence, there is no element of free will in the response to observed events, with reactions entirely determined by intracerebral noise. Subsequently, an actual action is executed based on the randomly chosen memory.

[STEP -4]: The outcome of the randomly selected action is stored within short-term memory.

[STEP -5]: The recognition process of "I performed this action" via retrieval of the memory stored in short-term memory constitutes "consciousness."

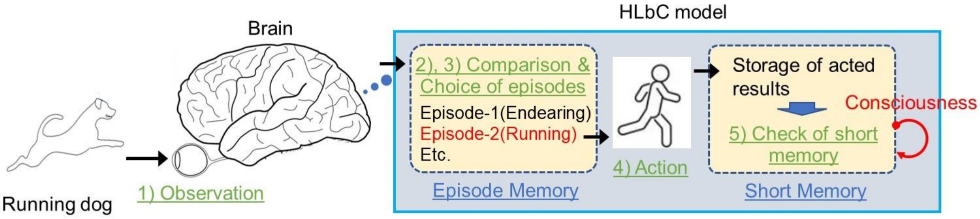


Figure 3. Concept of HLbC model.

Given that STEPs 1 to 4 can be fully explicated by physical processes alone, the HLbC model aligns with physical monism as a consciousness model."

Using the example of observing "a white dog running" in Fig. 3, let's explain the process described above.

STEP-1: This step involves observing "a white dog running" with your eyes.

STEP-2: Initially, compare the observation result with the episodes stored in episodic memory. Multiple episodes may exist, and each episode is expressed as [sentence] × [emotion] × [action]. For instance, "a white dog running towards me" × "fear" × "escape" or "a white dog running towards me" × "adoration" × "play together," and so forth. Even if the same words are included in the episode, the episode's meaning can vary depending on the emotion or action. Randomly select one of these multiple episodes and execute the behavior corresponding to the actual observation. In STEP-3, temporarily store the result of that behavior in short-term memory. In STEP-4, the moment of consciousness generation is defined as the point at which the result of the behavior stored in short-term memory is reiterated. According to this interpretation, if someone is asked why they "ran away from a white dog running towards them," they will answer, "Because I had a scary experience being chased by a white dog when I was a child," attributing their actions to their own consciousness. However, if they performed a behavior based on another episode, they should still claim that they acted based on their past episodes when randomly selecting their behavior.

Each process can be mathematically defined, but detailed explanations are omitted in this paper as they are elaborated upon in the work by Hebishima et al. [1]. Nevertheless, a summary of the selection of a similar past episode from memory to the observed event, crucial for the discussion herein, is as follows:

When modeling STEP-2 as a random walk, a mathematical equation akin to the Schrödinger equation below is derived. However, it should be noted that this is an analogy and does not imply that consciousness is governed by quantum mechanics.

$$i\nu\frac{\partial\psi}{\partial t} = \left[-\frac{\nu^2}{2}\frac{\partial^2\psi}{\partial x^2} + \frac{1}{m}V\right]\psi(x,t) \quad (1)$$

Here, x represents the Kullback-Leibler divergence, t represents time, and ν is a parameter. ψ corresponds to the wave function in quantum mechanics and represents the probabilistic nature of decision-making, while the distribution function ρ(x,t) is connected when it settles into a state.

$$\rho(x,t) = [\psi(x,t)]^2 \quad (2)$$

Regarding m and V, we need to add some explanation. When we remember something from our memory and must act on it, there is a delay in recalling it. This delay is called "inertia," and the degree of this inertia is called the mass of decision-making, m. In this paper, the quality of decision-making based on past episodes is assumed to be related to the "potential" V. So, once again using the analogy of mechanics, we define the potential V for past episode memories as a function that satisfies the following:

$$-\frac{\partial V}{\partial x} = m\alpha \quad (3)$$

Here, α is the second time derivative of the Kullback-Leibler divergence and corresponds to acceleration. Also, m×α represents "force" in normal mechanics, but within Eq. (3), it should be understood as the defining relationship for the potential V and should not be given any further meaning. This is the mathematical summary of STEP-2&3. The derivation of the above equations is described in the **Supplementary File 1**.

In particular, the quantum nature of this decision-making process is a characteristic of the HLbC model. Experimental attempts by Duffy and Loch-Temzelides support this quantum aspect, and the HLbC model corroborates those findings [27]. Additionally, in previous studies, the authors interpreted illusions and prospect theory in behavioral economics from the perspective of this quantum nature [2]. Further verification is needed, especially regarding the quantum aspects of decision-making. However, based on the HLbC model, we will interpret split-brain cases as follows.

Interpretation of Split-Brain

Below, the authors interpret the occurrences in the split-brain using the HLbC model. The HLbC model assumes that when the human brain makes decisions, it searches for choices from accumulated past episodic memories and involves a probabilistic element in decision-making. In fact, modeling this process as a random walk yields a mathematical equation similar to equation (1) of the Schrödinger equation. However, it is important to note that this is only an analogy and consciousness is not governed by quantum mechanics. In the HLbC model, selecting one option from countless choices is understood as one of the brain's functions. This process can be considered a convergence from numerous intentions, akin to the convergence of wave functions in quantum mechanics. Nevertheless, randomness in choosing actions is considered a fundamental concept in brain function within the HLbC model, and there are no unnatural aspects to the convergence from multiple options. This selection process is guaranteed by the axiom of choice when considering episodic memories as a set containing many elements. The axiom of choice, one of the fundamental axioms of set theory, asserts the existence of a function f that can choose one element from every non-empty subset S of a given set A. Symbolically represented as $\forall S \subseteq A\ (S \neq \emptyset \rightarrow \exists x \in S)$, where ∀ is the universal quantifier ('for all'), ⊆ denotes 'is a subset of,' ∅ represents the empty set, ∃ is the existential quantifier ('there exists'), and ∈ signifies 'belongs to.' This implies that for all subsets S, if S is not empty, then one element can be chosen from S.

In a split brain, despite the absence of a corpus callosum transmitting information between hemispheres, both hemispheres retain memory regions, with the right hemisphere governing actions on the left side and the left hemisphere controlling actions on the right side as usual. Consider, for instance, a scenario where the right brain receives the command 'walk' from the left ear. In this case, the right brain, guided by the axiom of choice and further by Eq. (1), selects and decides the next action based on past episodic memories, prompting the body to perform the walking motion. Let ψ_R denote the wave function in the right brain according to Eq. (1). When the right brain selects the next action based on past episodic memories, this event is denoted as $\langle \psi_R|$, contained within the right brain. Conversely, if the left brain, through the right ear, asks 'Why are you walking?' it randomly selects an answer from past episodic memories in response to the observation 'I am currently walking.' Similar to ψ_R, by introducing the wave function ψ_L in the left brain, the event in the left brain due to the action of the right brain becomes $\langle \psi_R|\psi_L\rangle$. This encompasses an answer such as 'I'm going to buy cola because I'm thirsty.'

However, in the case of a regular brain, it is believed that the left and right hemispheres select actions from shared episodic memories through the corpus callosum, where the event represented by the wave function ψ, denoted as $\langle\psi|$, naturally differs from $\langle \psi_R|\psi_L\rangle$. Hence, it is believed that the HLbC model can explain the behavior of the split brain described in the Introduction. If illustrated, it would resemble **Figure 4**.

Next, based on Eq. (1) that represents the process of randomly selecting actions for observed events from multiple episode memories, let's compute the entropy for the segregated brain and the normal brain. Like quantum mechanics, it is common to define a density operator using the pure state wave function to obtain a density matrix from the function ψ. Assuming the pure state wave function as $|\psi\rangle$, the density operator $\hat{\rho}$ is defined as follows:

$$\hat{\rho} = |\psi\rangle\langle\psi| \tag{4}$$

Here, $|\psi\rangle$ represents the wave function as a ket vector, and $\langle\psi|$ represents its Hermitian conjugate as a bra vector. Using this density operator, one can acquire information regarding the expected values of physical quantities and the state of the system. However, if the function ψ represents a mixed state, it is necessary to represent a state where multiple functions ψ are superimposed. In this case, the density matrix is defined using multiple functions ψ as follows:

$$\hat{\rho} = \sum p_i |\psi_i\rangle\langle\psi_i| \tag{5}$$

Here, p_i denotes the probability associated with the superposition of each wave function $|\psi_i\rangle$. The entropy is defined from the eigenvalues of this density matrix as follows:

$$H = -\sum p_i log(p_i) \tag{6}$$

This entropy will be applied to the segregated brain and the normal brain. Considering the perspectives of entropy, for instance, by examining the variations and probability density functions of the outputs of systems A (left brain) and B (right brain), one can define the entropy concerning the outputs.

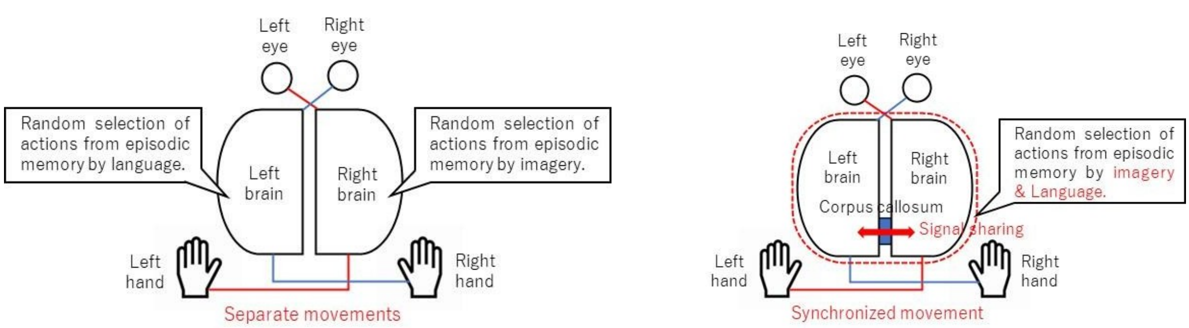
1) In the segregated brain scenario:

For independent systems A (left brain) and B (right brain), when each system independently generates outputs, the entropy of system A's output is denoted as H(A), and the entropy of system B's output as H(B). In this case, since both systems' outputs are independent and no information is transmitted between them, H(A,B)=H(A)+H(B) holds.

2) In the normal brain scenario:

When there's information exchange and interdependence between the left and right brains:

When both systems exchange information and mutually collaborate to generate outputs, the entropy of system A's output is denoted as H(A|B), and the entropy of system B's output as H(B|A). In this scenario, H(A,B)=H(A|B)+H(B|A) holds. Here, H(A|B) represents the uncertainty of system A's output given knowledge of system B's output, while H(B|A) represents the uncertainty of system B's output given knowledge of system A's output. If H(A,B)<H(A)+H(B), it indicates that systems A and B exchange



a) Case of split-brain b) Normal brain

Figure 4. Comparison of split-brain and Normal brain by HLbC model.

information, demonstrating mutual dependence in generating outputs. Conversely, if H(A,B)=H(A)+H(B), it indicates that both systems independently generate outputs.

In this manner, within the HLbC model, the reason for output differences is attributed to the random selection from multiple episodic memories.

Figure 5 shows the difference between the conventional interpretation of the isolated brain and the interpretation by the HLbC model. The first difference is that the conventional interpretation assumes "consciousness" in the right and left hemispheres, while the HLbC model includes the origin of consciousness itself. Traditionally, in split-brain cases, the lack of a corpus callosum, which facilitates communication between the right and left hemispheres, results in the left hemisphere being unable to comprehend actions performed by the right hemisphere, leading to the left hemisphere forming its own interpretations of the outcomes generated by the right hemisphere. The HLbC model maintains this conclusion, supporting conventional theories. However, while conventional theories imply an implicit understanding of how the left hemisphere independently interprets outcomes generated by the right hemisphere, the HLbC model demonstrates this 'how' through randomness in decision-making. This perspective presents a novel viewpoint. While the validity of the HLbC model requires ongoing verification, interpretations provided by the authors regarding illusions and Prospect Theory through the HLbC model, as well as the interpretation of split-brain cases in this study, are believed to enhance interpretational accuracy without contradicting existing knowledge.

Conclusions

In the HLbC model, it is postulated that consciousness is deeply intertwined with episodic memories, which are composed of "language" + "emotion" + "action and its outcome". Mathematically, language and emotion are defined as probability spaces, and episodic memories are represented as the Cartesian product of these probability spaces. Building upon this framework, the HLbC model hypothesizes consciousness emergence through five sequential steps: STEP-1 involves the observation of events through the five senses, STEP-2 entails comparison with past episodic memories, STEP-3 encompasses the random selection of behavior from multiple episodic memories related to the observed event—this randomness is

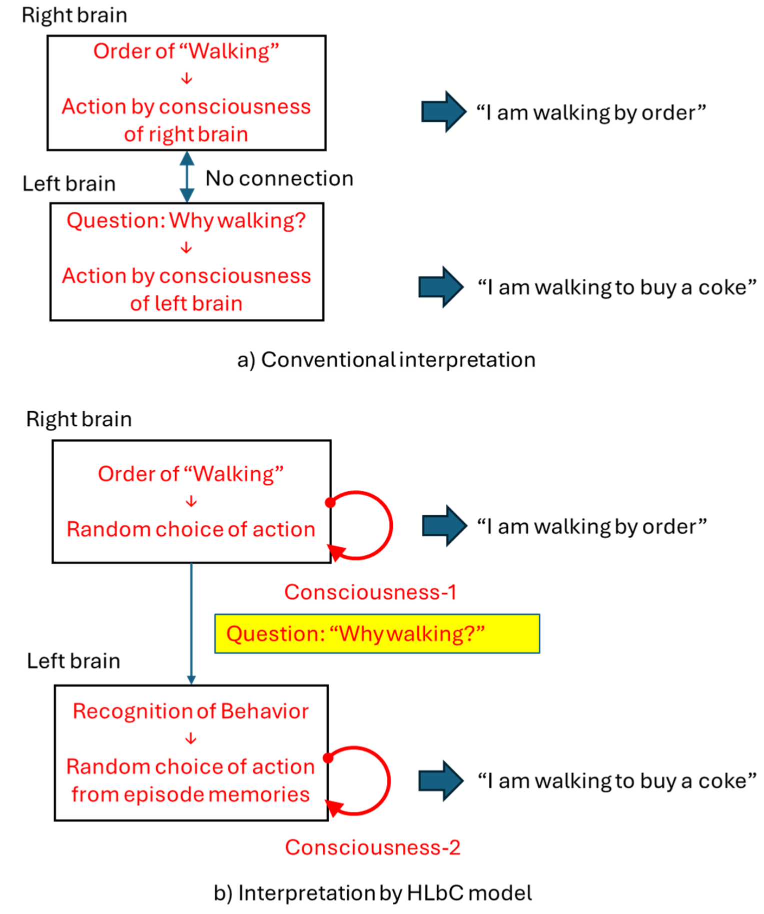


Figure 5. Comparison of interpretation between conventional idea and HLbC model.

contingent upon the brain's physical state—STEP-4 pertains to the execution of the selected behavior, and STEP-5 denotes the storage of the behavior outcome in short-term memory, followed by its retrospective recognition as part of consciousness. This recognition process in STEP-5 constitutes consciousness. Mathematical representation of STEP-3 as a probabilistic process reveals quantum-like behavior in the decision-making process, culminating in the expression of consciousness determination as a pseudo-Schrödinger equation. However, it's essential to note that this analogy doesn't imply a dependency on quantum mechanics for decision-making or consciousness.

This paper applies the proposed HLbC model to interpret the diverse behaviors exhibited by subjects with isolated brains. Consequently, it illuminates the innate comprehensibility of behaviors demonstrated by such subjects. Specifically, the process wherein the right brain makes decisions based on information entering the left eye is expounded upon. Within the HLbC model, the right brain randomly selects actions based on episodic memories stored in its memory region. Subsequently, it recognizes these actions retrospectively. However, since the rationale behind these actions isn't communicated to the left brain, when prompted with "why did you take that action?" the left brain selects a response randomly from its stored episodic memories and provides an answer accordingly. Hence, unique cases arise in subjects with isolated brains, which can be elucidated through the pseudo-Schrödinger equation, a mathematical outcome of STEP-3. While this concept has been previously noted, we contend that the HLbC model, incorporating randomness in action selection as a representation of consciousness, allows for a more lucid interpretation.

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