A QUANTUM-MECHANICAL INTERPRETATION OF METACOGNITION

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ABSTRACT
Metacognition is the awareness of what we know. By the virtue of our metacognitive capability, we are able to mediate the processing of both explicit and implicit data accumulated over time. Metacognitive capability is compromised in schizophrenia, drug addiction and by drug-treatment. In this paper, we first discuss neural and computational mechanisms of metacognition, and then we elaborate on pharmacotherapy from a quantum mechanical perspective.

1. INTRODUCTION

Metacognition concerns knowledge about knowledge, self-reflection on one's own cognitive and memory processing (monitoring) and self-regulation of one's own information processing and behavior (control). Metacognition enables correlation of learning and motivation, and of learning and cognitive development, as well [1].

Metacognitive system is accepted to operate basically at two levels, namely "object level" and "meta-level". The direction of information processing defines the kind of dominance relation between monitoring and control. During monitoring operation, which is analogous to listening to the telephone hand-set, the information flows from the object level towards the meta level. Conversely during control operation, which is analogous to speaking into the telephone hand-set, the information flows from the meta level towards the object level. Judgments through prospective monitoring are helpful to predict ease of learning (EOL), test performance on recallable items (judgments of learning, JOL) and nonrecallable items on a retention test (feeling of knowing, FOK) [2].Various views have been proposed to understand how metacognitive operation takes place. According to "direct access view", one has the capacity to directly retrieve the presence or the strength of recorded data (memory). If searching the database reveals the absence of an item, then an input will be sought for storage. An alternative approach, "cue utilization view" is based on theory- or experience-related cues; hence the accuracy of judgment depends on the validity of the cues [2].

In Koriat's crossover model, metacognition resides at the interface of implicit and explicit processes. In the explicit-controlled mode, behavior is under conscious control, whereas the implicit-automatic mode is driven by the unconscious. Thus metacognition is suggested to play a pivotal role in mediating between unconscious and conscious determinants of information processing [1].

By using a Clifford algebraic approach, Conte presents quantum mechanics (QM) as the first "physical theory" of cognition and adds: "QM enables to discover the first and also the fundamental principle that interfaces mind and matter. There are levels of reality in which we may not be able to separate the features of matter per se from the features of the cognition, of the logic and of the language that we use to describe it" [3]. Busemeyer and Trueblood have shown that quantum probability theory provides an understanding of cognition and decision making, where classical probability theory framework remains puzzled [4].

In this paper, we will elaborate on neural, computational and quantum mechanical explanations of metacognitive process and discuss the potential for pharmacological research.

2. IS METACOGNITION MERELY A HUMAN CAPACITY?

Till the last decade, metacognition has been accepted as a sophisticated human capacity. However, comparative psychology studies have shown the opposite [5].

Low-level conditioning mechanisms like rewarding, stimulus cues, overtraining and reinforcement contingencies may lead to erroneous interpretations in animal metacognition experiments. For this reason, memory tests have been utilized to investigate uncertainty responses in animals. In these experiments, animals are given the opportunity to withdraw under uncertainty conditions. Via their metacognitive ability, they recognize the difficult stimulus in a selective manner; hence they may decide to decline the test [5].

Rhesus monkeys were shown a list of pictures which was followed by a forgetting interval, then they were asked to discriminate whether a probe picture was in the list. They were given the alternative to decline the test if they were not sure. It was observed that the longer the list, the higher the uncertainty response, keeping the error rate

percentage constant [5]. In a similar experimental setting, monkeys appropriately declined memory tests in a match-to-sample paradigm, when they were unlikely to choose the correct image. If the delay between studying and matching the samples was prolonged, the rate to decline the matching test increased. In other words, they knew whether they remembered [6]. In another study, monkeys' confidence about their knowledge was measured by their gambling on their memories. When the monkeys knew that they did not know, they were able to ask for a hint by pressing an icon on the right side of the touch screen. Via this metacognitive control, monkeys chose to rectify their ignorance, instead of giving an uncertainty response. Availability of hints enhanced their performance during the first 3 days of training. However, on day 4, accuracy in the no-hint condition was found to be higher than in the hint conditions, implying the more difficult the condition, the better the long-term learning [7]. Not only monkeys [5-8], but also dolphins [5] and rats [9] possess metacognitive capability.
To sum up, there is an emerging consensus that animals' and humans' conscious metacognitive capabilities have functional parallelism. The use of animal paradigms has been suggested to explore metacognitive capacities of language-delayed, autistic and mentally retarded children [10].

3. NEURAL BASIS OF METACOGNITION

Various disciplines have been involved to identify the neural and computational mechanisms, which contribute to the displayed behavior upon receipt of information. A few of these disciplines include neuroscience, psychology and computer science. Uncertainty, challenging and ever-changing conditions necessitate optimization of judgments for a better outcome. Therefore, the incoming information should be both strong and reliable, hence in sufficient quality and quantity [11]. The goals of decision making are to achieve desired outcomes (getting it right for maximizing expected value) and to avoid undesired outcomes (getting it wrong resulting in minimizing value and wasting resources) [12].
In a recent review, incorporating decision confidence into formal models of perceptual choice behavior and the relevant biological substrates were highlighted [11]. In "drift-diffusion model" of perceptual choices, accumulating evidence of sufficient quality over time is needed for two-choice discrimination tasks: accuracy, mean response times for correct responses and for error responses, and the full response time distributions for correct and error responses [11, 13]. This diffusion decision model has been successful in explaining perceptual tasks, perception and attention tasks, signal detection tasks, lexical decision, recognition memory, and perceptual matching [14].
According to this "drift-diffusion model" of perceptual choices, information from a stimulus is accumulated continuously over time from a starting point till reaching to one of the two alternative response boundaries. During data accumulation process, signal-to-noise ratio is quite low resulting in high variability throughout the decision process. The mean rate of information accumulation is defined by the "drift rate". During the process of decision making, the drift rate and reaction times are inversely proportional. When the drift rate decreases, reaction times increase [14].

The model's diffusion processes seem to reflect neural activity. During accumulation of information from a stimulus for a two-choice task, the path is extremely noisy; hence the variability is extremely high, like which occurs over time in neural firing rates. This possible link between decision process and neural firing rates was investigated by simultaneous collection of behavioral and single-cell recording data. Monkeys undertook a test, which was designed to discriminate two dots, large and small, and to respond by left versus right eye movements, during which the evoked signals were recorded from the superior colliculus. It was demonstrated that the closer the diffusion process to a decision boundary, the higher the firing rate of the superior colliculus neurons [13].

4. COMPUTATIONAL BASIS OF METACOGNITION

Many computational models have been developed to explicate hierarchical models of behavior [15]. "Test-Operate-Test-Exit (TOTE)" is one of the pioneering computational models. TOTE considers the plan of the behavior as essentially the same as a program for a computer. The computer executes the instructions according to its given program under step by step operational control, and thus processes input for a desired output. When planning a behavior, the subject accrues information for a desired outcome (T), then puts into practice (O), tests the outcome (T) and exits (E) the program if the goal is reached. In this regard, brains are analogous to computers, and minds are analogous to programs [16].
During information processing, multiple sources of information (priors, evidence and value) are being recorded over the time span of the first data available till the integration of all data is complete for a final decision [12]. Recent research has helped us to understand how the incoming and the already accumulated information are encoded in the neural circuits. The data can be computed by direct integration /summing of neural signals over time. Pure integration can be achieved, when feedback and decay processes are tuned to balance [17].

Metacognitive (type II) sensitivity is the capability to discriminate between one's own correct and incorrect judgments based on differentiated stimuli (type I sensitivity). Signal detection theoretic (SDT) approach has been used for the analysis metacognitive performance in decision-making [18]. In the SDT model, decisions are formed by integration of priors /the probability $P(h_i)$, evidence (e) and values. Presence (h_1) or absence (h_2) of a stimulus as well as noise within the system will induce a decision variable from the observed evidence. In the sequential analysis procedure, the decision process continues with sequenced observations. Decision variable is determined according to the data accrued at each step [12]. In brief, type II analysis will depend on averaging type I outcomes and the accuracy of correct-incorrect discrimination may be expected to increase in line with task performance [19].

Bayesian SDT model provides a computational model to study metacognition. If two perceptual choices are available, then Bayesian decision theory indicates that resultant behavior is based on both priors and evidence, choosing the larger posterior probability. This model yields an X pattern, when computed as a measure of stimulus difficulty versus uncertainty: Making correct choices increases confidence [20].

As stated by Fleming et al., "*Science is a quintessentially metacognitive activity: it continually questions itself, probing and testing the robustness of accumulated knowledge*" [21]. In the next section, we will discuss metacognition in the light of quantum mechanical perspective.

5. QUANTUM MECHANICAL MODEL OF NEUROTRANSMISSION

The fact that cortical neurotransmission operates probabilistically was shown by many authors. The first quantum mechanical model was proposed by Walker in 1977, describing a virtual nervous system based on synaptic quantum tunnelling [3].

In 1992, a quantum mechanical model for button exocytosis in the cerebral cortex was introduced by Beck and Eccles [22]. Exocytosis is an all-or-nothing-event. Although there are around 40 vesicles in the presynaptic vesicular grid (PVG), following stimulation, only one vesicle is triggered for exocytosis. Interestingly, the other vesicles are blocked so that they don't release their contents. This fact has been explained by the paracrystalline structure of PVG, which enables long-range interactions. Exocytosis occurs with a probability between 0.2-0.3. In the resting state, a dendron is under the bombardment of thousands of buttons, and each button operates independently in a probabilistic manner. Beck and Eccles put forward the hypothesis that "*Mental intention increases the probabilities of exocytoses and introduces a coherent coupling of a large number of individual amplitudes of the hundreds of thousands of buttons in a dendron*". In this way, summation of these milli- excitatory postsynaptic potentials (EPSPs) results in a sufficiently high EPSP (10-20 mV) necessary for impulse generation [22]. Thus observation causes a change in the probability field and a quantum wave function collapse occurs.

Synaptic exocytosis acts as the regulator of the instable neural network in the brain. However, the probability of exocytosis per each excitatory impulse is low. In order to understand the nature of this low probability, the presence of an activation barrier was questioned. Such a barrier might be expected to prevent the opening of an ion channel in the PVG. The Quantum Trigger Model was developed to answer this important question [23]. This model suggests the superposition of two states, metastable and stable, separated by an energetic barrier. If an incoming impulse excites the PVG into a metastable state through quasiparticle tunneling (the trigger), then the process favors exocytosis. In brief, Quantum Trigger Model introduces two probability amplitudes for the same process. Measurement causes a collapse of the tunneling state and ends up with collapse into one definite state: either exocytosis or inhibition of exocytosis [22, 23].

6. QUANTUM MECHANICAL EXPLANATION OF HUMAN METACOGNITION

Complementarity and *Uncertainty*

Classical and quantum probability theories have distinctive approaches as summarized in Table I. The classical probability theory (CPT) assumes that during judgment process, the person has a *definite* value at each moment on a followed trajectory. The trajectory represents a definite state at each time point and is the only probabilistic component. This can be conceived as a particle which has a well-defined position and momentum on its path. The quantum probability theory (QPT) assumes the opposite: The person has an *indefinite* value at each moment on a followed trajectory. This indefinite state corresponds to a wave function covering all probability amplitudes [4].

In the world of quantum cognition, the abstract field of probabilities rules the judgment process. Coexistence of potentiality, superimposition of probability amplitudes and intrinsic indeterminism are the basic foundations QM, which can be explained by Clifford algebra [3, 24-28].

Let's introduce the three basic Clifford algebraic abstract elements [3]:

e_i , $i = 1,2,3$ (i= imaginary number)

These basic elements display the following basic feature (1):

$$e_i^2 = 1 \quad (1)$$

Clifford algebra shows that e_i possesses the ontological potentiality to value either + 1 or -1.
Both potentialities are superimposed to reveal a final state. In other words, it lies in a superposition of possible potential states, +1 and -1.
Clifford algebra is a valuable tool to explain *complementarity* and *uncertainty* principles. Bohr's *complementarity principle* is a basic principle of QM and also known as Copenhagen interpretation. Complementarity principle states that in our reality, a physical existent has multiple properties which are contradictory. It's impossible to view both at the same time, although they coexist simultaneously. The reality can be conceived only with observation, hence measurement. In terms of wave-particle duality, we will never be able to measure or observe both simultaneously. According to the *uncertainty principle,* both momentum and position cannot be measured simultaneously. When we try to measure the position more accurately, the uncertainty in momentum (Δp) grows; but when we try to measure the momentum more accurately, the uncertainty in position (Δx) grows (2), as formulated by Werner Heisenberg in 1927.

$$\Delta x \, \Delta p \approx h \quad (2)$$

From the perspective of QPT, measurement creates (but not records) a definite state from the probability field.
Although CPT treats human beings as passive observers and interprets the results independently from observation, QPT elicits that "*there are stages of our reality in which we no more may separate matter from cognition that we have about it*" [29]. "*Matter is constantly coupled to the principle of existence and to cognition"* [30]. In this new framework of reality, existence is related to cognition and has two possible outcomes, existence or non-existence, as shown by Clifford algebra [30].
In a system S, the relation between the quantum observables has been shown to be smaller than or equal to 1 (3).

$$<e_1>^2 + <e_2>^2 + <e_3>^2 \leq 1 \quad (3)$$

If we measure one of the observables in this system, for example $<e_3>^2$ = + 1, then a definite state is created from the probability field (4):

$$<e_1>^2 + <e_2>^2 + 1 = 1 \quad (4)$$

$$<e_1>^2 + <e_2>^2 = 0$$

$$<e_1> = 0$$

$$<e_2> = 0$$

Non-commutativity
Clifford algebraic abstract elements obey the non-commutativity principle (5). Non-commutativity means that the order of the quantum observables being measured has great impact on what is actualized [3].

$$e_i e_j = -e_j e_i = i e_k \quad (i, j, k = 1,2,3 \text{ , } ijk = \text{ permutation of 1, 2, 3 and } i^2 = -1) \quad (5)$$

Interference Effect
In QM, an electron is in a superposition of all possible states (A, B ...). The superposition is expressed by the following equations, c_1 and c_2 being the probability amplitudes (6) [30]:

$$|\psi\rangle = c_1 |A\rangle + c_2 |B\rangle \text{ ; It may also be expressed as: } \psi = c_1\psi_1 + c_2\psi_2 \quad (6)$$

The square moduli, $|c_1|^2$ and $|c_2|^2$, stand for the probability of measuring the electron at the positions A and B, respectively (7).

$$|c_1|^2 + |c_2|^2 = 1 \quad (7)$$

Therefore, in a bi-dimensional decision process, the uncertainty (U) is given by: $0 \leq U \leq 1$.
If P_1 and P_2 are the probabilities which indicate the possibility of electron's passing through the slit 1 and the slit 2, respectively in the famous Young's Double Slit Experiment, then the total probability calculation gives the below value, taking into consideration that c_1 and c_2 are "complex" numbers.

$$P = P_1 + P_2 + 2\text{Re}(\psi_1 {}^* \psi_2) \quad (8)$$

"$2\text{Re}(\psi_1^* \psi_2)$" is the quantum interference term, representing the interference fringes on the screen.
Interference effect has been observed in human psychology experiments. QPT is applicable to perception of ambiguous figures for binary choices [24, 31-38], categorization, disjunction effect, conjunction and disjunction fallacies, overextension of category membership, and memory recognition over distribution effect. In these experiments, the classical law of total probability is violated since a negative value for the interference term has been demonstrated, which denotes "negative probability / maintenance of wave function" A "zero value" for the

interference term implies the collapse of wave function, hence obedience to the Bayes formula of total probability [4, 39-42].
The quantum interference effect observed in cognition research is the evidence of superposition principle and helpful to explain how mental states follow quantum mechanics [31, 38- 40].
Mental wave functions (quantum like probability amplitudes) can be represented in hyper-trigonometric Hilbert space (cos-type interference) and also in hyperbolic Hilbert space (cosh-type interference). "*Thus the probabilistic structure of cognitive science is not simply nonclassical; but it is even essentially richer than the probabilistic structure of quantum mechanics"* [41-42].
Non-Locality / Violation of Bell Inequality
When four experiments (E1, E2, E3, and E4), each with two possible outcomes (for example plus or minus or up and down), are performed on the physical entity S, the following equation of Bell is never violated, if locality is involved.

$$|E13 - E14| + |E23 + E24| \leq 2 \qquad (9)$$

When two sub-entities *S1* and *S2* in a system *S* are connected via quantum entanglement, they will be in a superimposition of probable opposed states till measurement is made. This entangled state is given by the tensor product of Hilbert spaces $H1 \otimes H2$, which represent the state spaces for *S1* and *S2*, respectively. It has been shown that, the larger the violation of the Bell inequality, the more the system is quantum entangled, indicative of the presence of ontological, irreducibly indeterministic quantum structure.
Conte et al applied Myers-Briggs Type Indicator test to investigate whether quantum entanglement may exist between four psychological ego functions (intuition, sensing, feeling and thinking) and two psychological attitudes (introversion and extraversion) in the Jungian model of personality . In this model, the Self is at the center of total personality, covering consciousness, the unconscious and the ego. They showed the violation of Bell's inequality in at least 59 % of cases, revealing the quantum entanglement of psychological functions and attitudes in human subjects. Measurement performed on the entangled system resulted in a quantum collapse and the preferred functions for that moment shaped the attitude [32, 43].
The Self has a reflective nature: It's both the observer (e_i) and the observed (E_{0i} or E_{i0}) (Figure 1). They are separate but at the same time united [3, 36]. The Self involves continual interference of two complementary and antithetical units, consciousness and the unconscious. The quantum model of cognition may explain the manifestation of opposite and mutually consuming alternatives which are coexistent, intrinsically and irreducibly indeterministic [44].

7. PHARMACOLOGICAL IMPLICATIONS FOR METACOGNITION

Schizophrenia has been a topic of interest for metacognitive research. It has been demonstrated that judgment processes during "source monitoring" are disrupted in chronic and first-episode delusions in schizophrenic patients [45]. Episodic memory (spatial-temporal recording of events) and FOK judgments for both correct and incorrect answers are also impaired [46].
Drugs which induce cognitive disorders are opioids, antineoplastics, anticonvulsants, interferon alfa, benzodiazepines, anticholinergics, nonnucleoside reverse transcriptase inhibitors, antipsychotics, histamine type 2 receptor antagonists, NSAIDs, selective serotonin reuptake inhibitors, lithium and many others [47]. Especially long-term use of cannabis, heroin, cocaine, amphetamine, methamphetamine, 3, 4-methylenedioxymethamphetamine (ecstasy) and nicotine has been associated with cognitive deficits [48]. High doses of alcohol and hallucinogens like LSD are also known to impair cognition [49].
Studies on drug-induced metacognitive impairment are a few, including alcohol [50], triazolam [50] and zolpidem [51]. Deterioration in metacognitive function was also shown for nicotine-dependence and [52] and nicotine abstinence [53].
Emerging evidence points out the importance of "brain network integration" for screening the pro-cognitive effects of drugs. In the relevant studies, analysis of the brain's functional status as an interconnected network has shown that its overall behavioral response is greater than the algebraic sum of individual elements' responses. Cognitive performance increases with higher functional integration within the brain network. Neurotransmitters and drugs, by modulating synchronization in the alpha, beta or gamma bands, may promote brain network integration. Accordingly, sensitivity to pro-cognitive drugs depends on the basal efficiency of brain networks and disease progress [54].

8. CONCLUSION

Metacognition mediates human information processing by evaluation of unconscious and conscious determinants.
Throughout information processing, neural events, hence judgments are ruled by the abstract field of probabilities.
The quantum system evolves from a reversible to an irreversible state by means of measurement of quantum

variable. In this context, metacognition is processed by mental wave functions. By gaining insight into the quantum mechanical interpretation of metacognition, we are at a stage of leaving our traditional views behind and entering a new scope of understanding about reality, where information, cognition and principle of existence are intrinsically structured ab initio.

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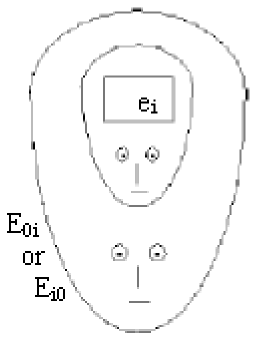
Table I. Distinctive understanding of cognition according to classical probability theory and quantum probability theory (Please see ref 4 for further reading)

	Classical Probability Theory (CPT)	**Quantum Probability Theory (QPT)**
1	A person has a *definite* value at each moment on a followed trajectory.	A person has an *indefinite* value at each moment on a followed trajectory.
2	Measurement records the definite state of the system, reflecting the state immediately before measurement	Measurement creates (rather than recording) a definite state from the indefinite state of the system.
3	A joint probability of answers can be simultaneously defined to a conjunction of questions; order dependent measurements are commutative.	A joint probability of answers cannot be simultaneously defined to a conjunction of questions; order dependent measurements are non-commutative.
4	CPT obeys the law of total probability.	QPT does not always obey the law of total probability.
5	A single sample space is sufficient.	Different sample spaces are required.
6	Judgments are decomposable: the whole can be understood in terms of its constituents	Judgments are non-decomposable: Quantum entangled constituents are in a superposition of opposite states.

Fig. 1 The Self has a reflective nature: It's both the observer and the observed (by the courtesy of E. Conte [3])



in which we no more may separate matter per se from the cognition and the principle of existence that we have to attribute to it.
The (2.97) clearly explains that such two basic features, matter from one hand and cognition from the other hand, and are indissolubly connected from its starting in the theory. Matter cannot be conceived per se but in relation to the cognition that it is possible to have about it.
In this manner a new framework of quantum reality arises in which ab initio information, cognition and principle of existence are structured in it. Matter does no