

# On the Existence of Quantum Wave Function and Quantum Interference Effects in Mental States

## An Experimental Confirmation During Perception and Cognition in Humans

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### Abstract

We introduce the quantum theoretical formulation to determine a posteriori, if existing, the quantum wave functions and to estimate the quantum interference effects of mental states. Such quantum features are actually found in the case of an experiment involving the perception and the cognition in humans. Also some specific psychological variables are introduced and it is obtained that they characterize in a stringent manner the quantum behaviour of mind during such performed experiment.

**Key Words:** quantum wave function, interference effects, mental states, cognition, perception

NeuroQuantology 2009; 2: 204 - 212

### 1. Introduction

Mental operations have content plus the awareness of such content. Consciousness is a system which observes itself, and evaluates itself being aware at the same time of doing so. Statements may be indicated by a, b, c, ..., .They

are self-referential or auto referential. Content statements of our experience may be expressed by x, y, z,... According to A.G. Kromov (Kromov, 2001),

$$a = F(a, x)$$

is the most simple definition of a single auto referential statement.

As an example, consider

x = the sun shines in the sky;

a=I am aware of this.

Human experience unceasingly involves our perception-cognition system. Mental and

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ISSN 1303 5150

www.neuroquantology.com

interface holds between mind/consciousness and brain.

Neuroscience and neuropsychology have reached high levels of knowledge in this field by the extended utilization of electrophysiological and of functional brain imaging technology. However, neuroscience finds it hard to identify the crucial link existing between empirical studies that are currently described in psychological terms and the data that arise instead described in neurophysiological terms. It is assumed that the measurable properties of the brain through functional imaging technology should be in itself sufficient to achieve an adequate explanation of the psychologically described phenomenology that occurs during neuropsychological experiments.

Instead, some investigators suggest that intrinsically mental and experiential functions such as “feeling” and “knowing” cannot be described exclusively in terms of material structure, and they require an adequate physics in order to be actually explained. To this purpose they outline the important role that quantum mechanics could carry out. In particular, we outline here the effort of Stapp in several years and still more recently (Stapp, 1933; Schwartz, 2005), and the prospects for a quantum neurobiology that were outlined already more than a past decade ago (Miller, 1996). Therefore, it becomes of fundamental and general interest for neuroscience and neuropsychology to indicate by results of experiments if quantum mechanics has a role in brain dynamics. In the present paper we give a contribution concerning this basic problem while previous results obtained by us on this matter, are given in (Conte, 2003; 2007; 2008; Conte et al., 2008). First we consider the problem to acquire (a posteriori) knowledge of quantum wave function starting directly from experimental data, and soon after we show that mental states follow quantum mechanics during perception and cognition of figures having intrinsic ambiguity.

## 2. Quantum Theoretic Approach

Quantum mechanics represents the most celebrated theory of science. Started in 1927 by founder fathers as Bohr, Heisenberg, Schrödinger, and Pauli (Zelinger, 1966; Shimony, 1997), it has revolutionized our understanding of physical reality. It was introduced to describe the

behaviour of atomic systems but subsequently its range of validity has turned out to be much wider including in particular some macroscopic phenomena. The conceptual structure and the axiomatic foundations of quantum theory repeatedly suggested from its advent and in the further eighty years of its elaboration that it has a profound link with mental entities and their dynamics. We retain that this feature represents an important connotation of the theory also if it is necessary a correct interpretation of the connection between quantum mechanics and mental properties in the sphere of our reality. One cannot have in mind a quantum physical reduction of mental processes. N. Bohr (Bohr, 1987) borrowed the principle of complementarity, which is at the basis of quantum mechanics, from psychology. He was profoundly influenced from reading the “Principles of Psychology” by W. James (James, 1890). However, N. Bohr had not in mind quantum-reductionism of mental entities. Starting with 1930, there was also an important correspondence between W. Pauli and C.G. Jung that culminated in the formulation of a theory of mind-matter synchronization (Meier, 2001). Also in this case these authors were distant to consider a quantum-reductionism perspective. V. Orlov (Orlov, 1982) proposed quantum logic to describe brain functions but also he did not look for reduction of mental processes to quantum physics. The correct way to frame the problem is not to attempt a quantum reduction of mental processes. We retain that we may arrive to give experimental evidence that cognitive systems are very complex information systems, to which also the laws of quantum systems must be applied. This should represent an important result since it might give a further chance to represent and to understand the principles and rules acting as counter part of human mind.

Let us introduce now the basic framework of our formulation. The wave function  $\psi$  of quantum mechanics represents a mental object. We have the problem of its determination that is to say the manner in which we may acquire a posteriori a knowledge about the fact that a given system is described by a function  $\psi$ . Starting with 1983 (Conte, 1983) and 2004 (Khrennikov, 2001; 2005; 2006) we considered this problem for biological and

mental exploration. The basic key is that wave function  $\psi$  is not an observable in the usual sense of quantum theory and, consequently, it cannot be measured in the usual sense of this word. On the other hand, it may be determined provided that one has an ensemble of similarly prepared systems, each describable by the same function  $\psi$ . To this purpose (Conte, 1983 see also Khrennikov, 2001; Khrennikov, 2005; Khrennikov, 2006) one measures an arbitrary but complete set of observables that we call A on a large number of systems and get a statistical distribution of eigenvalues  $A_n$ . This approach determines the absolute values  $|a_n|$  of the coefficients of the decomposed wave function

$$\psi = \sum_n a_n \psi_{A_n} \quad \text{with} \quad \sum_n |a_n|^2 = 1 \quad (1)$$

In order to determine  $\psi$  one must know not only the absolute values of the coefficients but also the phases

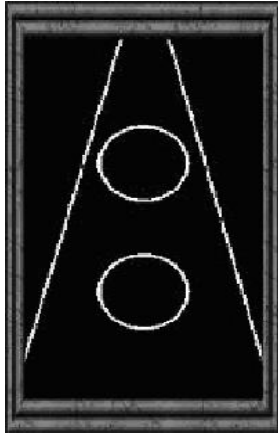
$$a_n = |a_n| e^{i\alpha_n} \quad (2)$$

Therefore, we have to repeat the same procedure again by measuring another complete set of observables B on a large number of systems to obtain an independent decomposition

$$\psi = \sum_m b_m \psi_{B_m} \quad \text{with} \quad \sum_m |b_m|^2 = 1 \quad (3)$$

and determine  $|b_m|$ . Let us admit that we find a number  $N$  and  $N'$  of coefficients different from zero, respectively. In the case  $N > N'$  we introduce the decomposition

$$\psi = \sum_n \sum_{mn} b_m \psi_{A_n}$$



Test A. Are these two equal circles ?

### 3. The Quantum Formulation of Mind Entities.

According to Eccles and Beck (Beck, 1992; 2008) the mind is a field of probability. In quantum mechanics, the abstract probability fields causally preside over the advent of events in nature. Mathematically, a quantum state  $\psi$  (wave function) is a vector in Hilbert space  $H$  over some field. Such a state has a probabilistic content, the vector that represents it, has to be of length one, that is to say  $\langle \psi / \psi \rangle^2 = 1$  (where  $\langle \cdot / \cdot \rangle$  denotes the inner product in  $H$ ). The basic key of intrinsic indetermination in quantum mechanics is the principle of superposition. It states that for any two states  $\varphi_1$  and  $\varphi_2$  of  $H$ , there exist at least one other state  $\psi$  of  $H$  that can be written as a linear combination of the first two:

$$\psi = c_1\varphi_1 + c_2\varphi_2 \quad (6)$$

$$\text{with } |c_1|^2 + |c_2|^2 = 1; \\ \langle \varphi_i / \varphi_j \rangle = \delta_{ij} \quad (i = 1,2 ; j = 1,2) \quad (7)$$

and  $|c_1|^2$  represents probability for state  $\varphi_1$  and  $|c_2|^2$  is probability for state  $\varphi_2$ . Mind states are represented by the quantum superposition principle.

In our quantum model of mind entities (for details see also Conte, 2003; Conte, 2007) we consider that a human subject can potentially have multiple mind representations of a given choice situation, also if actually he can attend to only one representation at any given time. In this quantum mechanical framework we

distinguish a potential and an actual or manifest state of consciousness. The state of the potential consciousness will be represented by a vector in Hilbert space. If we indicate for example a bi dimensional case of a decision situation with potential states  $|+\rangle$  and  $|-\rangle$ , in relation to a dichotomous observable  $A = +, -$ , the potential state of consciousness will be given by the superposition

$$\psi = a |+\rangle + b |-\rangle. \quad (8)$$

Here,  $a$  and  $b$  represent probability amplitudes so that  $|a|^2$  will give the probability that the state of consciousness, represented by  $|+\rangle$ , will be finally actualised or manifested during decision. Conversely  $|b|^2$  will represent the probability that state  $|-\rangle$  of consciousness will be actualised or manifested during decision. It will be  $|a|^2 + |b|^2 = 1$ .

The potential state, given in (8), represents in some manner the condition of doubt or of inner conflict or of intrinsic indetermination of the human subject in relation to the posed question ( $A = +, -$ ).

The amount of doubt of the subject (see also Orlov, 1982) or his inner conflict or indetermination, in relation to the posed question ( $A = +, -$ ), is given by

$$D = 1 - \left| |a|^2 - |b|^2 \right| ; 0 \leq D \leq 1 \quad (9)$$

When an actual or manifest state of consciousness is realized during decision, the (8) is reduced to  $|+\rangle$  with probability  $|a|^2$  or to  $|-\rangle$  with probability  $|b|^2$ .

As neurophysiological counterpart of the present quantum mechanical model of mind entities, as also previously outlined in (Manoussakis, 2006; Atmanspacher, 2004), we admit that, when a conscious decision or observation happens, the actual event that in correspondence is realized in consciousness, is linked to a particular neural correlate brain state. In this manner, in the (8),  $|+\rangle$  and

$|-\rangle$  represent two possible states having two distinct neural correlates.

For brevity we will not consider here the case of the evolution in time of the state of potential consciousness, see (Conte, 2003; Conte, 2007) for details.

Some comments may be now added to the previous formulation. The first is that this quantum model of mind entities must be confirmed experimentally in order to be accepted. It does not exist experimental evidence that states of mind may be represented as vectors in a Hilbert space as well as it does not exist experimental evidence that mind states may be represented by quantum wave functions. We retain that the experimental results obtained in this paper give a satisfactory evidence of this matter. Therefore, the consequences of such result are important. The principle of superposition of states implies that the state space is non- Boolean. Therefore, mind states pertain to a non-Boolean state space. The arising conclusion is that at least some perceptive- cognitive systems have such quantum-like abilities. The brain should result to emulate quantum dynamics at least under some conditions. Such emulation would allow for a three-valued logic in human cognition: true, false and the superposition of true and false. This could explain the peculiar human ability to hold contradictory notions in mind simultaneously, although usually there is collapse to one state or the other. This ability to see things from "opposite" views might have been valuable in the development of sociability, empathy and even cognitive innovation which seems to depend on seeing things in a radically different way as compared to social or cultural norms. The other important feature relates the nature of mind entities. If the previous model is confirmed, we have to conclude that they, at least under our conditions of experimentation, operate by quantum probabilities and analysing (even unconsciously) probabilities of various alternatives. They work directly with mental wave functions or probabilistic amplitudes.

#### 4. Theoretical Description of the Performed Experiment

In our formulation a decision is asked to a subject on a question ( $A = +, -$ ) selecting it

among a set of potential alternatives. According to quantum mechanical results that we have given in the section of the quantum theoretic approach, it becomes of interest to establish the dynamics of such decision mechanism when two or more questions  $A, B, \dots$  are posed to the human subject. As said previously, we associate to every decision situation an observable that we denote by  $A, B, \dots$  that we consider to act on  $H$ . We may study more that one decision situation, say ( $A = +, -$ ) and ( $B = +, -$ ) to be posed in rapid succession to the subject. We know that a key question in quantum mechanics is whether the corresponding observables are or not commuting operators in  $H$ , i.e., whether  $AB = BA$ . From a formal view point we have discussed the case  $AB \neq BA$  by the formulas (1-5) of the previous sections. From a cognitive view point we may expect that if  $A$  and  $B$  commute, a decision  $A$  will not affect the subsequent decision on  $B$ . The situation is completely different in the case in which observables  $A$  and  $B$  do not commute. We know that in this case the predictions of quantum mechanics differ radically from those of the classical probabilistic model. In this case the quantum probability calculus generates cross- terms also called the interference terms. In our formulation these cross-terms are the signature of an existing intrinsic indetermination, of an intrinsic doubt, of an inner conflict that characterizes the cognitive status of the subject in the sequence  $A$  and  $B$  of posed questions. Generally speaking, admitting that questions  $A$  and  $B$  have the same number  $n$  of possible choices, considering again the (1-5), we obtain

$$p_B(b_n) = \left( \sum_{j=1}^n a_j c_{nj} \right)^2 = \sum_{j=1}^n a_j^2 c_{nj}^2 + 2 \sum_{j \neq j'} \left[ (a_j c_{nj})(a_{j'} c_{nj'}) \right] \quad (10)$$

where the first term in the (10) indicates the classical term of Bayes probability to which it is added the interference term that is the quantum expression of an irreducible intrinsic indetermination during cognition of the subjects under investigation. In brief, if quantum

mechanics has a role in the investigated decision process, we have a violation of the classical Bayes formula for conditional probability. Let us examine the case of two dichotomous

observables and thus involving the sequence of two decisions, ( $A = +, -$ ) and subsequent ( $B = +, -$ ). We have the following wave functions

$$\begin{aligned} \psi(A = +) &= \sqrt{P(A = +)} e^{i\varphi_1}, \quad \psi(A = -) = \sqrt{P(A = -)} e^{i\varphi_2}, \\ \psi(B = +) &= \sqrt{P(B = +)} e^{i\vartheta_1}, \quad \psi(B = -) = \sqrt{P(B = -)} e^{i\vartheta_2} \end{aligned} \quad (11)$$

According to the (1-5) we have that

$$\begin{aligned} \psi(B = +) &= \sqrt{P(B = + / A = +)} \psi(A = +) - \sqrt{P(B = + / A = -)} \psi(A = -) \\ \psi(B = -) &= \sqrt{P(B = - / A = +)} \psi(A = +) + \sqrt{P(B = - / A = -)} \psi(A = -) \end{aligned} \quad (12)$$

The square modulus of such probability amplitudes gives

$$\begin{aligned} P(B = +) &= P(A = +)P(B = + / A = +) + P(A = -)P(B = + / A = -) \\ &- 2\sqrt{P(A = +)P(A = -)P(B = + / A = -)P(B = + / A = +)} \cos(\varphi_1 - \varphi_2) \end{aligned} \quad (13)$$

and

$$\begin{aligned} P(B = +) &= P(A = +)P(B = - / A = +) + P(A = -)P(B = - / A = -) \\ &+ 2\sqrt{P(A = +)P(A = -)P(B = - / A = +)P(B = - / A = -)} \cos(\varphi_1 - \varphi_2) \end{aligned} \quad (14)$$

We see that in the (13) and (14), in addition to the classical Bayes formula for conditional probabilities, an interference term appears that acclaims the presence and the role of quantum effects in the sequence B/A investigated at the cognitive level of the subject. The experimental determination of probabilities

$$P(B = +), P(B = -), P(A = +), P(A = -), P(B = + / A = +), P(B = + / A = -)$$

enables us to calculate the interference term

$$\begin{aligned} \cos \omega &= \frac{P(B = +) - P(A = +)P(B = + / A = +) - P(A = -)P(B = + / A = -)}{2\sqrt{p(B = +)p(A = + / B = +)p(B = -)p(A = + / B = -)}} = \\ &= \frac{\Delta p}{2\sqrt{P(A = +)P(B = + / A = +)P(A = -)P(B = + / A = -)}} \end{aligned} \quad (15)$$

and the phase  $\omega = \varphi_1 - \varphi_2$  by which the a posteriori determination of the quantum wave function (see the 12) is realized.

Finally, we intend to introduce here some new variables that may be able to characterize the mental condition of a subject in

the course of an experiment employing two non commuting dichotomous observables  $A$  and  $B$ .

The first variable was previously given in (9). As previously said, it characterizes the

amount of doubt, of inner conflict or of intrinsic indetermination of the subject, and it may be calculated also in the case of a sequence of posed questions  $A$  and then  $B$ .  $D_{B/A}$  will characterize in this case the amount of doubt of the subject also in relation to subject

quantum like observables of people S under investigation. We split the given ensemble S of humans into two sub ensembles U and V of equal numbers. To ensemble U we pose the question B with probability in answering, given respectively by  $P(B = +)$  and  $P(B = -)$ , and  $P(B = +) + P(B = -) = 1$ . We pose the question A immediately followed by the question B to the ensemble V. We calculate the conditional probabilities  $P(B = + / A = +)$  and  $P(B = + / A = -)$  and corresponding probabilities for the case ( $B = -$ ). We reach in this manner a no evadable feature of such experiment. If we obtain  $\Delta p \neq 0$  as given in the (15), we certainly are in presence of two no commuting quantum observables ( $AB \neq BA$ ), and we may estimate quantum interference effects and the mental wave function.

We analysed a group of 72 subjects giving geometrical figures (Figure 1) as Test A and Test B, respectively. All the subjects were selected with about equal distribution of females and males, aged between 19 and 22 years. The ambiguity induced by tests of Fig. 1 was ascertained for each subject after their answers to question ( $A = +, -$ ), and ( $B = +, -$ ). All had normal or corrected-to-normal vision. All they were divided by random selection into two groups (1) and (2). Group (1) was subjected to test B only, while the group (2) was subjected to Test A and soon after (about 800 msec. after choice for test A) to test B. Each subject was asked to select  $A = +$  or  $A = -$  (respectively  $B = +$  or  $B = -$ ) on the basis of what he was thinking about the figure at the instant of observation. A constant visual angle  $V = 2 \arctg(S / 2d) = 0.33 \text{ rad}$  was used with S object's frontal linear size and d distance from the centre of the eyes for all the subjects. The figures were placed in front of the eyes of the observer at a distance of 60 cm, and illuminated by a lamp of 60 W located above and behind the observer's head. The experimental room was kept under daylight illumination.

## 6. Results and Conclusions.

We obtained the following results. For group (1) with test B only:  $P(B = +) = 0.6667$ ;  $P(B = -) = 0.3333$ . For group (2) with test A and soon after test B:  $P(A = +) = 0.5556$ ;

$$\begin{aligned} P(A = -) &= 0.4444; \\ P(B = + / A = +) &= 0.6000; \\ P(B = + / A = -) &= 0.3750; \\ P(B = - / A = +) &= 0.4000; \\ P(B = - / A = -) &= 0.6250. \end{aligned}$$

Bayes formula for conditional probabilities gave

$$P(A = +)P(B = + / A = +) + P(A = -)P(B = + / A = +) = 0.5000;$$

$$P(A = +)P(B = - / A = +) + P(A = -)P(B = - / A = -) = 0.5000.$$

Consequently, we had

$$\Delta p(B = +) = 0.1670;$$

$$\Delta p(B = -) = -0.1667, \quad \cos \omega = 0.35363 \quad \text{for } (B = +),$$

$\cos \omega = -0.33549$  for ( $B = -$ ). A statistical analysis was performed. We had a chi-square value  $\chi^2 = 5.7143$  with a satisfactory statistical significance,  $\alpha = 0.0168$  (\*),  $df = 1$ .

The obtained results enable us to confirm that we had quantum interference effects during perception-cognition of figures having intrinsic ambiguity as given in Fig.1.

The wave functions of mental states may be now calculated on the basis of the (11-12), and they are given in the following manner

$$\begin{aligned} \psi(A = +) &= 0.7453 \text{ and} \\ \psi(A = -) &= 0.6666 e^{1.9322 i} \\ \psi(B = +) &= 0.8165 \\ \text{and} \\ \psi(B = -) &= 0.5773 e^{0.9038 i} \end{aligned}$$

The amount of doubt or of inner conflict and indetermination as induced from ambiguity of figures was calculated on the basis of the (9). It resulted  $D = 0.6667$ . Since  $0 \leq D \leq 1$ , we conclude that a rather consistent value of inner conflict was induced in the examined subjects as consequence of the intrinsic ambiguity of the observed figures. Using the (16), we calculated  $D'$ , the quantum interference effect, that resulted to be  $D' = 0.1112$ .

It resulted a rather high quantum interference effect induced from test A during resolution of test B. In the same manner we estimated

$$I_{\max} = 1.9937;$$



$$I_{\min} = 0.0062 ;$$

$$V = 0.9937 ;$$

$$V^2 = 0.9874 ;$$

$$D^2 + V^2 = 0.9997$$

We conclude that we examined a case of perception-cognition marked from very consistent quantum interference effects.

Finally, we must account that, according to quantum mechanics, passing from the representation of test A to test B, the subjects must realize an unitary transformation. We must inspect that this was indeed the case. In fact, on

the basis of the previous results of the experimentation, we had

$$U = \begin{pmatrix} \sqrt{0.6000} & -\sqrt{0.3750} \\ \sqrt{0.4000} & \sqrt{0.6250} \end{pmatrix}$$

and

$$UU^+ = \begin{pmatrix} 0.9748 & 0.0057 \\ 0.0096 & 1.023 \end{pmatrix}$$

Therefore, also the unity was granted during such experiment.

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