Chapter 8
Fiat Lux Versus Fiat Lumen: Quantum Effects in Linguistic Operations

Fortunato Tito Arecchi

8.1 A Methodological Premise

Classifying the information content of neural spike trains, an uncertainty relation emerges between the bit size of a word and its duration. This uncertainty is ruled by a quantum constant whose numerical value has nothing to do with Planck's constant. A quantum conjecture explains the onset and decay of the memory window connecting successive pieces of a linguistic text. The conjecture here formulated is applicable to other reported evidences of quantum effects in human cognitive processes, so far lacking a plausible framework since no efforts to assign a quantum constant have been associated.

Any scientific description entails a complementarity between its Extension and Detail. The two aspects of a scientific description, namely, Extension and Detail, result mutually conflicting.

For instance, a successful approach explaining the cosmic evolution from the Microwave Background to the Galaxy formation cannot explain the details of planet differentiation, why e.g., the Earth has a magnetic field providing the Van Allen belt shield from solar particles, or the water necessary for life. Two different sets of foundational principles must be introduced in order to explain the two classes of phenomena, that is, the fundamental objects of Planetology and their mutual interactions must be introduced appropriately and cannot be derived from the general principles of Cosmology.

In a similar way, a general powerful QFT (quantum field theory) approach has been developed to explain the brain and memory organization starting from the collective organization of water dipole quanta in living matter (Vitiello 2001; Freeman and Vitiello 2006).

F.T. Arecchi (✉)
University of Florence, Florence, Italy
e-mail: tito.arecchi@ino.it

F. La Mantia et al. (eds.), *Language in Complexity*,
Lecture Notes in Morphogenesis, DOI 10.1007/978-3-319-29483-4_8

Even though, the puzzling fact that in a human linguistic endeavor, words are mutually influencing through their meanings, so that an “infinite use emerges from a finite amount of resources” (Humboldt 1836) has no explanation whatsoever in the QFT of brain and memory, that has no tools to differentiate the human brain behavior from that of other animals.

In this work, we present a specific theoretical approach that provides that sound explanation for the linguistic performances is not achievable in the QFT of brain and memory.

8.2 Two Separate Cognitive Processes

In (Arecchi 2012), I have analyzed two distinct moments of human cognition, namely, apprehension (A) whereby a coherent perception emerges from the recruitment of neuronal groups, and judgment (B) whereby memory recalls previous (A) units coded in a suitable language, these units are compared and from comparison it follows the formulation of a judgment.

The first moment (A) has a duration around 1 s; its associated neuronal correlate consists of the synchronization of the EEG (electroencephalographic) signals in the so-called gamma band (frequencies between 40 and 60 Hz) coming from distant cortical areas. It can be described as an interpretation of the sensorial stimuli on the basis of available algorithms, through a Bayes inference.

Precisely (Arecchi 2012), calling h (h = hypothesis) the interpretative hypotheses in presence of a sensorial stimulus d (d = datum), the Bayes inference selects the most plausible hypothesis h^*, that determines the motor reaction, exploiting a memorized algorithm $P(d|h)$, that represents the conditional probability that a datum d be the consequence of an hypothesis h.

The $P(d|h)$ have been learned during our past; they represent the equipment whereby a cognitive agent faces the world. By equipping a robot with a convenient set of $P(d|h)$, we expect a sensible behavior. The second moment (B) entails a comparison between two apprehensions (A) acquired at different times, coded in a given language and recalled by the memory. If, in analogy with (A), we call d the code of the second apprehension and h^* the code of the first one, now—at variance with (A)—h^* is already given; instead, the relation $P(d|h)$ which connects them must be retrieved, it represents the conformity between d and h^*, that is, the best interpretation of d in the light of h^*.

Thus, in linguistic operations, we compare two successive pieces of the text and extract the conformity of the second one on the basis of the first one. This is very different from (A), where there is no problem of conformity but of plausibility of h^* in view of a motor reaction.

Let us make two examples: a rabbit perceives a rustle behind a hedge and it runs away, without investigating whether it was a fox or just a blow of wind. On the contrary, to catch the meaning of the 4th verse of a poem, we must recover the meaning of the 3-d verse of that same poem, since we do not have a priori algorithms to provide a satisfactory answer.

Once the judgment, that is, the $P(d|h)$ binding the codes of the two linguistic pieces in the best way, has been built, it becomes a memorized resource to which to recur whenever that text is presented again. It has acquired the status of the pre-learned algorithms that rule (A).

However—at variance with mechanized resources—whenever we reread the same poem, we can grasp new meanings that enrich the previous judgment $P(d|h)$. As in any exposure to a text (literary, musical, figurative) a rereading improves our understanding.

(B) requires about 3 s and entails self-consciousness, as the agent who expresses the judgment must be aware that the two successive apprehensions are both under his/her scrutiny and it is up to him/her to extract the mutual relation.

As a fact, exploring human subjects with sequences of simple words, we find evidence of a limited time window around 3 s (Pöppel 1997, 2004), corresponding to the memory retrieval of a linguistic item in order to match it with the next one in a text flow (be it literary, or musical, or figurative).

At variance with (A), (B) does not presuppose an algorithm, but rather it builds a new one through an inverse Bayes procedure (Arecchi 2007). This construction of a new algorithm is a sign of creativity and decisional freedom. Here the question emerges: can we provide a computing machine with the (B) capacity, so that it can emulate a human cognitive agent? Turing (1950). The answer is NOT, because (B) entails non-algorithmic jumps, insofar as the inverse Bayes procedure generates an ad hoc algorithm, by no means preexistent.

Figures 8.1, 8.2, 8.3, and 8.4 that follow and their captions explore in detail these aspects (Pöppel 1997).

After having shown evidence of this short-term memory window bridging successive pieces of a linguistic text, we formulate a quantum conjecture. This conjecture fulfills two needs, namely, (i) explaining the fast search in a semantic space, whose sequential exploration by classical mechanisms would require extremely long times, incompatible with the cadence of a linguistic presentation

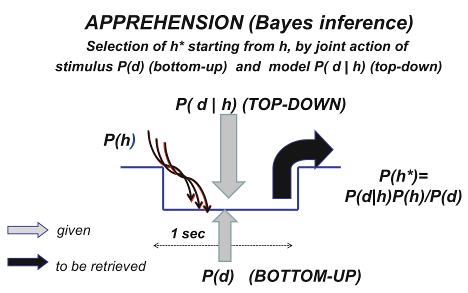

Fig. 8.1 Apprehension as a Bayes inference. One formulates a manifold of hypotheses; each one provides a datum through the *top-down* conditional probability; only the hypothesis that generates the actual datum (*bottom-up*) is the plausible one

tito.arecchi@ino.it

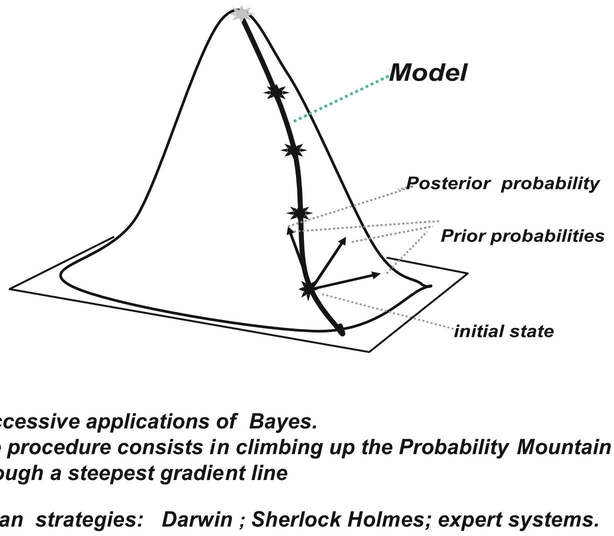

Fig. 8.2 Recursive application of Bayes is equivalent to climbing a probability mountain, guided by the model, that is, the conditional probability that a hypothesis generates a datum. This strategy is common e.g., to Darwin evolution and to Sherlock Holmes criminal investigation; since the algorithm is unique, it can be automatized in a computer program (expert system)

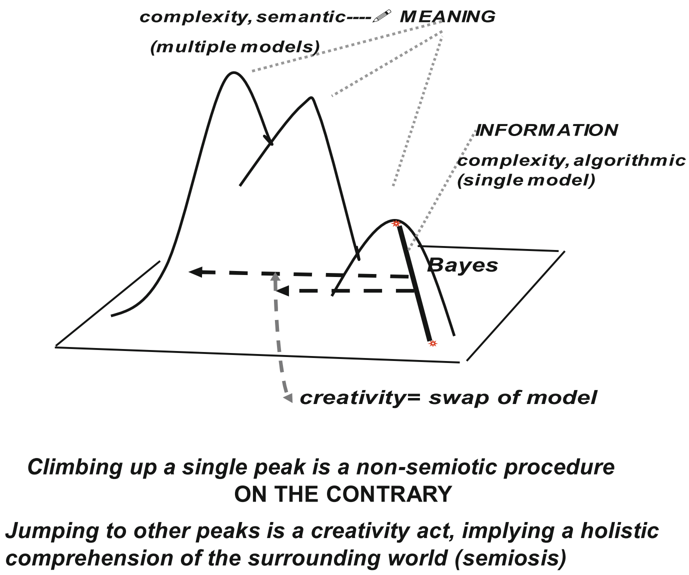

Fig. 8.3 Comparison of two different complexities, namely, (i) the algorithmic c., corresponding to the bit length of the program that enables the expert system to a recursive Bayes; and (ii) semantic c., corresponding to the occurrence of different models (provided they are countable); in fact they are not, because we will see that different meanings result from a quantum exploration

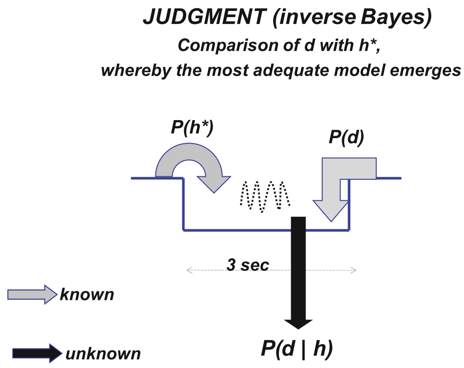

Fig. 8.4 The inverse Bayes procedure that occurs in linguistic endeavors, whereby a previous piece of a text is retrieved by the short-term memory and compared with the next one: the appropriate conditional is no longer stored permanently but it emerges as a result of the comparison (judgment and consequent decision)

(Grover 2001); (ii) introducing a fundamental uncertainty ruled by a quantum constant that yields a decoherence time fitting the short-term memory window.

The memory enhancement associated with linguistic flows is an exclusively human operation, not applicable to a cognitive agent that operates recursively, exploiting algorithms already stored in the memory. If the conjecture will be confirmed, the quantum mechanism would explain the a posteriori construction of novel interpretational tools.

Classifying the information content of spike trains, an uncertainty relation emerges between the bit size of a word and its duration. This uncertainty is ruled by a quantum constant that can be given a numerical value and that has nothing to do with Planck's constant. A quantum conjecture might explain the onset and decay of the memory window connecting successive pieces of a linguistic text. The conjecture here formulated is applicable to other reported evidences of quantum effects in human cognitive processes, so far lacking a plausible framework since no efforts to assign a quantum constant have been associated.

Models of quantum behavior in language and decision taking have already been considered by several authors but without a dynamical basis, starting 1995 (Aerts and Aerts 1995; Aerts 2009); and over the past decade (Khrennikov 2010). Most references are collected in a recent book (Busemeyer and Bruza 2012). None of these authors worries about the quantum constant that must replace Planck's constant.

However, a quantum behavior entails pairs of incompatible variables, whose measurement uncertainties are bound by a quantization constant, as Planck's in the original formulation of Heisenberg. One cannot apply a quantum formalism without having specified the quantum constant ruling the formalism. For this reason, all reported quantum attempts must be considered flawed, because (i) either they overlook the need for a quantization constant (Aerts and Aerts 1995; Aerts 2009; Khrennikov 2010), or (ii) use Planck constant and consequently arrive to very short decoherence times, incompatible with cognitive processes (Busemeyer and Bruza 2012; Penrose 1994; Hagan et al. 2002; Tegmark 2000).

After stressing in Sect. 8.3 the difference between (A)-perception and (B)-linguistic processes, we devote Sect. 8.4 to the quantum aspects of an interrupted spike train, that provide a non-Newtonian quantization suitable for the foundation of quantum linguistic processes.

8.3 Perceptions Versus Linguistic Processes

We have distinguished between two different cognitive processes, namely:

(A) Perception, whereby a sensorial stimulus is interpreted in terms of "models," or behavioral patterns, already stored in the long-term memory; the interpreted stimulus elicits a motor reaction; duration from a few hundred milliseconds up to 1 s; adequately described as a Bayesian procedure; common to all animals, and

(B) Linguistic processes, only human, whereby a sequence of pieces, coded as words of the same language, are sequentially presented to the cognitive agent; each piece is interpreted in terms of the previous one recovered by the short-term memory; such a comparison must be performed within 3 s; otherwise, the sequence must be repeated.

Focusing on (b), a decision, or judgment, is the interpretation of the last piece based upon the meanings of the previous one. Scanning all possible meanings of each piece entails a fast search process that requires a quantum search.

Plenty of approaches have tackled quantum-like aspects of language processing (Aerts and Aerts 1995; Aerts 2009; Khrennikov 2010; Busemeyer and Bruza 2012); however these approaches either did not discuss limitations due to a quantum constant, hence, they are purely formal without a physical basis or they refer to the quantum behavior of Newtonian particles (Penrose 1994; Hagan et al. 2002) and hence are limited by a coherence time estimated around 10–14 s. (Tegmark 2000; Koch and Hepp 2006) well below the infra-sec scale of the cognitive processes (Rodriguez et al. 1999).

8.4 A Novel Aspect of Quantum Behavior

Standard quantum physics emerges from the Newtonian physics of a single particle. Refer for simplicity to 1-dimension. The uncertainties of position x and momentum p obey the Heisenberg condition

$$\Delta x \Delta p \geq \hbar\,. \tag{8.1}$$

All quantum formalism is a consequence. For instance, comparison with the Fourier condition

$$\Delta x \Delta k \geq 1 \tag{8.2}$$

suggests the DeBroglie relation

$$k = p/\hbar \tag{8.3}$$

whence the single particle interference, which contains the only quantum mystery (Feynman 1966) and Schroedinger wave equation.

In the x, p space, instead of Euclidean points $\Delta x = 0$, $\Delta p = 0$, we have uncertainty rectangles; thus the uncertainty areas of two separate particles can overlap: this is the origin of entanglement.

Now, let us consider a non-Newtonian phenomenon consisting of a temporal train of identical spikes of unit area and duration τ_b = 3 ms (bin) positioned at unequal times. This is a sound model for the electrical activity of a cortical neuron (Rieke et al. 1996; Arecchi 2004a, b). The corresponding signal is a binary sequence of 0's and 1's, depending on whether a given bin is empty or filled by a spike. Spike synchronization, i.e., temporal coincidence of 0's and 1's, is considered as the way cortical neurons organize in a collective state (Singer and Gray 1995) (Fig. 8.5).

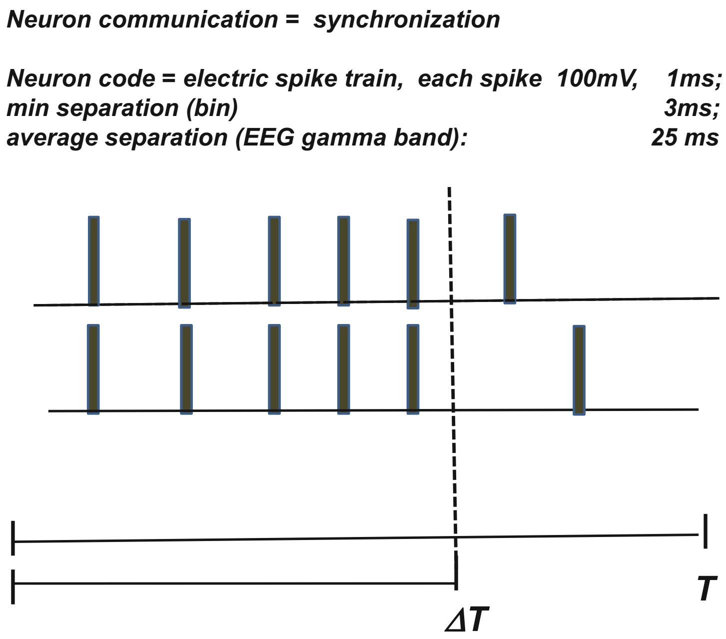

Fig. 8.5 Two spike trains of duration T, synchronized up to ΔT. The number of different realizations is $2^{(T-\Delta T)}$

Each cortical neuron has two ways to modify its spike occurrence, namely, either coupling to other cortical neurons or receiving signals from extra-cortical regions.

Let us take a processing time T = 300 ms, then, the total number of binary words that can be processed is $P_M = 2^{300/3} \cong 10^{33}$. At the end of a computational task, a decision center [called GWS = global workspace (Baars 1988; Dehaene et al. 2003)] picks up the information of the largest synchronized group and—based upon it—elicits a decision.

In the *perceptual* case (A), the cognitive action combines a bottom-up signal provided by the sensorial organs with a top-down interpretation provided by long-term memories stored in extra-cortical areas (Grossberg 1995).

In the *linguistic* case (B), the comparison occurs between the code of the second piece and the code of the previous one retrieved by the short-term memory. Here, we should consider a fact which so far had escaped a full explanation. Namely, spikes occur at average rates corresponding to the so-called EEG gamma band (say, around 50 Hz, that is, average separation 20 ms) (Rieke et al. 1996). However, superposed to the gamma band, there is a low-frequency background (theta band, around 7 Hz), which controls the number of gamma band bursts (Jensen and Colgin 2007). We show that interruption of a spike train introduces a quantum uncertainty, hence an entanglement among different words. This entanglement provides a fast quantum search of meanings that in classical terms would take a much longer time.

The theta-gamma cross-modulation corresponds to stopping the neural sequence at $\Delta T \leq T$. As a result, all spike trains equal up to ΔT, but different by at least one spike in the interval $T - \Delta T$, provide an uncertainty cloud ΔP such that (Arecchi 2003, 2004a, b):

$$\Delta P = 2^{(T-\Delta T)/\tau} = P_M 2^{-\Delta T/\tau} \tag{8.3}$$

Thus we have a peculiar uncertainty of exponential type between spike information P and duration T, that is,

$$\Delta P \cdot 2^{\Delta T/\tau} = P_M \tag{8.4}$$

By a variable change

$$y = 2^T \tag{8.5}$$

we arrive to a product-type uncertainty relation

$$\Delta P \Delta y = P_M \tag{8.6}$$

In the space (P, y) we have a Heisenberg-like uncertainty relation. Following the standard procedure of a quantum approach, we expect single-particle interference and two-particle entanglement in such a space

For ΔP = 1 (minimal disturbance represented by 1 spike) we have the *decoherence* pseudo time $\Delta y_d = P_M$.

The corresponding decoherence time (in bins) is

$$\text{decoherence} - \text{time} = \log_2 P_M \equiv 100 \cdot (\text{bins}) \tag{8.7}$$

and going from bins to sec:

$$\text{decoherence time} = 0.3\,\text{s} \tag{8.8}$$

very far from the naive value of 10^{-14} s evaluated for Newtonian particles disturbed by the thermal energy k_BT at T = room temperature (Tegmark 2000).

8.5 Conclusions

Innovations brought about by the linguistic processes in the brain: (1) The quantum constant for spike number–duration uncertainty has nothing to do with Planck's constant, a new type of quantum behavior has to be considered; spike synchronization is a peculiar physical process that cannot be grasped in terms of Newtonian position-momentum; (2) The energy disturbance which rules the decoherence time is by no means k_BT (k_B being Boltzmann constant and T the room temperature), but it is replaced by the minimal energy necessary to add or destroy a cortical spike. This energy corresponds to the opening along the axon of about 107 ionic channels each one requiring an ATP → ADP + P reaction involving 0.3 eV, thus the minimal energy disturbance in neural spike dynamics is around 108 k_BT (Arecchi 2004a, b). This is the evolutionary advantage of a brain: to live comfortably at room temperature and be barely disturbed, as it were cooled at 10^{-8} the room temperature.

As for the interpretation (hermeneutics) of a cognitive experience (be it perceptual or linguistic), we represent in Fig. 8.6 the procedural interpretation by a computing machine (CIRCLE) against that of any human language (COIL).

As for the *CIRCLE*, in information science, an *ontology* is a formal definition of the properties, and interrelationships of the entities that exist for a particular domain of discourse. An ontology compartmentalizes the variables needed for some set of computations and establishes the relationships between them. For instance, the booklet of the replacement parts of a brand of car is the ontology of that car. The fields of artificial intelligence create ontologies to limit complexity and to organize information. The ontology can then be applied to problem solving. Nothing is left out; we call this cognitive approach "finitistic" as nothing is left out beyond the description; no new LUX is provided by repeated trials.

On the contrary, in any human linguistic endeavor (be it literary, or musical or figurative) A starts building a provisional interpretation $A1$ of the text; whenever A returns to B, he/she has already some interpretational elements to start with, and from there A progresses beyond, grasping new aspects $B2$, $B3$ … and hence going

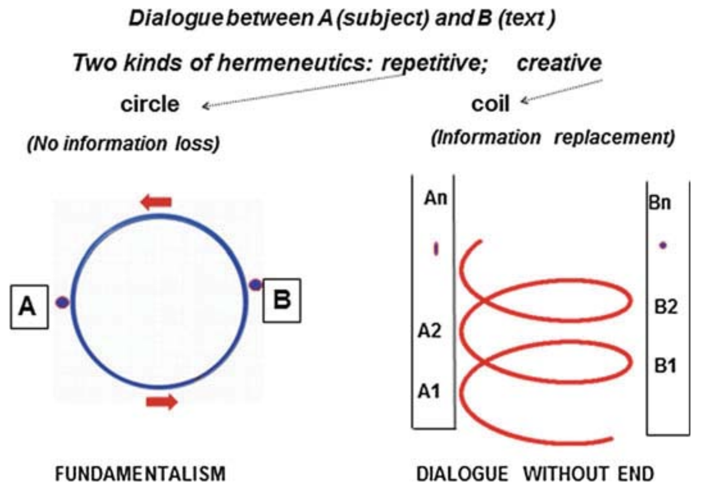

Fig. 8.6 Visual comparison between two kinds of interpretation of a text, or hermeneutics, namely, the CIRCLE, whereby the interpreter *A* attributes a finite and fixed set of meanings to the text *B*, and the COIL, whereby *A* captures some particular aspects of *B* and—based on that information—*A* approaches again the text *B* discovering new meanings. The novel insight provided at each coil is an indication of how LUX provides new semantic apertures

to *A*2 and so on (*COIL*). If *B* is not just a linguistic text, but another human subject, then *B* undergoes similar hermeneutic updates as *A*; this is a picture of the dialogical exchange between two human beings.

References

Aerts, D. (2009). Quantum structure in cognition. *Journal of Mathematical Psychology, 53*(5), 314–348.

Aerts, D., & Aerts, S. (1995). Applications of quantum statistics in psychological studies of decision processes. *Foundations of Science, 1*, 85–97.

Arecchi, F. T. (2003). Chaotic neuron dynamics, synchronization and feature binding: Quantum aspects TH. *Mind and Matter, 1*, 15–43.

Arecchi, F. T. (2004a). Chaotic neuron dynamics, synchronization and feature bindingc. *Physica, A, 338*, 218–237.

Arecchi, F. T. (2004b). *Caos e complessità nel viventeH*. Pavia: IUSS Press.

Arecchi, F. T. (2007). Complexity, information loss and model building: From neuro- to cognitive dynamics. In *SPIE Noise and Fluctuation in Biological, Biophysical, and Biomedical Systems* (pp. 6602–36).

Arecchi, F. T. (2012). Fenomenologia della coscienza: dall'apprensione al giudizio. in A. Ales Bello (Ed.) *…e la coscienza?Fenomenologia, psico-patologia, neuroscienze* (pp. 841–875). Laterza, Bari: Patrizia Manganaro.

Arecchi, F. T. (2013). La coscienza e il linguaggio: perché e come. Congetture quantistiche. In L. Urbani Ulivi (Ed.), *Strutture di mondo*, Vol. II, (pp. 199–226). Bologna: il Mulino.

Baars, B. J. (1988). *A cognitive theory of consciousness*. Cambridge: Cambridge University Press.

Busemeyer, J. R., & Bruza, P. D. (2012). *Quantum models of cognition and decision*. Cambridge: Cambridge University Press.

Dehaene, S., Sergent, C., & Changeux, J.-P. (2003). A neuronal network model linking subjective reports and objective physiological data during conscious perception. *Proceedings of the National Academy of Science (USA), 100*(14), 8520–8525.

Feynman, R. (1966), *The feynman lectures on physics,* Vol. III, Chapter 1.

Freeman, W., & Vitiello, G. (2006). Nonlinear brain dynamics as macroscopic manifestation of underlying many-body dynamics. *Physics of Life Reviews, 3*, 93–118.

Grossberg, S. (1995). The attentive brain. *American Scientist, 83*, 438–449.

Grover, L. K. (2001). From Schrödinger's equation to quantum search algorithm. *American Journal of Physics, 69*, 769–777.

Hagan S., Hameroff S. R., & Tuszynski J. A. (2002). Quantum computation in brain microtubules: Decoherence and biological feasibility. *Physical Review*, *65*(6).

Humboldt, W. (1836). *On language: On the diversity of human language construction and its influence on the mental development of the human species* (P. Heath, Trans.). Cambridge: Cambridge University Press, 1988.

Jensen, O., & Colgin, L. L. (2007). Cross-frequency coupling between neuronal oscillations. *Trends in Cognitive Science, 11*, 267–269.

Khrennikov, A. Y. (2010). *Ubiquitous quantum structure: From psychology to finance*. Berlin: Springer.

Koch, C., & Hepp, K. (2006). Quantum mechanics in the brain. *Nature, 440*, 611.

Penrose, R. (1994). *Shadows of the mind*. New York: Oxford University Press.

Pöppel, E. (1997). A hierarchical model of temporal perception. *Trends in Cognitive Sciences, 1*, 56–61.

Pöppel, E. (2004). Lost in time: A historical frame, elementary processing units and the 3-second window. *Acta Neurobiologiae Experimentalis, 64*, 295–301.

Rieke, F., Warland, D., de Ruyter van Steveninck, R., & Bialek, W. (1996). *Spikes: Exploring the neural code*. Cambridge: MIT Press.

Rodriguez, E., George, N., Lachaux, J. P., Martinerie, J., Renault, B., & Varela, F. (1999). Perception's shadow: Long-distance synchronization in the human brain. *Nature, 397*, 340–343.

Ronchi, V. (1957). *Optics. The science of vision*. New York: Dover Publications.

Singer, W., & Gray, C. M. (1995). Visual feature integration and the temporal correlation hypothesis. *Annual Reviews of Neuroscience, 18*, 555–586.

Tegmark, M. (2000). The importance of quantum decoherence in brain processes. *Physical Review*, E *61*, 4194–4206.

Turing, A. (1950). Computing machinery and intelligence. *Mind, 59*, 433–460.

Vitiello, G. (2001). *My double unveiled*. Amsterdam: John Benjamins.