Anatoly Nichvoloda

Quantum Uncertainty Reduction (QUR) Theory of Access and Phenomenal Consciousness

Abstract: *Consciousness is widely perceived as a phenomenon that poses a special explanatory problem for science. The problem arises from the apparent rift between immediate first-person acquaintance with consciousness and our inability to provide an objective/scientific third-person characterization of consciousness. In this paper, I outline a theory of perceptual consciousness called the 'Quantum Uncertainty Reduction (QUR)*[1] *Theory of Access and Phenomenal Consciousness'. The theory offers a functional solution to the hard problem of consciousness in terms of quantum information processing in a Bayesian-brain-inspired information processing system. I argue that the central aspect/step of information processing, namely, quantum uncertainty reduction, gives rise to qualitative properties of phenomenal and access consciousness.*

1. Introduction

From the outset I'd like to address the issue of using quantum theory to explain consciousness since quite a few philosophers and scientists have an aversion to these kinds of attempts because they think that one

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1 Pronounced 'cure'.

tries to explain one mystery in terms of the other. It is enough to peruse the *Stanford Encyclopedia of Philosophy*'s entry on 'Philosophical Issues in Quantum Theory' (Myrvold, 2017) to get an idea that, even though quantum theory is currently the most successful physical theory, there are profound issues with its interpretation. Thus, when quantum theory is used to illuminate problems of consciousness it feels that confusion only multiplies.[2]

I used to share that view and this project began as a straightforward attempt to use the Shannon communication theory of information in a way similar to Dretske's (1981), while enhancing it with ideas from research on Bayesian hierarchical predictive coding. However, as I tried to imagine a physical information processing mechanism that would naturally accommodate these ideas, three problems emerged. First, Shannon's notion of information is a probabilistic and quantitative measure of information that can be *associated* with many different physical processes. However, it says nothing about how information is encoded and processed in physical systems. Second, in spite of the success of Shannon's quantitative approach, it does not seem that conscious beings have experiences of quantitative and probabilistic measures of information. Rather, we are aware of information as content. Finally, investigation of physical information encoding and processing in a Bayesian-brain-inspired information processing system exposed conceptual limits of classical information theory, thus prompting the turn to quantum information theory. Quantum information and communication theory is a relatively recent but rapidly developing field and I use its central principles to argue that consciousness is a key aspect of quantum information processing in a computational mechanism.

2. Shannon Communication System with Two Sources of Information

According to Shannon and Weaver (1949, p. 31), 'The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point'. At its basic level the mathematical theory of communication is concerned with communication and primarily involves the quantitative study of

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2 For an excellent review of quantum approaches to consciousness see Atmanspacher (2015).

signals that are sent along a communication channel/system. As shown in Figure 1, the Informer (information source #1) generates a message, which is transmitted through a channel to the Informee (information destination). Along the channel, noise (information source #2) may interfere with the transmission of the original message, causing the Informee to decode the message in a way that differs from the sender's original intent.

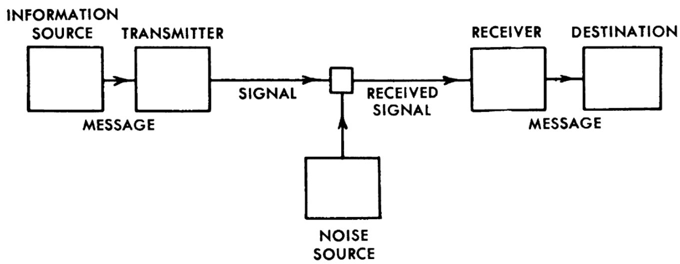

Figure 1. Schematic diagram of a general communication system (Shannon and Weaver, 1949, p. 7). According to Shannon and Weaver, '…the function of the transmitter is to encode, and that of the receiver to decode, the message' (*ibid.*, p. 17).

Information and uncertainty are technical terms that describe any process that selects one or more objects from a set of objects. Suppose we have a device that can produce/encode four symbols, A, B, C, or D. As we wait for the next symbol, we are uncertain as to which symbol it will produce. Once we see/decode a symbol our uncertainty decreases, and we note that we have received some information. In this regard, the Shannon information measure is a way to quantify a decrease of uncertainty or increase of information.

It is important to realize that the Shannon communication system is not just an abstract scheme, but also a functional blueprint for many physically realized information processing mechanisms. Physical instantiations of the Shannon communication system include many familiar electronic devices such as CD and DVD players, TVs, and radios. The important point for my discussion of information processing in the context of a predictive approach to perception is that, while information processing devices are often considered as passive receivers of information, they are, nevertheless, functionally organized to actively extract information from their respective information carriers, e.g. compact discs and electromagnetic waves. For example, in a CD player, the system '…relies upon detecting the momentary dips in the observed reflected light level which occur at the pit-land edges on the surface of CD' (Lesurf, 2001, p. 86). That is, the system projects a laser beam (uniform carrier wave) onto the spinning disc and a pattern of pits and lands of a CD modulates[3] the light. This modulated laser light is reflected into the optical pick-up of a player and after that it gets demodulated[4] by a series of electronic filters (e.g. diodes). These filters are tuned in such a way that they cut off the unmodulated parts of the signal carrier wave while letting the modulated parts go through. Thus, only the difference (or new information) between unmodulated laser light and modulated laser light makes it to the earphones of a CD player or information destination.

It is very important to note that, technically speaking, a CD's lands and pits serve as the source of noise that modulates the CD player's laser uniform carrier wave. That is, there are *two* sources of information that a CD player functionally implements. First, the CD player sends a uniform carrier wave from its laser (Informer) to its optical pick-up (Informee). Second, the disc's lands and pits serve as the source of information that modulates the original Informer's message and also gets delivered to the Informee. In effect, information that we as users of CD players are interested in is technically considered to be noise/modulation that interferes with communication between the Informer and Informee and it is in virtue of controlling the properties of the interference of a transmission through the information channel that communication of new information is achieved.

The import of the discussion of the Shannon communication system as a theoretical construct and as a physically instantiated mechanism is that, while Shannon information is essentially a quantitative measure of information, in order to be processed/manipulated information must be encoded into some physical signals (e.g. electric current) that are operated upon by certain kinds of mechanisms. In other words, quantitative measurement and abstract mathematical computations must be associated with a physical activity of information processing. The encoding of information in physical representations which are processed by a Shannon communication system-based mechanism is going to be the focus of my analysis in this paper.

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3 Modulation is the process of modifying the characteristics (frequency, amplitude, phase, etc.) of a carrier signal for the purpose of encoding the original message.

4 Demodulation is the process of recovery of the original message from the modulated carrier signal.

3. The Predictive Approach to Perception Implemented in a Bayes-Shannon Information Processing System

My ultimate goal is to explicate the nature of *access* and *phenomenal* consciousness in terms of two aspects of information processing/ computation in a mechanism. In order to do that I need to describe the structure of a Shannon communication system-based information processing system and its functioning, which, I will argue, gives rise to phenomenal and access consciousness while performing a teleological function of sensing and/or perceiving the environment. The suggested information processing mechanism (which I'll call a Bayes-Shannon system) is a predictive closed loop control circuit with negative feedback that is based on a Shannon communication system and incorporates the functionalities of Bayesian predictive coding (Friston, 2010a,b; Clark, 2013; Hohwy, 2012) and modal emulation (Grush, 2007):

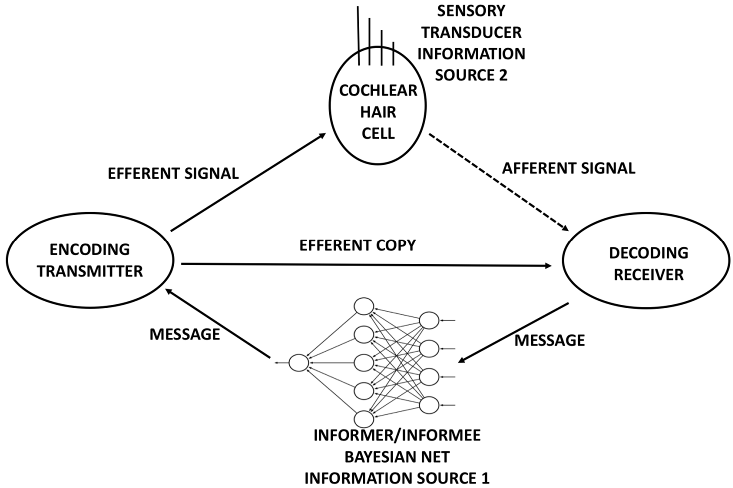


Figure 2. A Bayes-Shannon system: predictive closed loop control circuit with negative feedback.

The goal of this system is to control the behaviour of a sensory transducer (e.g. cochlear cell) by correctly predicting/emulating its physical states and, therefore, correctly predicting environmental stimuli associated with the states of the transducer. Modal emulation, according to Grush (2007, p. 400), is an adaptation of ideas developed in linear control theory centred around a Kalman filter (see, for example, Kalman, 1960; Kalman and Bucy, 1961; Bryson and Ho, 1969). Modal emulators are causally connected with their respective processes or plants, local environment, and other factors of a physical nature and can be construed as sensory-modality-specific dynamic models of the environment that predict the behaviour of sensory transducer inputs based on previous experience and current sensory feedback. In other words, a modal emulator is a device that attempts to implement an identical input–output signal functional dynamic as the plant (e.g. sensory transducers of a sensory modality) in terms of the plant's physical states.

A Bayesian neural network in the suggested mechanism performs a negative feedback function similar to Friston's minimization of free energy formulation of predictive coding. According to Friston (2010a), predictive coding is a neurobiologically plausible Bayesian filtering scheme that decomposes the optimization of the agent's model of the world into two tractable components: changes in expectations about the sensory inputs and computation of prediction errors that are needed to change expectations. At the core of the free energy principle is the system's goal to maximize model evidence or minimize surprise where perception makes free energy a good proxy for surprise that, under simplifying assumptions, can be reduced to prediction error.

In the suggested system a Bayesian neural network functions as the Informer (information source #1) and also, importantly, the Informee (destination of information). The first step in perceptual information processing involves the formulation of a prediction of a state of the sensory transducer by the Bayesian net (information source #1) and its encoding by an encoding transmitter into an efferent signal in terms of a suitably variable physical property, e.g. amplitude of electric current. This encoded prediction/message anticipates/emulates the properties of the sensory transducer's actual states that the system expects to register at the transducer. The signal carrying the encoded prediction from the encoding transmitter to the sensory transducer is called the 'efferent signal', while the signal carrying the prediction (after it has interacted with the transducer) to the decoding receiver is called the 'afferent signal'. The system also retains a copy of an efferent signal (the 'efferent copy'), which is sent directly to the decoding receiver to be compared with the corresponding afferent signal. Thus, a given prediction encoded into an efferent signal is sent through the information channel between the encoding transmitter and the decoding receiver via a sensory transducer. If the predicted state of the transducer is different from its actual state, the signal is modulated by the transducer/environment (information source #2). If the predicted state of the transducer is the same as the actual state, then the signal passes through the transducer unchanged. Once a given afferent signal arrives at the decoding receiver it is compared with the corresponding efferent copy signal carrying the initial prediction and either perfect correlations or differences/prediction errors, or a mixture of both, are observed between the two signals' amplitudes. These correlations and differences serve as inputs taken up by the Bayesian net which performs a negative feedback operation (prediction error minimization) on the signal and issues a new prediction which begins a new cycle.

The description of the function of a Bayes-Shannon system resembles the Bayesian neural network's function in Friston's free energy principle formulation. However, while the Bayesian brain hypothesis is one of the concepts that inspired this theory, there are several important differences between Friston's and my approach. First, free energy is an abstract information-theoretic quantitative measure, whereas my focus is on information encoding and manipulation in physical systems. Second, according to Friston (2010a), prediction errors (for which free energy is a proxy) must be minimized, while on this construal perfect correlations and differences between physical aspects of signals that encode information in prediction and feedback must be controlled/optimized. That is, free energy is seen as an undesirable quantity, while in my formulation differences/prediction errors that carry information are essential/desirable for the functioning of the Bayes-Shannon system in its goal to perceive the environment. Finally, (variational) free energy, like the Shannon information measure, involves an averaging of expectations, whereas differences/prediction errors and perfect correlations controlled by the suggested mechanism are observed at the decoding receiver every information processing/computational cycle similar to Ellison, Mahoney and Crutchfield's (2009) temporally indexed specific information measure that is computed over a single use of a communication channel. The idea behind specific information-theoretic measures, according to Beer and Williams (2015, p. 7) is to '…unroll such [Shannon information] averages in order to quantify the information that one random variable provides about each specific outcome of another, providing a more fine-grained analysis of informational relationships'.

4. Computation as Information Manipulation/Processing in Mechanisms

Alonzo Church, Kurt Gödel, Alan Turing, and John von Neumann were among the first architects of the theory of computation. They were mathematicians, and mathematical computational concepts refer to abstract objects that do not exist in time and space and do not enter into causal transactions. So, if computation is a mathematical notion, it seems to be misguided to enquire into the nature of concrete/ physical computation. However, while computation is an abstract notion, physical systems are required to perform computations.

According to Piccinini (2007; 2008; 2015) and Miłkowski (2013; 2016), physical computation is best understood as the operations of mechanisms. Piccinini and Miłkowski argue that mechanistic explanation is a species of causal explanation, and explaining a mechanism involves the discovery of its causal structure. The core idea is that mechanisms are organized systems, which consist of causally relevant component parts, the orchestrated operation of which implements the capacity of the mechanism. According to Miłkowski:

> To say that a mechanism implements a computation is to claim that the causal organization of the mechanism is such that the input and output information streams are causally linked and that this link, along with the specific structure of information processing, is completely described… Importantly, the link might be cyclical and as complex as one could wish. (2016, p. 193)

Miłkowski (2013) argues that the computational theory of mind should be understood literally since only in this way can computer models of the mind be exposed to scientific testing. In other words, 'computer models, rather than serving as mere demonstrations of feasibility or loose metaphors of cognitive processes, have to live up to the standards of scientific investigation when treated literally' (Miłkowski, 2013, p. 26). Moreover, computational processes are natural kinds for science and so is information: 'The world contains structural-information-content… before it gets into the cognitive system' (*ibid.*, p. 156). In other words, information in some objective sense is out there in the world before it enters into cognitive systems, which process, store, and act on information. According to Piccinini (2015, p. 10), a computational explanation is a special case of mechanistic explanation, and a physical computing system is a mechanism whose teleological function is to perform a physical computation by manipulating a medium-independent vehicle according to a rule.

5. Information Representation and Manipulation by Medium-Independent Vehicles

‘The intuitive test of the applicability of computational explanation is to ask whether the process under consideration might be realized *the same way* in a different information-processing medium’ (Miłkowski, 2013, p. 93, emphases in original). A medium-independent vehicle is a vehicle defined in terms of differences between different portions of the vehicles along a relevant dimension (e.g. voltage of electric current, water or air pressure, etc.), and not in terms of any of its more specific physical properties (e.g. thunder and lightning are defining features of thunderstorms). In other words, vehicles are medium-independent if and only if the rule (i.e. the input–output map) that defines a computation is sensitive only to differences between portions of the vehicles along specific dimensions of variation and it is not sensitive to any more concrete physical properties of the vehicles (Piccinini, 2007, pp. 510–11). Thus, medium-independent vehicles can be implemented in different physical media that have similar functionally relevant degrees of freedom, that is, the same information processing that is done in regular computers by manipulating voltage of electric current can, in principle, be performed by manipulating water or air pressure.

Piccinini and Bahar (2013, p. 459) define the atomic vehicles of concrete digital computation as ‘digits’, where ‘a digit is a macroscopic state (of a component of the system) whose type can be reliably and unambiguously distinguished by the system from other macroscopic types’ (*ibid.*). Digits must be unambiguously distinguishable by the processing mechanism under normal operating conditions in order to ensure reliable manipulation of digits based on their type since a physical system can manipulate at most a finite number of digit types.

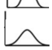
According to Piccinini (2007, p. 507), a computing mechanism may be described as performing elementary/atomic computations when its inputs and outputs are digits, and the relation between inputs and outputs may be characterized by a simple logical relation. The notion of mechanistic explanation applies to ordinary computers and other computing systems in a way that matches the language and practices of computer scientists and engineers.[5] In designing computing

[5] Piccinini (2007, p. 507) refers to Patterson and Hennessy (1998) for a standard introduction to computer organization and design.

mechanisms, not any wiring between components will do, because the components must be arranged so that it is clear where the input digits come in and where the output digits come out.

According to Piccinini and Bahar (2013, p. 459), digits need not mean or represent anything, but they can. I suggest that in the context of a Bayes-Shannon system a digit can be defined as a representation of an ecologically valid/significant state of a sensory transducer encoded in some suitable physical property, e.g. voltage amplitude variation of electric current.[6] The general goal of an auditory transducer (cochlear cell), for example, is to convert pressure waves of air vibrations into signals that can be processed by the brain, thus through mechanotransduction[7] cochlear hair cells detect movement in their environment since, according to Grigg (1986), stimulation of a mechanoreceptor causes mechanically sensitive ion channels to open and produce a transduction current that changes the membrane potential of the cell. Depending on the movement in the environment, a mechanoreceptor can either hyperpolarize or depolarize (Gillespie and Walker, 2001). These electrochemical states of a sensory transducer interact with the electric current of the efferent signal and encode the transducer's states into the current in terms of different amplitudes of the electric current's voltage corresponding to different states of the transducer.

To demonstrate how the encoding of digits would work in a Bayes-Shannon system, let's assume the transducer measures sound intensity and has four ecologically valid states: maximum intensity, 2/3 of maximum intensity, 1/3 of maximum intensity, and no intensity. These states would be encoded in the amplitude variations of the voltage of the electric current as the following digits:

1. Maximum intensity: 
2. 2/3 of maximum intensity: 
3. 1/3 of maximum intensity: 
4. No intensity: 

[6] Here I follow Bechtel's notion of information representation in James Watt's centrifugal governor where the governor's arm angles stand in for the speed of the flywheel and can regulate the valve opening because they carry this information (Bechtel, 2008, pp. 189–90).

[7] Mechanotransduction is any of various mechanisms by which cells convert a mechanical stimulus into electrochemical activity (Grigg, 1986).

Thus, a given value of the sound pressure wave causes a certain electrochemical state of the transducer that modulates an efferent (input) signal and transforms it into an afferent (output) signal by encoding the current state of the transducer in the amplitude of the electric current in terms of a corresponding digit:

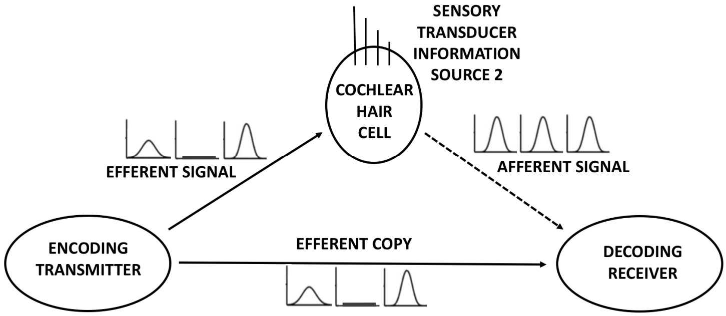


Figure 3. Sensory transduction as encoding digits into an efferent signal that carries initial expectations.

In Figure 3, the efferent (sensory transducer input) signal contains a prediction string of three digits: 'maximum intensity', 'no intensity', and '1/3 of maximum intensity'. The transducer registered three 'maximum intensity' digits and encoded this string into the afferent (output) signal. Thus, the transducer has manipulated digits by performing an operation of erasing the digits representing the original prediction string from the efferent signal and writing the digits that represent its actual states into the afferent signal. In other words, the transducer performed an elementary/atomic digital information processing/manipulation or computation.

A perfect correlation between relevant physical properties of the two digits being compared at the decoding receiver encodes the correlation of information content between predicted and registered states of the sensory transducer. Correspondingly, a difference (imperfect correlation) between physical properties of digits being compared encodes a difference in information content between predicted and registered states of the sensory transducer. Thus, if the two digits are identical then a perfect signal correlation and, therefore, perfect information correlation is observed at the decoding receiver. However, if the two digits are different then there will be a certain difference observed between them:

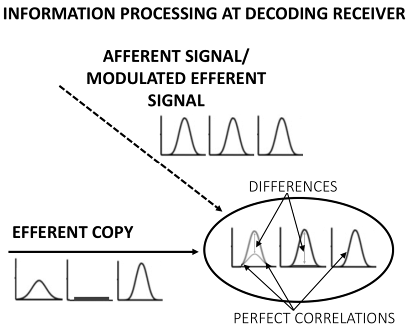


Figure 4. At the decoding receiver the physical properties of the digits are compared and certain correlations and differences emerge.

In the context of a Bayes-Shannon system, digits can be considered as encoded values of a classic random variable whose probabilities are controlled/determined by two sources of information: Bayesian net/ perceiver and sensory transducer/environment. Going forward I'll call these values 'classical digits'. In the next section I argue that perfect correlations between classical digits registered at the decoding receiver encode classical information while imperfect correlations encode quantum information.

6. Classical and Quantum Information Processing in a Bayes-Shannon System

The information processing cycle in a Bayes-Shannon system starts with a Bayesian net producing a prediction that's encoded by the encoding transmitter in terms of two perfectly correlated classical digits: the efferent signal digit and the efferent copy digit. After an efferent signal digit has interacted with the sensory transducer and turned into an afferent signal digit, but before the afferent signal digit and the corresponding efferent copy digit are compared at the decoding receiver, the comparison/observation results are in a superposition of two possible states: 'difference' and 'no difference'. That is, in a Bayes-Shannon system an interaction of an efferent signal digit with the sensory transducer/environment introduces uncertainty regarding whether there was a change of the original efferent signal digit encoded by the sensory transducer into the corresponding afferent signal and, correspondingly, whether a perfect correlation or a difference (imperfect correlation) between the information carrying properties (in this case amplitude) of digits of the afferent signal and efferent copy is going to be registered/observed at the decoding receiver.

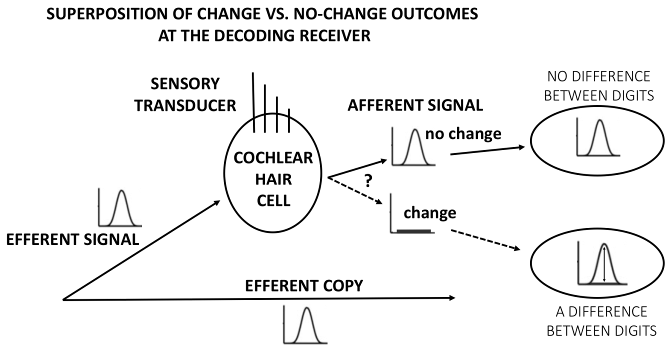


Figure 5. Superposition of difference vs. no-difference outcomes registered at the decoding receiver depending on whether the efferent digit was changed by the sensory transducer.

The act of comparing the two classical digits at the decoding receiver, in the context of a Bayes-Shannon system as a perceptual mechanism, collapses the superposition between two possible observation outcomes: a perfect correlation between the digits if no change occurred at the sensory transducer and a difference/prediction error between the two compared digits if the sensory transducer replaced an input efferent digit with a different one. When a perfect correlation is observed between an afferent signal digit and the corresponding efferent copy digit this means that the Bayes-Shannon system performed classical information communication from the sensory transducer/environment to the decoding receiver/perceptual system. However, when imperfect correlations are observed between an afferent signal digit and the corresponding efferent copy digit, the Bayes-Shannon system performed quantum information communication. Such information communication is quantum because for classical communication a perfect correlation/match between the sent and received digits must be registered. So, if a Bayes-Shannon system was equipped with a classical decoding receiver, upon registering a mismatch between an afferent signal digit (e.g. ‘maximum intensity’) and a corresponding efferent copy digit (e.g. ‘no intensity’), such a decoding receiver would then make a note of a mismatch, discard the ‘no intensity’ digit, and proceed to compare the afferent signal digit ('maximum intensity') with one of the remaining digits from the list of available digits ('maximum intensity', '2/3 of maximum intensity', '1/3 of maximum intensity') until it finds a perfect match. In other words, a classical decoder would have to match each available digit one after another, thus performing more information processing steps (on average) in order to achieve communication of information from the sensory transducer to the decoding receiver than the number of steps that would have to be performed in quantum communication.[8]

In a Bayes-Shannon system the decoding receiver accomplishes this goal in just one step by comparing the two classical digits and registering perfect and/or imperfect correlations between them. Since classical digits are encoded in particular patterns of some physical property (e.g. amplitude of the electric current) then a unique difference will be observed between any two different classical digits at an instance of decoding/comparing. Such unique differences would repeatedly appear between pairs of different classical digits over multiple uses of a Bayes-Shannon system thus carrying information about any two classical digits and their particular relationship to each other. Thus, in a Bayes-Shannon system, quantum information can be conceptualized as information about classical information, and repeating patterns of differences between classical digits could be considered as quantum digits that encode quantum information. This property of quantum digits might be responsible for an effect where quantum communication can carry more than 100% of classical information (Vedral, 2010, pp. 128–9) and, along with one-step decoding, it can contribute to quantum speed-up in quantum information processing.[9]

More formally, it appears that a Bayes-Shannon system implements an information processing algorithm that is inverse of the dense coding algorithm. According to Bennett and Wiesner, in dense coding:

> Alice, the intended receiver of the message, first prepares a pure EPR state and lends one particle of the pair to Bob, the intended sender. Bob then operates on the particle via one of four unitary operators so as to put the two-particle system into a chosen one of the four states… and then returns the treated particle to Alice. Now possessing both particles,

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8 For an introductory discussion of the difference between classical and quantum information processing see Vedral (2010, pp. 140–3).

9 'Quantum speed-up' refers to the higher efficiency of quantum algorithms with respect to their classical equivalent. For an introductory discussion see Vedral (2010, pp. 142–4), for a more technical treatment see Castagnoli (2010).

> Alice can in principle measure them jointly in the orthonormal basis…, and so reliably learn which operator Bob applied. (1992, p. 2883)

That is, the dense coding algorithm consists of three distinct parts: the EPR[10] source (Alice) generating entangled photons in a well-defined state, Bob's station for encoding the messages by a unitary transformation of his particle, and Alice's coincidence logic analyser to extract classical information from the signal sent by Bob back to Alice:

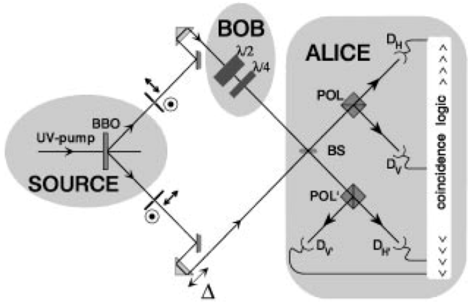


Figure 6. Dense coding algorithm. Reproduced with permission from Mattle *et al.* (1996, American Physical Society).

The dense coding algorithm implements what Schumacher and Westmoreland (2010, p. 152) call Type II quantum communication, in which

> …quantum information lies in the entangled state of system Q and a 'bystander' system R, which does not participate in the communication process but merely serves as an 'anchor' for the entanglement carried by Q… (*ibid.*, p. 152)

According to Schumacher and Westmoreland, Type II quantum communication is not so different from classical communication:

> If Alice sends a bit *b* to Bob, what does it mean operationally to say that bit *b'* received by Bob is correct? This presumes the potential existence of a 'reference bit,' a fiducial copy of *b* to which *b'* may be compared. Alice, for example, could retain her own copy of the transmitted message, and later on this can be compared with Bob's version. The

10 EPR refers to an Einstein, Podolsky and Rosen (1935) paper where they used an entangled pair of particles to argue that quantum theory was incomplete since it seemingly allowed superluminal information communication.

> [classical] communication is accurate provided the two bits are properly correlated. In quantum communication we cannot make and keep copies, but the bystander system R plays a similar role. The quantum communication from Alice to Bob is successful provided R and Q' are properly correlated (i.e., in the correct entangled state). (*ibid.*, p. 152)

Similarly to dense coding, an algorithm implemented by a Bayes-Shannon system has three distinct parts: the source of perfectly correlated classical digits (Alice), the sensory transducer station for encoding the states of the environment by manipulating efferent digits into afferent ones (Bob), and the decoding receiver that decodes what digits have been transmitted from the environment to the system relative to the initial expectation (Alice). While the general set-up is quite similar, there are important differences between dense coding and a Bayes-Shannon system's algorithm. (1) In the dense coding algorithm, Alice uses a pair of EPR entangled particles (quantum systems) while a Bayes-Shannon system starts with two perfectly correlated classical digits. In other words, in dense coding the EPR pair serves as a resource for information communication while in a Bayes-Shannon system this function is performed by a pair of perfectly correlated classical digits. (2) In dense coding, Alice always issues the same prediction about Bob's state while a Bayes-Shannon system can issue different predictions about the state of the sensory transducer depending on the perceptual goals of the system. Further, an initial prediction digit serves not only as a 'reference bit'[11] but also context for decoding of communicated information. (3) The last step in dense coding, coincidence logic analysis, outputs Shannon-type quantitative information while, in contrast, a Bayes-Shannon system's algorithm outputs either classical or quantum information or both encoded in perfect and/or imperfect physical correlations between an afferent signal digit and a corresponding efferent copy digit.

Let's suppose, for example, that the transducer erased the original digits 'maximum intensity', 'no intensity', and '1/3 intensity' and wrote three 'maximum intensity' digits instead. The decoding receiver will register a perfect correlation of classical digit's amplitudes (100% classical information) for the first pair of digits, 100% imperfect/ quantum correlation (no overlap of classical digits' amplitudes) for the

11 One, of course, should always keep in mind that bits are quantitative units of information measurement while digits in a Bayes-Shannon system are representations of the states of the sensory transducer. However, for the purpose at hand they both perform the same function of reference against which decoding takes place.

second pair, and a mix of classical and quantum correlations for the third pair (partial overlap of classical digits' amplitudes):

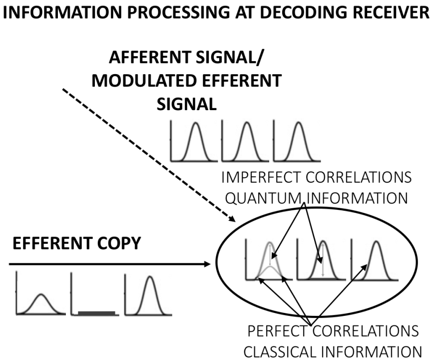


Figure 7. Quantum uncertainty reduction at the decoding receiver by comparing physical properties that encode digits in a given afferent signal digit and a corresponding efferent copy digit.

Quantum uncertainty reduction, in the context of a single use of a Bayes-Shannon mechanism, is an episode/instance at the decoding receiver when relevant physical properties of an afferent signal digit (encoding an actual state of the environment) and a corresponding efferent copy digit (encoding an initial system's expectation) are compared. At the moment of comparison, the superposition between 'difference' and 'no-difference' at the decoding receiver is collapsed and information about how the sensory transducer/environment has modulated the initial prediction is obtained. This information is encoded in terms of perfect or imperfect or mixtures of correlations between physical properties that encode the compared digits. What we get as a result of decoding is the extent to which the physical properties that encode the two digits overlap/match (perfect correlation encodes classical information) and/or differ/diverge (imperfect correlation encodes quantum information). The reduction of uncertainty at the decoding receiver in terms of two kinds of correlations — perfect (no difference between the two compared digits) or imperfect (a difference between the digits), or both[12] (a certain part of total information was transmitted by perfect correlation while the rest by

12 In other words, the decoding receiver implements 'inclusive or' logic gate/operation.

imperfect correlation) — is central to my approach to explicating phenomenal and access consciousness.

7. Phenomenal Consciousness is Quantum Information and Access Consciousness is Classical Information Registered/Observed at the Decoding Receiver

The notions of phenomenal and access consciousness were initially introduced by Block (1995) where he identifies phenomenal consciousness as consciousness that defies characterization in 'cognitive, intentional, or functional terms' (Block, 1995, p. 381). Phenomenal consciousness is a 'pre-theoretic' notion characterized by mental states that have *qualia* or something it is like for the subject to be in or what it is like to have an experience. According to Chalmers (1996), confusing this kind of consciousness with one of the others leads to the false sense that the mystery of consciousness is easily solvable by the methods of a functionalist cognitive science or neuroscience, which deal in cognitive, intentional, and functional explanations. On the other hand, the properties of access consciousness can be characterized as 'easy problems of consciousness' (influencing behaviour by flexibly interacting with the beliefs, desires, and goals of a creature) since they '…seem directly susceptible to the standard methods of cognitive science, whereby a phenomenon is explained in terms of computational or neural mechanisms' (*ibid.*, p. 200). In this paper, I'm going to use the formulation of consciousness as a mongrel concept, however I argue that both phenomenal and access consciousness are two kinds of information processed by a Bayes-Shannon perceptual system and, consequently, both the easy and hard problems of consciousness have an information processing/functional solution.

Based on the information processing dynamic in the Bayes-Shannon system outlined in Sections 5 and 6, and a distinction between two aspects of consciousness, I can now formulate the hypothesis about the nature of phenomenal and access consciousness:

> Phenomenal consciousness in the context of quantum uncertainty reduction taking place over a single use of a Bayes-Shannon system is an instant of observation of quantum information encoded in differences/imperfect correlations between a given afferent signal digit and a corresponding efferent copy digit. Access consciousness is an instance of observation of classical information encoded in perfect correlations between the two digits.

Thus, the information processing picture of Figure 7 gives the following first-person perceptual picture (Figure 8). A quantum uncertainty reduction episode of comparing the first pair of digits results in 100% access consciousness; comparing the second pair of digits results in 100% phenomenal consciousness; and the third pair produces some balance of access and phenomenal consciousness:

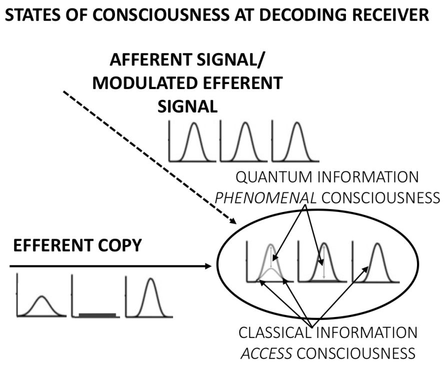
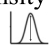


Figure 8. Quantum uncertainty reduction at the decoding receiver registers/observes access consciousness as classical information and phenomenal consciousness as quantum information.

7.1. Information encoding in terms of quantum digits implements qualitative aspects of phenomenal consciousness

Digits that carry classical information are encoded by unique patterns of some physical property, e.g. amplitude of the electric current. If the actual state of the transducer is different from a predicted one, at the moment of decoding/comparing of classical digits there will be unique differences that encode quantum information observed at the decoding receiver. Such differences would repeatedly appear between certain pairs of classical digits over multiple uses of a Bayes-Shannon system. In other words, repeating patterns of differences between physical properties that encode classical digits would give rise to digits that carry quantum information. For example, every time one of the classical digits being compared is 'maximum intensity' and another is 'no intensity' a particular difference will always be observed at the decoder: . Another particular difference will be observed when the compared digits are 'maximum intensity' and '1/3 of maximum intensity': , and so on for all other possible classical digit combinations that produce differences when compared. Thus, the differences between the physical properties that encode information in classical digits can be considered as digits that encode quantum information. In the case when the following classical digits 'maximum intensity' and '1/3 of maximum intensity' are encoded in amplitudes of an electric current's voltage, the quantum digit that arises as the difference between the two classical digits would be encoded as a difference between amplitudes of the two currents' voltages. I suggest that it is this way/manner of quantum information encoding in terms of particular differences between physical properties of digits that carry classical information that instantiates/implements (is responsible for) the qualitative nature of phenomenal consciousness. When, on the other hand, the two classical digits are perfectly correlated (classical information communication), there is no difference between the digits' physical properties registered at the decoding receiver and, therefore, an instance of access consciousness occurs with the corresponding absence of qualitative properties. Importantly, not just any difference between two random physical properties will have the qualitative feel of phenomenal consciousness, rather, physical properties must serve the function of classical digits and differences between them must serve the function of quantum digits.

Thus, I suggest that the proposed formulation of phenomenal consciousness offers a functional solution to the hard problem of consciousness, which, according to Chalmers (1996), is the most elusive problem in the study of consciousness. The hard problem of consciousness is the problem of explaining why experience comes about, how and why the subjective aspect of our experience arises from the processing of neural interactions. QUR theory offers an information processing/computational answer to the hard problem, since, *ex hypothesi*, phenomenal experience comes about in the context of a subject's perceptual information processing system interacting with the environment in terms of quantum information. To emphasize, in this functional solution it doesn't matter whether classical digits are encoded in properties of e.g. electric current, water current, or air pressure, since, if the operation of decoding gives rise to an identical imperfect correlation (difference) between correspondingly implemented classical digits, according to this view, that difference would encode the same quantum digit and, therefore, would have the same qualitative feel to it.

7.2. Zero-sum and hierarchical relationship between quantum and classical information

The four classical digits in the system, discussed in Section 5 above, can give rise to different degrees/ratios of perfect and imperfect correlations between digits within two limit cases. Limit case 1: all information between the two digits is carried/encoded by a classical perfect correlation. Limit case 2: all information between the two digits is carried/encoded by a difference/imperfect quantum correlation. Thus, in limit case 1 (the first pair of digits at the decoding receiver in Figure 8), perception of the environment state that registers 'maximum intensity' digit at the sensory transducer would be decoded exclusively in terms of a perfect classical correlation and, therefore, observed/experienced in terms of 100% access consciousness. In limit case 2 (the second pair of digits at the decoding receiver in Figure 8), perception of the same event at the sensory transducer (encoded by a 'maximum intensity' digit) would be decoded exclusively in terms of a difference/imperfect correlation and, therefore, observed/experienced in terms of 100% phenomenal consciousness. Importantly, the two different observation results were determined by the interaction of the same environmental state of 'maximum intensity' with two different original expectations of 'maximum intensity' and 'no intensity'. The third pair of digits at the decoding receiver, 'maximum intensity' and '1/3 of maximum intensity', partially overlap and partially diverge, thus carrying the total information in a mixture of both kinds of correlations: perfect and imperfect. Thus, it appears that in the course of a single use of a Bayes-Shannon system if a certain part of the information is carried by a perfect correlation then it cannot be carried by an imperfect correlation and vice versa. In other words, perfect and imperfect correlations observed at the decoding receiver are in a zero-sum relationship and, therefore, it appears that the qualitative aspects of access and phenomenal consciousness also share the same zero-sum relationship.

However, conceptually, classical and quantum information don't seem to share this relationship, but rather have a hierarchical relationship. Since a given quantum digit is encoded as a unique difference between two particular classical digits it carries information about a particular relation between two classical digits. This means that a single digit of quantum information carries information about two digits of classical information, or, in other words, quantum information is information about classical information. This construal fits

Shrödinger's views of the quantum description of reality, who, according to Bub (2016, p. 208), thought about it like the sort of description provided by 'a shaky or out-of-focus photograph' where some information is lost, or, in other words, an *incomplete* description of something quite *definite*. In other words, a quantum digit (phenomenally conscious experience) carries only the difference relationship part of the total information that the system registers, and for the description to be complete it also must account for information carried by classical digits.

Further, on a more speculative note, one might argue that this property of quantum information (namely, that one quantum digit carries information about two classical digits) contributes to quantum computational speed-up in quantum computers relative to classical ones. If this is correct, then this property of quantum information offers a computational answer to the question of why it is advantageous for a system/creature to perceive its environment phenomenally consciously vs. non-phenomenally. According to this formulation, phenomenally conscious (quantum information) processing allows for more information to be acquired and processed faster (with fewer computational steps), thus giving a phenomenally conscious creature that performs quantum information processing an important computational advantage over a non-phenomenally conscious one that performs classical information processing. Also, this property of quantum information may account for some aspects of meta-cognitive properties usually ascribed to consciousness.

8. Arguments For and Objections to the QUR Theory of Consciousness

8.1. Argument from overlearning and attention

In the context of the Bayes-Shannon system implementing only the prediction error minimization principle, a stimulus that was initially completely phenomenally conscious will gradually become less and less phenomenally conscious and more and more access conscious. This dynamic appears to correspond to the commonly observed phenomenon when frequently practised tasks or regularly observed stimuli seem to gradually fade from consciousness, that is, the qualitative content of phenomenal consciousness (or a combination of phenomenal and access consciousness) gives way to non-phenomenal content of access consciousness. Examples of this dynamic include many overlearned phenomena like learning to ride a bicycle, drive a car, etc. — cases where initially highly phenomenally conscious awareness is gradually replaced by access conscious awareness, a condition that Langer and Imber (in Baars, Banks and Newman, 2003, p. 643) call ‘mindlessness’.

There is a substantial amount of empirical research showing that perceptions, ‘…though initially conscious, become, by some process such as overlearning, automatic and unconscious’ (Baars, Banks and Newman, 2003, p. 19). According to Langer and Imber (*ibid.*, p. 643): ‘When an individual first approaches a task she/he is necessarily attentive to the particulars of the task. With each repetition of the task, less and less attention to those particulars is required for successful completion of that task.’ They conclude that learning in a sense is learning what elements of the task may be consciously ignored:

> It would seem from their daily interactions that most people in the world are aware that overlearning serves this function, since they appear to be constantly adding familiarity, predictability, and structure to their lives, which facilitate overlearning. (*ibid.*, p. 660)

Thus, to the extent that regular humans overlearn everyday routines and become less and less phenomenally consciously aware of considerable perceptual tasks involved in e.g. walking, biking, and even articulating sentences, they can be considered, at least partially, to be philosophical zombies — creatures physically identical to us that nonetheless lack phenomenal consciousness. According to the view developed here, the situation regarding phenomenal vs. non-phenomenal aspects of perception is more complicated. On the one hand, human beings are not perfect predictors of the environment, which closes off the possibility of us becoming 100% philosophical zombies. On the other hand, partial zombiehood is actually beneficial since overlearning and expert perception point to the ecological desirability of non-phenomenal perception. In other words, since we are essentially information processing creatures our highly variable environment (in the form of exogenous attention) and ability to endogenously focus on different aspects of the environment preclude the phenomenal lights of our consciousness from going out completely. That is, the prediction error minimization principle, according to this account, while being important, is just a part of the more comprehensive story.

As I argue in Nichvoloda (2019), endogenous attention can selectively reverse the effects of attenuation for selected stimuli in the context of a Bayes-Shannon system’s process of prediction error minimization and thus bring any stimulus into a contextually appropriate and cognitively salient balance of phenomenal and access consciousness. Such endogenous attention can be implemented by negative feedback on the initial negative feedback mechanism that implements prediction error minimization. Thus, the idea of prediction error control (PEC) by double negative feedback enables a hierarchical Bayes-Shannon system to selectively attenuate error minimization in a controlled, precise, and contextually salient way, which we normally call endogenous attention.

8.2. Objection: Consciousness doesn't seem to be digital/discrete

On this formulation the functioning of a Bayes-Shannon system is conceived as a continuous series of predictions, encodings, transmissions, and decodings that give rise to observational outcomes in terms of phenomenal or access consciousness, or both. Thus, both kinds of consciousness are defined as episodes of observation of, respectively, quantum and/or classical information at the decoding receiver. This means that consciousness is not a continuous, but rather discrete phenomenon, yet, intuitively, one might object, it doesn't seem to be that way.

The digital/discrete property of consciousness under the offered formulation can serve as a straightforward empirically testable criterion for falsification of the theory. An intuition about consciousness appearing to be a seamless/continuous experience, while appealing, is disputed by empirical research that gives us indications that perception, attention, and cognition are discrete phenomena that follow certain rhythmical patterns. According to Landau *et al.* (2015, p. 2332), 'The ability to predict behavior from a rhythmic neural process suggests that attention may directly entail a sampling mechanism, rather than a resource that can be continuously deployed'. They found that active attentional sampling is a spatially specific process indicative of a mechanism of selective endogenous attention that operates in distinct frequencies from the ones characteristic of distributed attention. Furthermore, by studying rhythmic neural signatures, Herbst and Landau (2016, p. 86) found that the systems implicated in cognition produce rhythmic temporal structures that provide a structure to our perceptions and to the way processing resources (i.e. attention) are deployed. Similar findings are reported by Busch, Dubois and Van Rullen (2009), Mathewson *et al.* (2009); for a comprehensive treatment of the subject, see Buzsaki (2006).

In an extensive review article White (2018, p. 1) evaluates proposals that '…conscious perception consists, in whole or part, of successive discrete temporal frames on the sub-second time scale, each frame containing information registered as simultaneous or static'. He concludes that the idea of discrete frames in conscious perception has a lot of empirical support and cannot be regarded as falsified. However, there are quite a few problems associated with this view; for example, evidence does not consistently support any proposed duration or range of durations for proposed frames of consciousness, and, while EEG waveforms provide evidence of periodicity in brain activity, this periodicity is not necessarily related to conscious perception. Further, temporal properties of perceptual processes are flexible in response to competing processing demands, which is hard to reconcile with the relative inflexibility of fixed-frames proposals. 'There are also problems concerning the definition of frames, the need for informational connections between frames, the means by which boundaries between frames are established, and the apparent requirement for a storage buffer for information awaiting entry to the next frame' (*ibid.*).

Many of these problems can be accommodated relatively straightforwardly in the context of the predictive Bayes-Shannon perceptual hierarchy. Thus, duration of conscious frames would depend on the level of the hierarchy that's engaged in processing the perceived stimulus, since according to Parr and Friston (2017) the higher the level of hierarchy the slower the processing and vice versa. The problem of periodicity not being related to phenomenally conscious perception can be regarded as an instance of 100% access conscious perception. The problems concerning the definition of frames, informational connections between frames, the means by which boundaries between frames are established, and the need for a storage buffer for information awaiting entry to the next frame can all be accounted for in terms of the information processing dynamic within a Bayes-Shannon computational system. Thus, frames can be defined as durations of instances of quantum uncertainty reduction at the decoding receiver on levels of the perceptual hierarchy, which also can serve as computationally and psychologically natural frame boundaries. Finally, the neural network performs the function of endogenous working memory (storage buffer) that is instrumental in formulating a next prediction that will give rise to a certain balance of phenomenal and access consciousness at the decoding receiver for the next frame of consciousness. This is just a very brief sketch of how the suggested system would address these issues that needs to be developed in more detail. However, *prima facie* a predictive Bayes-Shannon hierarchical computational system is equipped to address the shortcomings of the discrete approach to perceptual consciousness identified in White (2018). Thus, while there are still important issues that must be worked out, overall it appears that empirical evidence supports the formulation of consciousness as a discrete phenomenon, which supports Quantum Uncertainty Reduction Theory's view that consciousness is a digital information processing phenomenon.

8.3. Objection: The human brain cannot support quantum information processing

Current quantum information systems require very special conditions (low temperatures and isolation from the environment) in order to prevent quantum states from decohering. The human brain, on the other hand, is warm and noisy, therefore it cannot implement quantum information processing. In response one can point out that in a Bayes-Shannon system all information processing until the very last step is classical and, therefore, doesn't require any special conditions. It is only at decoding that quantum information is observed/registered during a short instance that's quite possibly enough for the system to not require special arrangements.

9. Conclusion

The Quantum Uncertainty Reduction Theory of phenomenal and access consciousness is a rather ambitious view of the nature of consciousness and its place in the world. On this view, quantum information carries and phenomenal consciousness gives awareness of the difference between an observer's classically encoded question and the environment's classically encoded response to that question, while classical information carries and access consciousness gives awareness of perfect agreement between an observer and the environment.

Going forward, an important issue, among many, would be to investigate how this view fits into a larger picture of current theorizing about the nature of reality. This formulation appears to move quantum phenomena from the outside world and into an observer's mind which is a rather counter-intuitive picture. However, on first approximation, QUR can be construed as a theory of conscious and non-conscious experience of Quantum Bayesianism or QBism (Fuchs, Mermin and Schack, 2014) with certain modifications. QBism is an information-theoretic and epistemic (as opposed to ontological) reformulation/

interpretation of quantum physics that holds the experience of a quantum theory user as the central subject of scientific investigation:

> But quantum mechanics itself does not deal directly with the objective world; it deals with the experiences of that objective world that belong to whatever particular agent is making use of the quantum theory. (*ibid.*, p. 3)

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