

Human Consciousness: A Systems Approach to the Mind/Brain Interaction

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This paper focuses on a logical systems flow-down of a set of consciousness requirements, which together with biological quantification of human brain anatomy sets limits on the neurological network in the cerebrum in order to produce the mind. It employs data (where available) to validate inferences, or when data do not exist, proposes methods for acquiring valid evidence. Many of these systems requirements will be imposed after some fundamental assumptions are made. These assumptions are not new to theories on consciousness. However, their application as fundamentals may actually represent a new approach. Concurrent with these fundamentals, explicit periods of awareness while conscious are employed. Justification for their use is found in a theoretical process described as cerebral fusion. Additionally, storage of memory elements is postulated within local glia sites, proximal to synaptic nodes, and conductive transport through the astrocytes responsible for recall of data. The model permits variations in neural-glial interface physics and allows forecasts of mind/brain dysfunctions to be inferred. One key result from the model is hypothesized and expanded upon, and may have impact in certain types of dementia, such as Alzheimer's disease.

Advances in imaging technologies, along with a focus on the importance of cerebral processing in medicine and computer development during the last two decades, have provided the framework for many new approaches in both the theory and experimental data pertaining to the mind/brain interaction (Baars, 1997; Damasio, 1994; Dennett, 1991; Newman, 1977). During this period, newly formed departments of conscious awareness and cognitive science have appeared at university centers worldwide. Together with institutional research and development projects, scientists and philosophers from many disciplines have joined this quest: How indeed does the human mind perceive reality, form thought and reason, and experience qualitative emo-

tion through the elements of cognition? Much of the research has centered about developing an understanding of consciousness, and the role of awareness within that process (Chalmers, 1995; Crick and Koch, 1995b; Scott, 1995).

The primary theories that have evolved to date are generally derivatives of either a unity theory, wherein the mind is what is directly produced by the physical brain within us, or a dualistic theory, which propounds the separateness of the mind and brain, relating cerebral functions as "flow-downs" from a more central, perhaps spiritual center (Wilber, 1997). Within these two general classes, theories on whether the conscious mind can be directly attributed to physical phenomena that are measurable, or are outcomes of statistical processes that are describable through quantum mechanical analogues, extend the borders of the primary concepts into several hybrid definitions. All of these theoretical approaches, however, have the same global constraint that does not permit easy verification: at best, we each know our individual thoughts and experiences, but to a level not entirely measurable by experimental instrumentation. We can only presuppose, but do not know for sure, that each of us interprets or feels a specific experience in a similar manner to the other — instead we rely on verbal reporting for this type of data. We can teach one another to react similarly to some types of external stimuli, but left to our own devices, we probably develop our own individual catalog of responses to objective events, i.e., a sunset. Since we recognize that our individual subjective feelings and emotions, which form a large part of the conscious experience, are likely to be different for different individuals, it may be that the mind is the least capable tool to examine the functional responses of itself (Chalmers, 1995; Robinson, 1996). Rather, direct experimental data would be required in the area of the fundamental systems architecture of the mind/brain interface to de-couple the origin of subjective feelings from those belonging to objective information processes.

Despite this limitation, vast amounts of data have been collected on the neural physiology and cognitive process to reveal the responses of the mind/brain interface to external stimuli (Crick and Koch, 1995a; Gardner, 1985; Gray, 1995; Libet, 1982). There is no doubt that we can relate many physiological activities to the occurrence of specific neuron firings, or the presence of neural matter in various cerebral areas. Likewise, deficits in the operation or performance of motor skills or psychological dysfunction can be related to the presence or absence of tissue. However, except for the science of human behavior as a set of learned responses, we have not been able to overcome the paucity of experimental evidence to relate your conceptual conscious awareness to mine, or that of your friend's to that of your brother.

Therefore, many of the theories presented to date are typically empirical or heuristic approaches to cognitive awareness, relying on the volume of neuro-

physiological data surrounding brain functions, and perhaps interspersed with mathematical formulations that relate quantum mechanical probabilities to the evolution of thoughts (Penrose, 1989; Stapp, 1995). All of this is insightful, highly valuable and potentially will lead to the final understanding of human mind/brain dynamics, but it currently does not provide a more immediate answer to how or why the brain is able to produce the mind or why the brain is such an extraordinary organ within the body to be the seat of such activity. As both human thought and subjective experience are believed to be imbedded within the conscious moment, they clearly must be coupled in some manner, so as to be simultaneously produced during the conscious process. Chalmers (1996) indicates that these qualitative experiences of conscious moments are essentially the hard problems surrounding all theories. Some researchers (Clark, 1995; McGinn, 1989) feel all aspects of quantification of human consciousness are hard . . . some harder than others.

Since most of these hypotheses connect at the "neuron" level, that is, they require performance constraints on the neural switching process itself, they can lead to a "conundrum" regarding the formal operational capability of the neuron. The problem centers about the use of the neuron as either a "switching" element, passing along a stimulus from an input sensor, much as a conduit in a circuit, or conversely as a "storage" site, wherein some electrochemical change or polarization (temporary or permanent) has occurred to produce a memory. Since the properties of any single neuron will change to produce either capability (through charge or chemical biases), it is unreasonable to expect the neuron to "know" which characteristic it is supposed to exhibit at any given time. This would be true irrespective of its operating alone or within a circuit aggregate (neural network).

It is remarkable how much detail is known about the biology of the human brain along with its chemical complexities, yet how little is understood about the capability of the brain to form a permanent memory. Damasio (1999) notes that while the neurophysiologic details of memory formation have not been worked out, the "contours" of the processes are understood. Yet, without that fundamental property accounted for in a biological format, little progress can be made in an empirical model of consciousness. This condition is no less fundamental in the design of a computer system — that is, where is program storage going to occur, and how do data physically get manipulated, re-stored and ultimately retrieved? While there is no attempt to equate the mind/brain system to that of a highly sophisticated computer, there are at least these fundamental data access (and probably other) analogies. Therefore, this paper will describe a heuristic approach to formulating a cerebral processing system, satisfying the observed limits and physical quantification of the system's biological components. This includes describing storage capabilities for memories and learned responses. In the process of addressing

these fundamental questions and expanding the basic models developed, allied approaches may become apparent, as well as new confirmatory experiments to be performed. The paper attempts to flow the observed capabilities of the human mind through a general systems design procedure, and to examine the consequences of such results. It will be beyond the scope of this work to provide extensive chemical detail beyond inferring the biological and physical interactions that actually produce memory storage and retrieval.

Initial Concepts

The human cerebrum is composed of approximately 10 billion neurons, while the brain itself has at least ten times that many (Greenfield, 1996). While this is a relatively large number of either elemental storage or relay sites, one can no longer be impressed with that value when compared with densities of hard drives on minicomputers. Here storage elements already exceed two hundred billion bytes, and most computer aficionados have some quantitative feel for what volume of programmatic storage those numbers represent. In fact, one could never compare the complexities of human actions and thoughts to the types of programs currently written into 200 billion bytes of ROM (read only memory). Several newer proposals concerning storage phenomena in the human brain hypothesize that data may be encoded on individual interconnections between neurons (Herbert, 1993). Since the number of interconnections typically formed by neurons ranges from 10^3 to 10^5 , the number of storage elements could be as high as 10^{15} or one thousand (1000) trillion. This may very well be a respectable quantity of memory sites to perform the dynamics that humans are capable of exhibiting, but how these sites are addressed and enabled becomes problematical. Also, whether these sites act individually or collectively (neural nets), and what if any area of the brain ties these interactive neuronal synaptic firings together, become the central challenge for a basic model.

The centerpiece systems issue that arises is: If data is stored at neuronal nodes, either through changes in polarization or through the establishment of chemical pathways, how are data explicitly retrieved? Since it has been clearly demonstrated through years of research that thoughts and memories have components that are stored physically as distributed elements in non local sites of the brain (Finkbeiner, 1993), how is the brain stimulated explicitly to find and centralize the remote pieces to form the global memory? One would expect that these mechanisms must be explored (at least empirically) prior to establishing a complete theory on conscious behavior. Some theories have avoided these obstacles by resorting to quantum mechanical analogues (Globus, 1998; Hameroff, 1994; Vitiello, 1995),

principles that work well on atomic or sub atomic levels. While these approaches have produced remarkable accuracy in predicting observed behavior within physical systems, their applicability to biological processes that involve many electrons (typically 30,000, see Merkle, 1989) per neuronal firing (Kuffler, Nichols, and Martin, 1984) or the coherent processes associated with those events, have yet to be demonstrated. Inferring that human thoughts are the statistical outputs of quantum event probabilities (coherent or otherwise) does not produce further mind/brain systems descriptions, but rather focuses the analysis of conscious behavior within mathematical operations.

What may be helpful in shedding additional light on this ongoing debate, and perhaps forge new directions in empirical thinking, could involve defining a straw-man physical process. The process should be based on the observed and measured characteristics of the brain and mind, and be attuned to the consequential physical and/or biological ramifications of any system construction required to handle those capabilities. In order to do this, several fundamental properties of the mind/brain system need to be established, along with basic operating assumptions.

Fundamental Assumptions

As a starting point for memory management and a hypothetical design of the mind/brain, initial assumptions are required to provide levels of boundary conditions on the available solutions. For purposes of this work, the following statements will be used as fundamentals, requiring no proof beyond the recognition of their obviousness.

1. While the human brain as an organ contains a large variety of biological elements and many types of neurons, it shares the same level of biological-macro complexity as do other human organs. As such, neuronal aggregates or cortical *functions*, while marvelous in their intricacies, should be on par conceptually, for example, with the role nephrons play in kidneys and alveoli in lungs.
2. There is no "micro-manager" homunculus, or librarian function in the brain that keeps track of where specific facts or pieces of those facts are stored. This assumption is in consonance with other theoretical models. It is also assumed that no lookup table exists focally in the brain to assist in locating already learned or stored concepts (Restak, 1994). The lack of a homuncular region in the brain also precludes the identification of a compiler function or executive collator anywhere in the cerebral matter.

Stated simply, no particular area of the cortical brain has been found wherein its surgical removal would prevent the remaining brain tissue from supporting some level of consciousness and awareness.

3. At birth, most (but not all) cerebral neurons are unconnected, but become so (axons to dendrites) over the course of the next several years, subject to some modifications throughout a lifetime (Greenfield, 1996). This includes (under normal circumstances) the loss of unused or diseased pathways, and the attrition of neurons that occurs with aging.
4. Once a neuronal connection(s) is made, it cannot be disconnected (except through disease, attrition or pruning and degeneration). This axiom is equivalent to the hypothesis that we do not specifically or decidedly unlearn facts, but rather supplant them with new ones.
5. Each cerebral neuron can be connected to up to 10^4 – 10^5 other neurons.

Corollaries of these fundamental assumptions would include the following:

1. No fundamental locator of specific facts, memories or concepts is present in the human brain. Therefore, there is no map or specific programming for locating where data on any individual item exist or whether these items are topologically co-located or spread out in various areas of the brain.
2. Facts that are learned (those that have neuronal paths and connections established, and can be recalled — also known as long term memory) can never be specifically unlearned.¹

These fundamentals become the starting point for a systems model of the brain, and, together with the assumption that the brain produces the mind, may provide a pathway for understanding the dynamic behavior of the conscious mind. To pursue an investigation of storage capabilities of the brain and link it to mind phenomenology, one must apply these fundamental statements to the gross human cerebral anatomy. These assumptions provide an artificial, but reasonable structure that allow the buildup of system capabilities, and also provide boundaries on acceptable and functional design alternatives.

¹Rather, they can be surpassed by new learning, or forgotten (the latter term is defined for purposes of this paper as the inability to recall from a memory state, but not necessarily lost) [MacLeod and MacRae, 2001; Slamecka, 1960]. We probably are not ever going to forget that "ain't" is not a word — but we've learned not to use it.

System Flow of Memory Requirements

An analysis of requirements for memory considerations within the human brain that would be capable of supporting the known and understood qualities of mind must begin at the level of *allocation* of requisite memory sites and storage phenomena. To start, all data input to the memory system from the external environment must come through the sensory routes. Thoughts and image constructs must also be accounted for, and for the time being, it will be assumed that all external ports have a corresponding virtual internal port(s) that can evoke a mind-produced data entry. This approach is not intended to invoke *any* methodology (initially) for the type of memory operating within the human brain. The initial arguments that are made here focus only on populating storage sites with data (by whatever means data get stored). How quantified bits of data are retrieved and assembled into thoughts can follow any methodology, e.g., digital bit construction via an algorithm not yet understood, linear reconstruction based on analog levels of quantified bits of storage or weighted constructs based on neural network combination of storage sites, to name a few. The important point here is all of these potential methodologies rely on getting data to synaptic nodes as bit-level information, and there are only approximately 10^{15} locations for this process.

Data or stimuli transported from sensory organs into sub-cortical regions of the brain occur at relatively fast neuron firing rates, typically every few milliseconds, up to about 10 msec. Therefore, depending on the size (neuronal density) of the data paths, or the number of data paths that could provide inputs to the various input ports to the brain (visual sub cortex for the eyes, the somatosensory cortices for the body, etc.), the effective data rates at which information flows to the brain could range as high as 10^8 bits per second for visual images and as low as 3×10^4 bits per second for audio inputs. The somatosensory rate is about 10^7 bits per second when all receptors across the body are considered (Herbert, 1993). As far as measurements that have been made, these rates are continuous; that is, during consciousness, sensor data flood the brain in a steady stream of data bits, ready for processing. Clearly, if all the data were to be processed indiscriminately, and stored for future recall, we could compute the number of required sites for data accumulation (without regard to topology) over a human life span.

If we presuppose that an (as yet) undefined specific electrical or chemical process is responsible for both the permanent storage and recall of data from locations that behave as "write once, but read mostly" memory, then the maximum number of available sites for data would be 10^{15} or 1000 terabits. This assumes that incremental bit storage occurs at nodal sites described earlier. This does not obviate theories where additional memories can be formed by the aggregation of nodes, biased as in neural nets. Rather, it just addresses

populating synaptic sites with bit level data. However, to invoke higher-order collation of *individual synaptic storage sites* would require defining where in the cortex (and how) that was happening. At the simplest level, it does invoke the properties inherent in the second fundamental assumption above. At the optical data rate, memory locations would fill in as little as 10^7 seconds or within weeks to several months. Clearly, this does not happen. The question then becomes: What processes can the brain perform (autonomously) that would prevent the early and complete filling of all the neuronal synapses? If preference for specific data to be stored and others to be rejected was to occur, there would need to be a full time (and prejudicial) librarian or homunculus at work, sorting and saving data from a continuous flow of information reaching the sensory cortices. Even invoking the properties of short term or temporary store memory features places a burden on humans to find time within the data flow to determine which data to archive, and which to reject. Based on the fundamental hypotheses established earlier, we are forced to reject this approach.

However, what may be needed is an approach that shows no cognitive preference to any portion of an ongoing data stream, but would allow the conscious mind/brain to exert preferences by interrupting its continuous processing of data to denote a thought, image or memory. Such a systems process would be more in consonance with the observed human sensory capabilities (Murchie, 1981). However, this presupposes at least three new requirements within the system.

- 1.0 Storage of data in the human brain cannot occur at neuronal nodal junctions per se as there are simply not enough of them to accommodate the continuous stream of data arriving to the brain every second, and there appears to be no way to purge the overflow. What may be needed to preserve the concept of storage proximal to nodal sites is the establishment of a media nearby each dendrite contact/synaptic junction to contain the data, thus enabling the nodes to be simple switches, but not the storage element itself.
- 2.0 Insofar as no homunculus exists to direct this data traffic, and there are no specific maps as to where categories of data are located, lengthy times (by neural switching standards) would be required to recall specific items (if a selection method could be devised to find it). Typical computer architectures that have no unique address-selectable memories enable recall of data through block-data select techniques, and consequently, sampling and de-selecting those items not being directly sought. This type of architecture, while simple and potentially in concert with the complexity level of human organ anatomy, would require

postulating significant off-time for a person to perform these selections. More importantly, these selections would have to be made from among other alternatives, implying an actual selection (thought, word, etc.) might be chosen before the realization that it was to be the next item within the conscious stream of thought. The key within this architecture is that no template exists within the brain to locate specific data and therefore, some unwanted sampling is required to find a *specific* item.

- 3.0 A corollary of second condition (2.0) is that the temporal difference between an actual event occurring, and the realization of that event in the aware mind would, in effect, not be simultaneous in real time, but may appear to be so in consciousness.

Therefore, the systems architecture that would be required to meet these criteria could include brain matter proximal to the terminus of the neural switches, capable of storage of data through a quantifiable physical mechanism, and conductive within its own right. The latter requirement would be necessary to produce ongoing communication between neural segments, as the synaptic junctions would now only be switching networks. As will be pointed out below, this material could easily be postulated to be the brain's own support matter, the local glial cells (Zanotti and Charles, 1997). More importantly for the moment, the flow-down requirements on timing imposed by the second criteria on the mind/brain architecture requires expansion. The need for periods of off-time within the cycle of producing thought, recalling or storing memories, primarily related to sorting or finding facts probably fits comfortably within our own realms of experience. This type of general architecture could be constructed by postulating the existence of a master "process clock," against which all perceived cognitive events could be referenced. This may not be necessarily surprising, since other organs require clocking for their operation such as the various muscle functions of the heart and peristalsis within the intestine.

The brain's intrinsic timing would have to allow for data input, retrieval, encoding (establishing a mechanism to allow it to be re-interpreted) and then de-coding. During these physical processes (some of which could conceivably be done in parallel within various topologically non-coincident sites in the physical brain), a bifurcated periodicity must also exist where the brain is conscious-and-aware vs. conscious-but-unaware of underlying processes or choices. These two states are not dissimilar to the terms of consciousness and subconscious. The labeling is forcibly highlighted as always conscious, but aware part of the time, and unaware the rest of the time, to emphasize both the periodicity and exclusive need to have both states

allowed with a continuous stream of data storage and recall. The unaware state is a definite requisite to accommodate the de-selection process discussed previously. Without it, one could be conceivably lost to the dementia of listening and/or seeing all the alternatives we have to pick from. Because of the fundamental requirement of having no dynamic memory manager, the conditions of awareness and unawareness cannot run simultaneously without the aforementioned cerebral process timing. Otherwise, it would take a cognizant function to know when to switch between states, and therefore, an *a priori* cognition of what conscious choice was to be made — a Herculean feat even for quantum mechanics.

We actually have several indications within the experiential world and through recorded experiments that demonstrate that we have a two-cycle state of consciousness, aware and unaware. The ability of the visual system to produce continuity from discrete, but changing images (a process known as flicker fusion) can be related to a discrete state change within the mind (aware-to-unaware intervals) together with some compensation for interruptions. These visual phenomena would correspond to a total transition from an illuminated frame to a black (no information) background. Whereas the physical event is actually a sequence of discontinuous and discrete frames, and would appear that way to any recording instrument, such as a rapidly shuttered camera, it nevertheless is blended into continuity by the mind. Often the frequency with which it is observed can depend on the background light level (Greenfield, 1996). Since we have already indicated that the optic nerve data support individual neuron firing rates in the millisecond range (Herbert), the concept of a flicker rate ranging from approximately 12 Hz to 80 Hz (dark backgrounds to light backgrounds) does not comport with simple synaptic communication. However, studies have shown that images do take about 50 msec to arrive at the visual cortex of the brain from the retina (Nijhawan, 1997). Other studies have shown that very short duration images (10–30 msec) are not perceived within conscious awareness, and whereas there is controversy over the effects of unconscious perception, the arguments do not contest the fact that the stimulus may be perceived within a conscious, but unaware state (Merikle and Daneman, 1998). Any explanation tied to simple saturation effects of retinal structures cannot of itself account for flicker fusion since these effects would be strongly related to quenching (recovery) rates of the rods, cones and ganglion cells, and not the firing rates of neurons. As we all have experienced, strong saturation of the retina produces blooming and persistent ghosting of previous images, so that latency from earlier images could present visual errors. That is not, however, what we experience during image fusion.

The tactile senses operate much in the same fashion. If we ask at what rate of repetition we can no longer distinguish individual or discrete pulses to the

same or proximal points on the skin, observations similar to those quoted for the visual domain have been reported, with the shortest duration approaching 12 msec (Herbert, 1993; Menon and Freeman, 1996). Likewise, the onset of audible hearing in humans occurs with sounds at or around 20 Hz. As sounds are heard, either from our ears as the source, or through the virtual, internal port that feeds our minds with verbal thought, we do not hear individual vibrations, but rather the blend of vibrations that give the tone and quality to those particular sounds. Lance (Lance, Peterson and Swanson, 1997) has reported that the shortest duration between auditory signals that can be distinguished has also been measured to be 12 msec to 15 msec. The distinctness of two sounds is lost if they are not separated by at least 5 msec. Clearly, the brain provides sensory fusion at rates varying between approximately 5 to 30 msec, depending on the sensor or receptor, and the background conditions.

The requisite systems level architecture, allowing for both unaware processing and aware processing can only be accommodated in very few formats to be consistent with the initial set of fundamentals established in this paper. In essence, this bifurcated state of awareness can become available in two primary ways: either by co-parallel processing of both data streams (aware and unaware), along with a temporal or threshold queue provided by the brain to sample from or transfer to one mode or the other, or by a serial mode of processing, in which one data stream is on at a time. The latter mode is not likely to be a pure operation by itself because it may be limiting as to when data can be sampled, and from where data are sampled. The most compelling structure can occur as a hybrid of the first methodology — that is, a co-parallel process, ongoing at all times, serially streaming data into conscious awareness as a result of perhaps threshold cues, continually updated by new external inputs. In this approach, we would always be conscious of something; however, where we drew the content of our consciousness would not be fixed. In essence, this proposed structure is consonant with Baars (1996), in which the central elements of consciousness are those that are currently within the awareness cycle, i.e., those within the spotlight.

As a digression to enhance these points, it appears to most of us that we are always conscious and aware while awake. It would never occur to us as otherwise. There is no hint of discontinuity. However, there are those things we do that appear to be hidden from our awareness almost all the time. When we speak, we use strings of words, but the thought processes that gave birth to those specific words are hidden. Likewise, our abilities to walk and navigate appear automatic, with minimally aware pre-planning, but with ongoing assistance from visual cues. Additionally, we perform mathematical calculations mentally, and perhaps adroitly, but have little awareness of the prerequisite steps of how we retrieved numbers and where we performed

any operations on them — instead, we just become aware of the answer. We appear to be truly unaware of these intermediate processes or thoughts. We would expect in any alternating or discrete sequencing between aware and unaware states there would be inexplicable events, caused by the variation between those states. There appear to be none, and in fact, consciousness appears continuous.

In a sense, this concept of blended aware/unaware processing is in concert with Baars' (1994) contrastive analysis. Whereas Baars and others (Logothetis and Schall, 1989; Marcel, 1983; Reber and Squire, 1994) have indicated while they believe information processed during unaware states may have direct impact on conscious representations, the form of that conscious product can vary, depending strongly on the method by which the unaware stimulus occurs. Baars et al. appear to agree, however, that there is ample empirical evidence that inputs made during unaware moments are an integral part of the functioning of conscious states. Reber and Squire (1994) demonstrated the ability of the brain system to learn in the unaware mode and experiments run during ongoing hypnosis sessions (Brown, 1991) demonstrate that subjects can verbally report on information received during earlier hypnotic functions, but masked from conscious awareness, suggesting again that learning and memory operate during the unaware processing of the brain. Studies reported on by Murphy and Zajonc (1993), as well as Libet (1991) and coworkers, also show that the detection of applied electrical thalamic stimuli in patients with implanted electrodes is not dependent on whether or not the patient is cognitively aware of the pulses.

This process requires the reader accept the notion that the brain (mind) has made a decision or choice precedent to the action or vocalization of the next thought. While the time necessary to transport information from the brain to motor outputs of the body (hand, feet, etc) are not zero, it is relatively shorter than, or comparable to the fusion rates, discussed earlier. Therefore, the relative time differential between actual sensing of motion and awareness of the action should be minimal. Unfortunately for the theorist, the latter presumption appears not to be true. Libet (1964, 1979, 1982) has shown that there is a delay of up to 500 msec between the measured arrival of a stimulus and the beginning of awareness of that event. A complete systems architecture that blends the timing elements between aware and unaware states, along with the experimentally observed effects of delays between perception and physical events may explain these phenomena in an implicit fashion. If we draw on the concepts presented earlier, where the contents of conscious aware processing and the unaware components are blended continuously at rates commensurate with a cerebral process clock, we begin to complete a systems description capable of exhibiting the features of human cognition and awareness. The model proposed in this work includes a

rapid blending of both states at the gamma band frequencies, typically centering about 40 Hz (Jeffreys, Traub, and Whittington, 1996) wherein the contents of consciousness are fused in much the same manner as the visual flicker fusion, audio fusion and tactile stimulus fusion experiments described earlier. To simplify terms, the process will be referred to as cerebral fusion. The contents of the cerebral cortex, as either experienced from the body's external sensors, or as perceived from memory and replayed through virtual sensor sites in the brain, integrate completely to form an ongoing vignette of scenes, thoughts and emotions. The systems description must further postulate that in no event can the mind sense the discreteness of the events. Complete continuity of consciousness at these cerebral process clock rates would prevent individuals from ever comprehending the detail between the windows of awareness. On the other hand, this same mechanistic process would allow for the appearance of simultaneousness between sounds and images occurring between temporally adjacent windows, even though we know that some audio stimuli arrive sooner to the cerebral cortex than do visual signals. Essentially, with the process of cerebral fusion, events can occur discretely, but near enough in time, and are captured during either an aware or unaware cycle (within say 20 to 50 msec). It is proposed that the mind will not discriminate between the separateness of the events, insofar as in this fusion process, the evolution of adjacent windows provides the illusion of continuity of thought. This concept is not dissimilar from the often-discussed binding problem (Llinas, Ribary, Joliot, and Wang, 1994).

To complete the systems model, cerebral fusion must therefore have three fundamental properties that allow for both blended information processing, and the observed sensory stimulation to perception delays. These properties are globalization, integration and persistence. Globalization refers to the ability of the cerebral workspace to respond to those areas across the cortex containing features of current thoughts. Since the fragments of pictures, words, associated smells, memories and sounds are not necessarily topologically co-located (Freeman, 1991), the active centers contributing to an aware moment must be accessible to a centrex of processing (perhaps, the thalamus), much like a planetarium with a series of highlighted elements. This is conceptually not very different from Baars' global workspace, with its attendant spotlight on the most current neural locations corresponding to the contents of a thought. At this juncture, no statement is made as to the interpretation of the discrete data items into recognizable images or sounds; what is implied within the globalization process is that all excited neurons are globally accessible and as such, are momentarily "highlighted." Integration refers to the process of assembling the quanta of thought elements described in the globalization process. As already discussed, together with the process of cerebral fusion, integration is a temporally driven capability of the

brain wherein it is not possible for us to distinguish the non-simultaneity of successive events within one window of consciousness. The integration process guarantees that some fixed amount of time will be necessary post sensation before we are either partially depending on the elements currently undergoing globalization, or totally aware of what is occurring in the mind (or within the spotlight of the global workspace). At this juncture, integration assures that the recognition of already known or selected items can be made, but does not preclude the non-recognition effects of new items as well (Deubel, Schneider, and Bridgeman, 1996). Additionally, integration during unaware cycles allows for the de-selection of unwanted materials or intermediate results, as described earlier.

Lastly, the establishment of a persistence component to cerebral fusion refers to a capability of individual neuronal sites to retain, with some finite lifetime, the contents of their stimuli that are undergoing integration during any one window. The observed nature of how human thought is continuous would require that sites be active for at least adjacent temporal windows (no less than 50 msec), but would not limit it to that minimum. In essence, this capability of the brain would enable the smoothing of memory and thought transitions from vignette to vignette. Persistence does not preclude sensory stimuli from appearing different to us if the actual input occurred simultaneously vs. separate in time (but within at least 50 msec). On the contrary, there are differences in tone and pitch of sound bites that are temporally separated by more than 15 msec (Herbert, 1993). However, persistence will prevent the perception that each short stimulus (within 50 msec) appears discrete from its temporal neighbor. Persistence, as a feature of memory, would occur as a natural consequence of both ongoing sensory stimulus and the quenching or recovery times of neural nodes post stimulus. Whether or not neural nodes are electro-chemically induced or otherwise, there is an expected decay time post stimulus that is associated with the process and this would be consistent with the observed general properties of neural networks as well. Studies done with patients awakened from dream sleep stages show that these patients remember their dreams with varying clarity, indicating that neuronal persistence is indeed at work. In studies of various memory systems (direct recollection, short term recall, etc.) measured event related potentials have indicated windows to total awareness of times ranging from 350 msec to 1900 msec (Duzel, Yonelinas, Mangun, Heinze, and Tulving, 1997; John, Easton, and Isenhardt, 1997). Poetzel (1960) claims that information perceived while unaware can remain in conscious memory for several hours.

Up to this point, the systems description of the brain establishes a methodology to utilize the physical contents of the brain (specifically, the physical quantity of neural matter), and permits its processing as information we can

experience in consciousness. However, the description of a mind/brain interface is incomplete without a discussion of a relevant data storage mechanism. This storage mechanism, as the initial premise of the paper indicates, must be supportive of the thesis presented so far, and must account for the concepts of temporary storage, long term memory and sensory delays. The technical description given so far only allows for a system that can input to or recall from an information location, with no definition of where that location is or how it has been biased so as to form a memory. Likewise, it also cannot provide any knowledge as to whether or not a given site is currently used to accommodate stored data.

An earlier requirement placed on the systems definition included the fact that storage of data could not occur simply at neural interconnect sites, even given their large number, because they cannot handle the lifelong exposure of human sensory input data rates without a method for erasing previously existing data. This would be true irrespective of the methodology of storage, e.g., polarization changes, local chemistry changes, or charge storage at the mini-capacitor dendrite nodes. If, as suggested, the dendrite nodes were to be immersed in another media, one whose conductive properties were substantially different from the neuronal matter, then the neurons themselves can act as switches, and storage can take place within the media. The storage, in this instance could be similar to that of a small capacitor, where each interrogation of a neuron synapse could inject charge, much like a semiconductor, and the quantity of charge could signify the resultant strength of the signal. Repetitive stimuli to the same site would inject more charge, thus reinforcing whatever information (bias) was stored. The brain's own intervening glial cells can meet the conditions required for this inter-neural media. Previous research has shown remarkable properties for the various forms of glial cells themselves, beyond the classical picture of support media for the grey matter of the brain, and myelin rebuilding of injured neurons (Muller, 1992).

This assertion that storage of ionic charges due to stimulated neuronal firings will reside in astrocytes can be very significant in the development of a systems description of the mind/brain interface. First of all, it would be declarative as to where individual portions of memories are stored. It would comport with all recent articles advocating the global nature of both consciousness and distributed memory (Damasio, 1989; Dennett, 1991). However, unlike previous theories, we introduce the concept of permanency. Continuous firings of individual neuronal dendrites cause charge insertion into the semi-conductive glial media, some of which are expressed in Ca^{+2} waves (Cooper, 1995; Sneyd and Charles, 1994) to nearby dendrites or axons, and some that remain to establish a charge prejudice or bias. This, in essence, can form the basis of memory. Work ongoing by Newman and others (Charles, 1994; Newman and Zahs, 1977; Vernadakis, 1996) shows increasing observations of

the functionality of glial cells to regulate the extracellular charge environment of the central nervous system as well as the modulation of neuronal activity.

Suppose now that an interrogation (firing) of any neuron occurs in reaction to some objective portion of the conscious process — that is, occurring during the input of various data stimuli either in the aware or unaware portion of aforementioned cycle. Consider, for example, input from the optic nerve, relayed from the visual cortex in the parietal lobe to its ultimate destination in regions of the cerebral cortex: as the neurons transmitting those signals branch off into thousands, if not millions of nodal sites, each either firing or inhibiting transmission based on site-specific neurotransmitters within their synapses, they are imbedded in glia. Based on the state of previous charge located within the local glia, the signal strength within that media is modulated to stimulate (or not stimulate) a transmission to other axons or dendrites not within a synaptic distance. Therefore, what we have proposed from this systems description are two distinct modes of transmission. The first is the commonly understood switching between dendrites across synapses, enabled by neuro-chemicals within the gaps and representing the primary switching paths commonly referred to as neural networks. The communication continues into the cortex as far as the networks extend as a result of input, say to the visual cortex or somatosensory cortex. It also stops when all dendrite-to-dendrite nodes (that are activated chemically) fire, or when the transmitted stimulus can no longer provide energy to continue neuronal discharges or establish activation potentials. The second mode of transmission is slower than the first, since it is not enabled by charge transport across small, multi-micron gaps within the synapses, but by Ca^{+2} transmission through local glia (Lev-Ram and Grinvald, 1986) to, say, the proximal dendrites of a nearby neuron. The impulses can then either stimulate other local neurons, or neurons that ultimately propagate back to the main relay center, the thalamus. This secondary Ca^{+2} wave transmission is considerably slower than neuronal firing rates (typically 23 micrometers/sec.), as compared to the 10–100 msec for a neuron action potential.

Whereas the earlier sections of this paper argued for a division of the moments of consciousness into two periods (aware and unaware) based on design or systems development concepts, the overall active model described here would *predict* a division based on the differences between neuronal switching (firing) rates and neuron–glia stimulation and transmission rates. If memory is related to the storage effects at local glia sites, then the latter (but delayed) conduction through the glia must take place before a return stimulus through the thalamus can be processed with awareness and recognition of the inputted sensory data. Looking at the numbers involved in these processes differentiates the rates more clearly. Synaptic clefts on the order of

15–25 nanometer range fire in a millisecond or less. At a minimum, neuron–glia separation distances can be on the order of the thickness of cortical glia, typically 5–10 microns, although along with neuron thickness, can vary to several times that size within the brain. With the Ca^{+2} wave speed noted earlier this would predict in excess of 300 msec. It is clear therefore that no sensation of currently inputted data (vision, touch) could reach awareness in real time, but rather must be delayed for hundreds of milliseconds in this model.

The concepts of Ca^{+2} communication between neurons imbedded in glia, along with attendant modification of charge content within glial cells as a consequence of neuronal firings, have been alluded to in current glia research, as noted above. Post any set of neuronal firings, one would expect embedded charges proximal to the neuronal dendrites causing latent, but persistent polarization of the localized glial matter. This type of charge builds up as the result of persistent firing (interrogations) can represent the fundamental basis of local memory. The concept has several exciting ramifications. First, memory, as we know it, would be related to charge storage/charge transfer processes, easily identified with other similar physical mechanisms, such as dynamic charge storage found in solid state memory devices or charge coupled electronic devices. The network of interconnected neurons, despite its extensive geometry and very large numbers, would only be switching pathways to macroglia memory sites within the brain's topography. In fact, one may even pre-suppose that the networking of neurons could follow the pattern of charge depositions into the glial matter, enhancing the interactivity of closely related neurons. The phenomena of charge deposition into the glial cells comports with the earlier stated requirements to find additional storage sites, other than the dendrite nodes, due to an insufficiency of synapse sites for accommodating a lifetime of memories and thoughts. With this proposed systems model, the constitute elements of what will be integrated into one complete memory would not occur at nodal sites, but rather would be the combination of an internal multi-site stimulus, and the interpretation of that pattern with respect to others. Thoughts, ideas and actions are therefore not related to simple neuronal firings, but rather to their collective patterns. The available combinatorial expansions of dendrite nodes that could be used to store the elements of a person's total lifetime memory would be far in excess of the original 10^{15} nodal sites proposed on the basis of dendrite interconnects alone.

It would be expected that if this process were the basis of memory, the overall system just described would have a mechanism for ongoing growth, to accommodate new thoughts and memories, along with the ability to strengthen those already formed. Early in human development, the brain contains all the neurons it will have throughout its lifetime. For the first five

to seven years, inter-connects between various neurons form, and the basic network is established. While this continues for several years beyond this peak time, the pruning of neural matter will also occur. Essentially, the degree of neural plasticity becomes substantially less beyond these early build-up years (Huttenlocher, 1990). To enable the memory model described above, glial matter must continue its growth well into human lifetimes. That is precisely what happens, as glial cells continue to grow and replace themselves well past fifty years. Additionally, Burne (Burne, Staple, and Raff, 1996) has analyzed how glial cells respond to increases of retinal ganglion cell axons, and found proportional growth of oligodendrocytes, micro glial and astrocyte cells.

With the basis for memory located in the surrounding glia media that interact with the neural structures of the brain, it is appropriate to discuss the pathways to the storage sites, and recovery of data from those sites. Storage, recall and ultimately the weighting of the components of a thought are (in this model) related to the quantity of charge stored at or pumped through local dendrite/glia interfaces. Neurons going into the cerebrum and those exiting would simply be conduits (wires) transmitting patterns of modulated firings that represent the basic elements of the thought. Areas of the cortex, wherein neurons fire as well as those where they do not, are determined by chemical enablers within the synaptic areas, i.e., neurotransmitters, amines, etc. Those cortical areas that are stimulated through this pattern of conduit neuronal firings consequently receive new pulses of charge that change the Ca^{+2} content within the local glia. It is proposed that this change can induce a Ca^{+2} wave that ultimately triggers a return signal to the thalamus.

It is therefore postulated that neuronal firings from external or virtual ports are stimuli that are transmitted to the cortex through the assistance of neurochemical releases, and based on the localized neurochemistry, wind up in various portions of the cortex. Essentially, the neuronal firings via the chemically-assisted synaptic gaps provide cortical stimulus to various storage sites. The subsequent glial transmission of that stimulus to proximal, but not to synaptic contiguous neurons, provides a major component of the return signal or feedback that is ultimately interpreted as memory or thought. Clearly, within the six cortical layers in humans, there are neurons that enter the cortex from a focal centre (the thalamus), and those that return. These paths represent the ingress and egress networks that are buffered by the glia material. Since the path is a closed loop it can form the basis of a selective, yet macro addressable memory system.

One can think of the neural system from the brain stem upward as a partially fixed wire harness to the cortex, where the inputs from the physical body and its external sensors pass through the thalamus and much of the

limbic structures. Putting the physical basis for neural plasticity aside for the moment (Hebb, 1949), the foundational neural wiring leading to the cortex is in place at birth, and the quasi-plastic wiring within the cortex begins immediately with sensor inputs from birth onward. The brain itself does, however, exhibit maximum plasticity of neural networking in early years, with smaller (but non-zero) capabilities throughout adult life (Buell and Coleman, 1981). Using the argument that all the fixed wiring will pass through the limbic structures on the way into the cortex and outbound from the cortex, it would be reasonable to advance that the cortical maps first produced in the brain would be those that corresponded to body-level emotional patterns and feelings. Together with the data provided by external sensors (images, sounds, etc.) that accompanied those feelings, associative memories would begin to be structured (globally distributed throughout the cortex). This web-work would essentially be a constant in topological organization from brain to brain, corresponding to an observed constancy in functional specificity among people (Kolb and Whilshaw, 1995). However, regional differences in neural morphology must be responsible for the measured localization of the various cerebral functions. That would include variations in types of neurons, connectivity (outbound and inbound), and perhaps, most importantly, differences in chemical messenger generation.

Cortical Neural-Glia Signature

As is common in many physical events that are predicated on a charge exchange or charge transport dynamics, and involve electro-chemical charge potentiating or discharging mechanisms, one would expect to be able to equate a wavelength or set of wavelengths to the processes. The system features described in the preceding text include the concept of a generic neuron-glia interface, but in reality there are more glial cells than cerebral neurons within the brain. This means that one neuron can be expected to have its synapses enveloped by several astrocytes. Due to the morphology of astrocytes, one astrocyte may also exert influence onto more than one individual neuron synapse. The shapes of astrocytes and their processes have been shown to extend geometrically toward neurons (Mason, Edmonson, and Hatten, 1988), so that any firing of a neuron may have a sequential effect on several adjacent glial cells. That is to say, each proximal astrocyte may in turn transmit a Ca^{+2} wave upon the firing, and subsequent repeat firing of a single neuronal synapse. If one assumes typical fast cortical synapse firing rates of 1 msec coupled with quenching or recovery rates measured between .4 msec to 2 msec, the system picture for each multi-firing neuron would include a cycle time of 2.2 msec on the average (Hausser and Roth, 1997; Wahl, Pouzat, and Stratford, 1996). Given anywhere from four to ten astroglia adjacent to all

synaptic junctions, this permits a repetition firing of a train of 1.0 msec pulses (four to ten of them), providing a cyclic 30 to 90 Hz pulse of spikes. The exact frequency of a measured wave train would be dependent on the switching speed of the neuron (here assumed to be 1 msec), the total time course of the synaptic conductance (an additional recovery time of 1.2 msec), and the number of adjacent astrocyte processes to the neural synapse (no less than one, and perhaps up to ten). Since the astrocyte Ca^{+2} signal propagates at speeds of approximately 27 msec, together with astroglia dimensions stated earlier, the fundamental wavelengths would appear to be theta type. The signature would then be expected to be a series of high frequency bursts (perhaps 30–90 Hz) containing 1k Hz or slower spikes, correlated to theta type waves of 2–4 Hz. These types of patterns have been observed in both cortical neurons and hippocampal, thalamic and reticular formation neurons, and are similar to some of the observed gamma frequency or 40 Hz waves reported (Chrobak and Buzsaki, 1998; Suave, 1999).

Discussion

The original scope of this paper was to investigate whether or not, from a systems hierarchical viewpoint, the brain could indeed produce something as complex as the observed human mind. Some of the issues confronting the theoretical modeling of the mind/brain interaction have been addressed. Given the initial assumptions made earlier, a methodology has been developed that would allow for the complexity of human thought, while preserving some of the simplicity of the brain's fundamental operations. The systems model does propose a methodology to provide storage sites for archival memory (both short term and long term) and procedures to access those sites. The latter are related to an original web-work of foundational neurons hard-wired within each lobe, coupled to a more plastic development of neuronal networks, continually addressed through limbic coding. The model centers about the thalamus functioning as a centrex from the midbrain to the cortex, coordinating the inbound sensory signals with the outbound control and action signals.

Because the thalamus, basal ganglia and reticular formation display intrinsic timing signals, the model has extended these phenomena into the concept of a systems clock (or clocks), whereby periods of awareness are preceded by segments of unawareness, both periods occurring during consciousness. Since ordinary experience and verbal reports from most subjects confirm that there are tasks we perform where we are unaware of some of the intermediate results (Kunst-Wilson and Zajonc, 1980), our theory has extended the periodicity of these cycles into a blended, homogeneous format. It is precisely this seamless blending of the two facets of consciousness that permits us to

evolve thoughts continuously. The persistence of localized neural excitation presented in the model allows for, at least theoretically, the progression of higher-level thinking and the compounding of ideas into plans and decisions. The charge storage effects between neuron–glia interfaces support this persistence. In a sense, it is no different from watching the plot of a movie unfold in a cinema — we are unaware of the discontinuities between frames of the visual and audio components and we integrate the scenes within our mind on a frame by frame basis.

This paper began with a boundary condition that there was no perceived “homunculus” in situ within the brain. That premise is true based on the absence of data supporting the concept of any area of the brain performing that type of micro-management. However, given the complexity of mental processes, in a sense, there must be a homuncular process. The two-phase consciousness concepts (neural switching and glia conduction, as well as conscious-aware and conscious-unaware) presented here potentially require the ability to “sample and hold” data in a manner consistent with higher-level thoughts. This requirement permits inbound streaming of focused data to complete any particular thought or event. Therefore, this model suggests that the process of conscious awareness is itself the “missing” micro-management event. Bringing attention to bear on the set of thoughts or action is tantamount to “steering” the conscious-aware state into completion of a particular train of events to the exclusion of others.

Several formats for system level errors may correlate with defective functions within the human brain. For example, errors in the timing of the fusion between aware states and unaware states could potentially occur in individuals, leaving poorly defined boundaries between conscious events and intermediate thinking. Interestingly enough, thought disorders described in some schizophrenic patients (McConaghy, Catts, Michie, Fox, Ward, and Shelley, 1993; Bucheri, Trygstad, Kanas, and Dowling, 1997) wherein patients display semantic difficulties and overlays of internal voices, noise and visualizations, could be an analogue of this type of error. To the extent that these manifestations are related to a breakdown of synchronicity, as described, chemical interventions that alleviate symptoms may provide clues to the control or alteration of control of the system-level timing.

However, the focus of the most serious anomalies that could occur with a mind/brain system would occur in the neuron–glia interface. As described, the glial cell media and its semi-conductive properties are the proposed basis for intercommunication between neural network *switches* (Attwell, 1994; Cooper, 1995), and the glial stimulated neurons that return signals to the thalamus. The intervening glial media is both the semi-conductive conduit between those neurons, and the ionic storage site for ongoing memory. One could consider the glial cell requirements for partial or semi conductivity, at

the very least, functional only within a zone of acute balance. If the glia are too conductive, pathways amounting to quasi-shorts might occur, leading to random, spurious neuronal firing within the limited or focal regions where the glial cells are highly ionic. If the theory expounded above is valid, one might precipitously hear, see, smell or sense some non-proscribed sensation due to the random stimulation of the memories housed in the affected neuronal–glial tissue just prior to suffering total electrical breakdown in those regions. If the ionic content of the astrocytes within a focal region were too high, despite the regulatory efforts of the blood–brain barrier, the local neural networks together with their 70-microvolt action potentials may induce intercellular breakdowns. The process is descriptive of some of the effects that can accompany epileptic seizures.

Likewise, too low a conductivity within regional glial matter (for whatever reason, for the moment), the more difficult those regions of the brain would have in experiencing inter-neuron–glia signaling. Since this model presupposes that memory retention is enabled through the storage of ionic Ca^{+2} interspersed in this medium, the inability to connect across it can lead to loss of that memory. This loss would either be temporary or permanent, depending again on the rate of return of the glial media conductivity to a level within an acceptable operational zone. The potential dysfunction caused by too low a conductivity of glial cells for propagating Ca waves could appear to be similar to the features of amnesia.

Glial cell homeostasis is required in this scenario for continued communication and charge transport. Without the issuance of a Ca wave, communication from a switching neuron bringing an inbound stimulus is silenced. Concurrent with weakened or aged glial cells, poor transmissions or sub-threshold transmissions of Ca waves can provide weakened or marginal clinical responses to stimuli that were reacted to in a normal manner years before. These observations would occur in all sensory paths and affect memory recall as well as motor/somatosensory responses.

Lastly, it can be compelling to discuss the end of life of glial cells, or more accurately, the completion of full glia production in any human brain. In most humans, glial cell development begins in utero, and stops at or around ages 50–60, but varies from person to person. To preserve storage sites for the memories formed during our lifetimes, including those formed as a consequence of deductive reasoning, more glial cells must be manufactured to accommodate the ever-increasing requirements for additional physical volume to store charge content. Vernadakis (1996) has postulated that astrocyte–neuron coupling both through mutual chemical interactions as well as electrical signaling continue well into the aging brain cell. However, clearly, when glial cells are no longer produced, the capacity for additional local site storage (per this model) could diminish. In areas where continuous interro-

gations have taken place, it would be expected that the local glia would be charge saturated. These areas would correspond to the common, repetitive knowledge base we use in our lives or the actions or motor skills we regularly perform. Likewise, they also correspond to the areas interrogated with the highest frequency, that is, the pathways with the highest data rate. Calcium wave expression, while furthering communication, would no longer be sufficient to reduce the local charge content.

In a sense the local site would be similar to a fully charged capacitor, with an inability to add more storage volume. In the same manner, additional charge input (occurring as a natural consequence of normal sensory stimulation) could potentially tax the overcharged capacitive site to a catastrophic discharge. Such discharges could hypothetically be energetic enough to burn out the immediate neurons, causing a local de-myelination and perhaps tangles where axons and dendrites existed previously. The local site might resemble frayed wires with debris (plaque) that burned out due to an over-voltage experience.

This anecdotal but descriptive process of a charged saturated neuron–glial interface can provide a physical basis for neuronal demise in a manner commensurate with the observed degradation in Alzheimer's disease (Saitoh, Kang, Mallory, DeTeresa, and Masliah, 1997). The mechanistic reduction of neural matter in this model is simply, at the system level, consequential to an end of the growth of brain cell support structures. It would be then a matter of timing as to when each neuronal interface loses the ability to transfer charge to existing glial cells and faces its demise. Since all neurons do not get interrogated with the same frequency, certain neuron sites will be more vulnerable than others. Interestingly enough, this leads to the issue that Alzheimer's may represent a natural end to neurons, not a selective degenerative disease. Any correlation of Alzheimer's with genetics would similarly need to display the same correlation with glial cell production for this hypothesis to be correct.

Insofar as the theory propounded in this paper shows that the brain can physically produce the mind, it also levies two caveats on that conclusion. The first is that the so-called continuity of consciousness, wherein we observe no discontinuous events in our everyday lives (people move in smooth, steady manners, not incrementally; clocks do not display intervals of missing time where consciousness lapsed, etc.), is explainable employing two states of consciousness — aware and unaware. The two states blend together at a master frequency, in a manner not dissimilar to that of observing a motion picture, with properties such as persistence and integration, which guard against any loss of conscious continuity (Zeki, 2001).

The second caveat involves the use of the neuron–glia interface as the site for both charge storage (and hence, memory), as well as communication

return pathways to the midbrain region (in particular, the thalamus and reticular system). Herein lies the most intriguing part of this system proposal. By introducing the neuron–glia interface as a part of the memory/communication system, the model establishes a bimodal mechanism for rate-dependent communication. More specifically, it establishes many of the outbound neurons (from the midbrain region to the cortex) as chemically enabled electrical switches, allowing stimuli to reach various portions of the cerebral hemispheres, and many of the inbound neurons (back to the thalamus) as stimulated selectively through ionic transport within glial cells. The neuronal switching rates are not governed by the transmission rate through a neuron (this can be as fast as 200 mph), but rather the firing times across synapses (typically 1–5 milliseconds). However, since the transmission through glia, as discussed, is significantly slower, we have an integral two-time phase model that helps yield a conscious moment. The bimodal rate process could produce Libet's experimental results, wherein stimuli and responses were separated by an average of 350 msec in time. It also reinforces the need for neuronal firing persistence and global integration effects. These system features are required attributes to ensure that the delayed events are perceived as "current."

Therefore, the conscious moments themselves are assembled through the cooperative efforts of several mechanical functions within the physical brain, working together to produce these elusive, but interleaved cycles. Consciousness is certainly governed by functions emanating from the midbrain reticular activation system (RAS) [Petty, 1998]. The reticular formation extends upward from the medulla to just below the thalamus, while the RAS itself is part of the wiring extending through the thalamus to the cortical hemispheres. The RAS also is the site where we find the functional master clock, and therefore the basis of conscious event timing. Eliminating key elements through tissue destruction most certainly will alter or end consciousness immediately (Strub and Black, 1977). Information is also disseminated, coded, and decoded through the thalamus and limbic elements. Again, consciousness can be dramatically affected through losses within the former and memory altered through changes in the latter. Ultimately, the elements of consciousness assemble and integrate within the glial cells between neurons, and as such are quasi-immune from individual tissue losses. The incremental changes made by losing small amounts of cortical brain matter would be *de minimus*, and would lead to the conclusion that there is no central seat of consciousness, but rather an assemblage of ongoing local excitations, all contributing to the global awareness of any given moment. This series seems to be borne out by the reality of our individual experiences, and is in concert with a straightforward interpretation of some of the most exciting results in brain research to date (Carter, 2002; Perea and Araque, 2003).

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