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Necessary Ingredients of Consciousness: Integration of Psychophysical, Neurophysiological, and Consciousness Research for the Red-Green Channel

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Running title: **Necessary Ingredients of Awareness**

Short Abstract

The *necessary* ingredients for *access* (reportable) awareness are (i) wakefulness, (ii) reentrant interactions among neural populations that bind stimulus attributes, (iii) fronto-parietal and thalamic-reticular-nucleus attentional signals that modulate the stimulus related feed forward signal and awareness, (iv) working memory that retains information for awareness, (v) stimulus at or above threshold level, and (vi) neural-network proto-experiences (PEs) that are superposed subjective experiences (SEs) embedded in a neural-network. Attention and the ability to report are not necessary for *phenomenal* awareness. The neural source for the arousal system is ascending-reticular-activating-system. The psychophysical Red-Green Channel, its neurophysiological correlates V4/V8/VO-neural-network, and related experiences (such as *redness*) are integrated. The dual-aspect-dual-mode PE-SE framework was used to address the explanatory gap (how *experiences* can be created from non-experiential matter). The mental aspects of elementary particles are considered as the *carriers* of superposed multiple possible *experiences* in unexpressed form. A simple fMRI experimental design is suggested to address the *necessary* and *sufficient* attributes of awareness.

Long Abstract

Visual awareness is the visual subjective experience (SE) or the first person experience that occurs/emerges in the visual neural-network of thalamocortical system (which includes dorsal and ventral visual pathways and frontal cortex) during dynamic interactions among widely distributed neuronal groups. Awareness can be either *access* (reportable) or *phenomenal* awareness. For *access* awareness, the interactions are between feed forward stimulus dependent signals and fronto-parietal feedback attentional signals. The *necessary* ingredients for *access* (reportable) awareness are (i) wakefulness, (ii) reentrant interactions among neural populations, (iii) fronto-parietal and thalamic-reticular-nucleus attentional signals that modulate awareness, (iv) working memory that retains information for awareness, (v) stimulus at or above threshold level, and (vi) neural-network proto-experiences (PEs) that are superposed SEs embedded in a neural-network). Attention and the ability to report are not necessary for *phenomenal* awareness. The neural source for the arousal system is the ascending reticular activating system in the brain stem, which brings the thalamocortical neural networks to wakeful state as a baseline for awareness to occur. Reentrant interactions among neural populations bind stimulus attributes (such as location and features) and entail awareness. Attention could be the results of reentry and competitive interactions, and modulates the stimulus related feed forward signal and awareness. The 'sources' of attention may be thalamic reticular nucleus for bottom-up or frontal cortex for top-down direction. The 'target' of visual attention is 'V4/V8/VO' for Red-Green (R-G) channel. The neural correlates of the psychophysical entity R-G channel appear to be 'V4/V8/VO'-neural-network (retina → LGN ↔ V1 ↔ V2 ↔ 'V4/V8/VO', and areas for attention, memory, and wakefulness). The psychophysical Red-Green Channel, its neurophysiological correlates V4/V8/VO-neural-network, and related experience (such as *redness*) are integrated. The dual-aspect-dual-mode PE-SE framework (Vimal, J Integr Neurosci 7:49–73, 2008) was used to address the explanatory gap problem of materialism. Neural-network and related SEs are the results of the co-evolution and co-development of the material aspect (mass, charge, spin, force, quanta, and space-time) and the mental aspect of fundamental particles (strings or elementary particles (fermions and bosons)). Their mental aspects are considered as the *carriers* of superposed multiple possible *experiences* (SEs/PEs) in unexpressed form. These possibilities are actualized when neural-networks are formed via *neural Darwinism*, and a

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specific SE is selected by a *matching* process when the *necessary* ingredients of awareness/SE are satisfied. A simple experimental design is suggested to address the *necessary* and *sufficient* attributes of awareness.

Key words: *Access and phenomenal awareness; arousal system; reentry; attention; memory; executive functions; proto-experiences; subjective experiences; string; elementary particle; fermion; boson; Red-Green channel; neural correlates of consciousness; computational vision; fMRI; psychophysics.*

1. Introduction

Awareness aspect of consciousness (Vimal, 2008b) is an *emergent phenomenon* that is "the result of dynamic interactions between widely distributed neuronal groups" in thalamocortical neural-networks (Edelman, 2003). One could also argue that awareness is simply neural activity so mysterious emergent phenomenon is not needed. However, both materialistic frameworks and have the famous problem of explanatory gap (Levine, 1983) (how *experience* can emerge/arise from non-experiential matter such as brain) (Chalmers, 1995). In general, there are multiple meanings or aspects that are attributed to the term 'consciousness' as elaborated in (Vimal, 2008b) and (Vimal, 2008a). In this article, only some of the aspects of consciousness, such as awareness, subjective experiences (SEs), proto-experiences (PEs), and so on are discussed and the dual-aspect-dual-mode PE-SE framework (Vimal, 2008c, 2009b) is introduced to address the explanatory gap problem.

Our goals are as follows: (A) to investigate the *necessary* ingredients of visual awareness with an example of the awareness of colors in the Red-Green color channel; (B) to investigate how to link/unify/integrate the three aspects in a conscious system, namely structure, function, and SE; and (C) to propose an experimental design to investigate the *necessary* and *sufficient* ingredients of visual awareness.

For goal (A), the methodology included (i) literature search for color related awareness, (ii) meta-analysis (comparison of various authors' studies), (iii) search for consistency among various studies, and (iv) a sort of axiomatic consistency (as in theoretical physics). For example, psychophysical, neurophysiological (including fMRI), psychological, philosophical, and metaphysical articles for color related awareness were searched. While doing meta-analysis, the following questions were raised: what are the structure and function related to color? How can we link the three entities, namely, structure, function, and experience? How can *access* awareness and SE (say *redness*) aspects of consciousness occur/emerge with respect to various metaphysical views such as materialism, dualism, and dual-aspect framework? What kinds of problems are encountered while searching for consistency among studies? How can we resolve them? Which framework has the least number of problems? This investigation resulted (a) the 'V4/V8/VO' red-green neural-network as structure, and color detection and discrimination as functions, (b) six *necessary* ingredients for *access* awareness, and (c) the dual-aspect-dual-mode PE-SE framework for linking SE (such as *redness*). Furthermore, the criterion for necessary ingredients was that if a specific ingredient is deleted the specific awareness cannot be explained. For example, if the *necessary* ingredient attention is excluded, then *access* awareness cannot occur.

The goal (B) is achieved by following the methodology similar to that for the related goal (A). In addition, using the technique of a narrative, we follow experience on its way from the superposed PEs/SEs in the mental aspect of elementary particles to the SE aspect of consciousness. The goal (C) is accomplished by following the experimentation methodology, as proposed in Section 4.

In Section 2, we use the methodology for goal (A) as described above to examine relevant studies for each *necessary* ingredient. That is, visual awareness and its *necessary* ingredients are concisely discussed in Sections 2.1-2.7: Awareness can be either *access* (reportable) or *phenomenal* (non-reportable) awareness (Block, 2005; Lamme, 2003). The *necessary* ingredients for *access* awareness are wakefulness, reentry, attention, working memory, stimulus at or above threshold level, and neural-network proto-experiences (PEs) (Bruzzo & Vimal, 2007; MacGregor & Vimal, 2008; Vimal, 2008c); whereas attention and the ability to report are not necessary for *phenomenal* awareness (Lamme, 2003). For example, in *phenomenal* visual awareness, lower visual areas such as 'V4/V8/VO' for color may be involved but attention system may not be necessary. For '**wakefulness**', the ascending reticular activating system (ARAS) in the brain stem is necessary (Siegel, 2004), which is discussed in Section 2.1. **Reentry** process in a neural network binds various stimulus attributes such as location and features (color, motion, orientation) and entails awareness (Edelman, 2003; Hamker, 2005);

this is discussed in Section 2.2. **Attention** could be the results of reentry and competitive interactions (Hamker, 2005), which modulates the stimulus related feed forward signal. This modulating signal could be in forward (bottom-up) direction or mostly in backward (top-down) direction. The 'sources' of attention may be thalamic reticular nucleus (TRN) for bottom-up or frontal cortex for top-down direction. The 'target' of visual attention is 'V4/V8/VO' (color area for the Red-Green channel: (Bartels & Zeki, 2000; Hadjikhani, Liu, Dale, Cavanagh, & Tootell, 1998; Tootell, Tsao, & Vanduffel, 2003; Wandell, 1999)). However, it is not clear that all bottom-up attentional modulating signals are reentrant. The color area 'V8/V4/VO' refers to visual area V8 of Tootell-group (Hadjikhani et al., 1998; Tootell et al., 2003), visual area V4 of Zeki-group (Bartels & Zeki, 2000), and VO of Wandell-group (Wandell, 1999); they are the same human color area (Tootell et al., 2003). VO is ventral-occipital cortex. Attention is central to both basic and clinical researches and is essential to the construction of every subjective experience (Kanwisher & Wojciulik, 2000). Attention plays important role in vision, perception, emotion, reward, memory, awareness, and action selection (Hamker, 2005). The above roles of attention are significant because (a) attention modulates all aspects of related processing and (b) impaired mechanisms of attention are essential characteristics of a variety of human disease (Vimal, 2008a). Psychophysical studies such as ours (Vimal, 1997, 1998a, 1998b, 2000, 2002a, 2002b) related to visual system were performed with high degree of attention; nevertheless, a research with low levels of attention is also needed to explicate the effects of attention (Vimal, 2008a). Attention is further discussed in Section 2.3. Iconic memory appears to be essential for *phenomenal* awareness and working memory for *access* awareness; the stimulus should be at or above threshold otherwise it will be at subconscious level; these are discussed in Section 2.4. The stimulus level, executive functions, and neural-network PEs are concisely discussed in Sections 2.5, 2.6, and 2.7, respectively; a question is raised if they could be parts of *necessary* ingredients.

For goal (B), the Red-Green channel at various levels including visual awareness level is discussed in Section 3. The neural correlate of the psychophysical entity 'Red-Green channel' may be 'V4/V8/VO'-neural-network. Furthermore, the goal (B) is related to the investigation of a unified mechanism for how SEs of color occur/emerge in color-related neural-network structure (that has color related functions such as detection, discrimination, recognition and so on) starting from superposed elemental PEs/SEs. This goal is accomplished concisely in Sections 2.7 and 3, and detailed in our previous articles in the following order: (Vimal, 2008c), (Vimal, 2009b), (Vimal, 2008d), (Vimal, 2008a), (MacGregor & Vimal, 2008), and (Bruzzo & Vimal, 2007).

For goal (C), in Section 4, future research projects are suggested (i) to separate areas for the four *necessary* ingredients of awareness: attention, memory, reentry, and wakefulness, (ii) to separate *access* and *phenomenal* awareness, and (iii) to test the hypothesis that these *necessary* ingredients are also *sufficient* for awareness. Finally, the conclusion synthesizes our main thesis in Section 5. The findings are synthesized in each section, which simplifies and leads readers to new conceptions for further research.

2. Awareness and its *necessary* ingredients

The various aspects or meanings that are attributed to the term 'consciousness' were identified and categorized according to whether they were principally about *function* or about *experience* in (Vimal, 2008b). We discussed (i) SEs and PEs aspects of consciousness in (MacGregor & Vimal, 2008; Vimal, 2008a, 2008c, 2008d, 2009b), (ii) the 'Self' aspect in (Bruzzo & Vimal, 2007), (iii) the attention and emotion aspect in (Vimal, 2008a), and (iv) the phenomenal time aspect in (Vimal & Davia, 2008). In this article, the *phenomenal* and *access* awareness and SEs aspects are investigated; here, awareness and SE are interchangeably used unless noted.

One always wonders, why certain neural-networks are privileged to have awareness and others not? How SEs, such as *redness*, occur/emerge in brain? What are those factors that entail a neural-network being conscious? To address these interesting questions we need to investigate the *necessary* and *sufficient* ingredients involved in generating awareness in neural-networks. Based on available literature, at least six entities appear to be *essential* or *necessary* ingredients for *access* (reportable) awareness: **wakefulness** (Coull, 1998; Posner & Petersen, 1990; Siegel, 2004), **reentry** (Edelman, 2003; Wray & Edelman, 1996), **attention** (Crick & Koch, 2003; LaBerge, 1997; Tallon-Baudry, 2004), **working memory** (Chow, 1986; Frankland &

Bontempi, 2005; Magnussen, Greenlee, Asplund, & Dyrnes, 1991; Naghavi & Nyberg, 2005; Pasternak & Greenlee, 2005; Yeh, Yang, & Chiu, 2005), stimulus **at or above threshold leve**l for detection or discrimination (Vimal, 1997, 1998a, 1998b, 2000, 2002a, 2002b), and **neural-network proto-experiences** (a set of SEs embedded in a neural-network) (Bruzzo & Vimal, 2007; MacGregor & Vimal, 2008; Vimal, 2008a, 2008c, 2008d; Vimal & Davia, 2008). The criterion for the selection of *necessary* ingredients is that if any of them is missing, we will not have *access* awareness. For *phenomenal* (non-reportable) awareness, however, the *necessary* ingredients are wakefulness, reentry, iconic memory, stimulus at or above threshold level, and neural-network-PEs, whereas attention is not needed (Lamme, 2003). They are discussed below.

2.1. Wakefulness and Arousal system*:* Neural networks must be in wakeful state for awareness to occur. In other words, when wakefulness signal from ascending reticular activating system (ARAS) activate the neural-network, then SEs related to wakefulness will occur in the brain; this means that retina cannot be awake because it has no projection from ARAS. Whether neural-network is awake or not can be verified by EEG or by psychophysical experiments; for example α and β waves represent wakefulness and one can ask psychophysical questions to subjects and if answers are correct within normal range, then subjects are awake. SEs related to dreams are not the same as that related to wakefulness.

The neural source for the arousal system is the ascending ARAS in the brain stem (Siegel, 2004). According to (Faw, 2009), "While a sufficient level of **cortical arousal** is needed for each of the characteristics of consciousness, it seems most tied to qualitative experience. Cortical Arousal is produced by the reticular core of the upper brainstem in its projections to the cortex through two interacting routes: through the thalamus and through the hypothalamus and basal forebrain. The *thalamic* route involves brainstem acetylcholine projections to thalamic reticular nucleus to disinhibit the cortex, and brainstem glutamate projections to thalamic intralaminar nuclei to activate cortico-thalamic loops (Parvizi & Damasio, 2001). The *hypothalamic* route also involves brainstem acetylcholine and glutamate and hypothalamic hypocretin and histamine systems in projections to the basal forebrain whose acetylcholine projections to sub-cortex and cortex are involved in both REM and waking conscious arousal and attention (Faw, 2006; Schiff, 2004)."

In (MacGregor & Vimal, 2008), we have elaborated (a) the origination of signals related to cortical arousal in the cholinergic cells of brain stem reticular formation peribrachial nuclei, and (b) the signals that modulate the arousal (sleep and waking) states such as serotonergic, noradrenergic, and dopaminergic signals in other brain stem nuclei. The cells in the anterior hypothalamus and the adjacent preoptic area of the basal forebrain are critical for sleep (Siegel, 2004). In the anterior hypothalamus, the suprachiasmatic nucleus (SCN: the biological clock) synchronizes the sleep-wake cycle with the day-night cycle and plays an important role in the activation of sleep and arousal system with the help of melatonin; its high level in night leads to sleep and low level in the morning leads to arousal. Our fMRI study suggests that the BOLD activations of the SCN (in anterior hypothalamus) and that of the primary visual cortex vary in their response to light as a function of the time of day; however, the direction of change is opposite between these two regions (Vimal et al., 2009; Vimal et al., 2006). Furthermore, sleep state can also be considered as the inhibition of arousal system by the basal forebrain nuclei that send inhibitory GABAergic signal to the histaminergic neurons of posterior hypothalamus. The attentional system may interact with the arousal system (Coull, 1998; Mesulam, 1981; Posner & Petersen, 1990); attention of varying degree is involved in awareness in both awake and dream states (Kahn, Pace-Schott, & Hobson, 1997; Pareja & Gil-Nagel, 2000; Sarter & Bruno, 1999). In general, attentional areas also need to be aroused for proper functioning. Under deep sleep and deep anesthesia, signals for wakefulness and attention are missing; in dreams, the inputs for SEs are endogenously generated, but are different from SEs during wakefulness (Vimal, 2008a). Since awareness changes drastically from zero awareness during deep sleep to the high level of awareness during wakefulness, awareness study in the sleep-dream-wakeful cycle and also using anesthesia may lead to useful information (John et al., 2001). Thus, from the meta-analysis of above studies and the consistency among studies, we argue that wakefulness is *necessary* ingredient for awareness.

2.2. Reentry process: According to Edelman (Edelman, 2003), reentry is (i) a continuing process of 'recursive signaling' in neural-networks and (ii) a selectional process that occurs in parallel. Reentry links, binds, and dynamically alters the activities of distributed multiple brain areas for generating consciousness in the context of thalamocortical 'dynamic core'. In 'dynamic core', a group of neurons that were not present are included in the core at the next moment, whereas some of the neurons that were present leave the core.

For reentry, the related signal does not have to reenter to the same neuron; rather signal can reenter to the cells with similar receptive field (RF) center (in space). It is the RF that matters for reentry. Reentry can be direct (single synapse) or indirect (multi-synapses). Reentrant signals such as V2 ↔ V4 (from V2 to V4 and back to V2) and FEF ↔ V4 are not necessarily based on a single synaptic connection (Hamker, 2006). It could be argued that the reentry process in the neural network (consisting of dorsal and ventral visual pathways and frontal cortex) binds location (from dorsal pathway) and features (from ventral pathway). However, Hamker argued, "the receptive fields in V4 and TEO are not that big, so in the early stages the ventral pathway also encodes location" (Hamker, 2006). In addition, since both dorsal (such as LIP, MT, MST) and ventral areas (such as V4, TEO, IT) project to FEF, there might be more than one route for reentry and binding process.[b] Therefore, these two routes should be separated using appropriate psychophysical tasks combined with fMRI. We, thus, argue that reentry is another *necessary* ingredient for awareness.

2.3. Attention: Neurophysiologically, visual attention can be defined as a neural signal (including reentrant signal such as FEF ↔ V4) that modulates the main feed forward pathways (Treue, 2001) (ventral pathway: retina → LGN ↔ V1 ↔ V2 ↔ 'V8/V4/VO' ↔ IT ↔ GF and dorsal pathway: retina → LGN ↔ V1 ↔ V2 ↔ V5/MT/MST ↔ IPL/PPC) (Vimal, 2008a).[c] For example, attention modulates the activity of V2 and V4 neurons (Luck, Chelazzi, Hillyard, & Desimone, 1997; Spitzer, Desimone, & Moran, 1988).

Reentrant interactions among neural populations entail consciousness, whereas attention modulates consciousness (Edelman, 2003). In addition, attention might either transduce unconscious/subconscious information into reportable conscious experience or contribute in transduction process; attention is also essential for memory formation and planned action for future. Furthermore, Hamker argued, "attention is an emergent phenomenon that arises from reentry and competitive interactions. […] Attention is the result of mechanisms that act on the processed variables, such as gain control, by reentry and competitive interactions" (Hamker, 2005). Movement cells of FEF are the origin of spatial reentry (FEF ↔ V4, FEF ↔ IT); spatial attention, emerged during reentry from the FEF (to IT and V4) may enhance the gain of IT and V4 cells (Hamker, 2005).

There are reentrant signals at many areas. However, all reentrant signals are NOT attentional signals. Some of the reentrant signals are for processing information (including binding process) such as in unconscious processing. A slightly different but complementary view is as follows: there are top-down and bottom-up modulations at various levels such as (i) subcortical and cortical levels (LGN, V1, V2, V3, V4, V5, IT and so on) and (ii) conscious, subconscious, and unconscious levels (wakeful, sleep, dream, anesthesia and so on). However, all modulating signals are NOT attentional signals. Therefore, those reentrant signals or those modulations that consciously enhance the sensitivity of (or sharpen) the feed forward stimulus related signals are attentional signals; inhibition is also a part of modulation. Most of the attentional modulations are reentrant.

When we attentively look at any external object, the reflected light from the object is transduced by photoreceptors into electrical signal. This signal is transformed into feed forward glutaminergic signal at various stages such as retinal, LGN, and visual cortical levels. The faster (Chambers, Payne, Stokes, & Mattingley, 2004) part of this signal eventually reaches frontal cortex via dorsal pathway (V1 and/or SC (Chambers et al., 2004) → parietal cortex → frontal cortex (LaBerge, 1997; LaBerge, Auclair, & Sieroff, 2000)), which activates cholinergic (Bentley, Vuilleumier, Thiel, Driver, & Dolana, 2003; Sarter, Givens, & Bruno, 2001) attentional system. The slower part is the main stimulus related feed forward signal in the ventral pathway (retina-LGN-V1-V2-V8/V4/VO-IT-GF) and dorsal pathway (retina-LGN-V1-V2-V5/MT/MST-IPL/parietal cortex) (Chambers et al., 2004; Treue, 2001). The attentional signal from prefrontal cortex feeds

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[b] The double arrow (↔) indicates reentry. TEO: inferior temporal-occipital visual area at occipito-temporal junction, located between the ventral portion of V4 and temporal cortex. FEF: frontal eye field; V5 is visual area 5, MT is middle temporal visual area, and MST is middle superior temporal area; they are related to motion. LIP is the lateral intraparietal area.

[c] LGN: Lateral geniculate nucleus. IT is inferior temporal cortex related to object recognition. GF is fusiform gyrus face area. IPL is intraparietal lobule and PPC is posterior parietal cortex. PFC is prefrontal cortex, which has two parts: dorsolateral PFC (DLPFC) and ventrolateral PFC (VLPFC).

back (i) to parietal area for location-based attention (LaBerge, 1997; LaBerge et al., 2000) and then to visual areas (Belmonte & Yurgelun-Todd, 2003; Coull, 1998; Di Russo, Martinez, & Hillyard, 2003; Pessoa, Kastner, & Ungerleider, 2002; Small et al., 2003; Yantis & Serences, 2003) and (ii) to occipitotemporal area for object-based attention (LaBerge, 1997; LaBerge et al., 2000).

Where is attention and its effect located?: The 'sources' of attention may be located in frontal cortex (such as ACC, MFG, DLPFC, VLPFC (ventro-lateral PFC)) and thalamic reticular nucleus (TRN). Attentional modulations are reported in almost all visual cortex including V1 and LGN (O'Connor, Fukui, Pinsk, & Kastner, 2002). However, the strength of attentional effects increases as one moves up from LGN (Cook & Maunsell, 2002; Treue, 2003). The biphasic involvement of angular gyrus (AG) of the right parietal cortex suggests that both fast (retinotectal: retina-SC-pulvinar-intraparietal lobule (IPL)) and slow (geniculostriate: retina-LGN-V1-V2-'V5/MT/MST'-IPL) parietal visual pathways are necessary for orienting spatial attention (Chambers et al., 2004).

What is selected by attention?: Attention selects places/locations, target's features/attributes, objects, or more complex representations such as faces and surfaces (Morrone, Denti, & Spinelli, 2004; O'Craven, Downing, & Kanwisher, 1999; Pashler, Dobkins, & Huang, 2004; Reynolds, Alborzian, & Stoner, 2003; Reynolds & Chelazzi, 2004; Sanborn, Malmberg, & Shiffrin, 2004; Sohn, Papathomas, Blaser, & Vidnyánszky, 2004; Treue, 2003; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). Non-spatial feature-based attentional modulations are found even outside the cell's receptive field (RF) (McAdams & Maunsell, 2000; Treue, 2001, 2003) and in human MT-complex (Saenz, Buracas, & Boynton, 2002). Attentional effects could be both retinotopic (Brefczynski & DeYoe, 1999; Tootell, 1998) and object-based (Duncan, 1984). Object-based (selective) attentional modulation is found in ventral occipitotemporal cortex (Avidan, Levy, Hendler, Zohary, & Malach, 2003; Yantis & Serences, 2003). The location ('where') area may be parietal cortex and the identification ('what') area may be IT (Baars, 1999).

How attention generates saliency map?: The top-down visual attentional feedback signal from fronto-parietal network modulates the visual feed forward color signal in visual area 'V8/V4/VO' (Tootell et al., 2003), motion signal in visual area V5 (Buchel & Friston, 1997), face recognition signal in GF (Aharon et al., 2001; Wojciulik, Kanwisher, & Driver, 1998), emotion signal in amygdale (Gallagher & Holland, 1994), or reward signal in nucleus accumbens (Knutson, Adams, Fong, & Hommer, 2001). Bottom-up signal (Wörgötter & Eysel, 2000) including thalamic reticular nucleus (TRN) (Barrett et al., 2003; Pinault, 2004) for stimulus-salience and other modulatory signals (such as dopaminergic, serotonergic, and noradrenergic) could also be considered as attentional signals. The top-down and bottom-up processes interact to optimize attentional performance (Egeth & Yantis, 1997; Sarter et al., 2001). That is bottom-up saliency map (enhanced representation of attended relative to unattended stimuli) is strengthened or weakened by its interaction with the top-down saliency map (feedback attentional modulation based on the behavioral relevance of a specific feature, object, or location) (Treue, 2003). *Why saliency map?*: For high-resolution examination, overt eye movement (tightly coupled to the attentional gain increase) brings the fovea to the most salient stimuli, using the saliency map and FEF (Schall, 2002) and lateral IPL (Kusunoki, Gottlieb, & Goldberg, 2000) activations (Treue, 2003).

Furthermore, the **top-down** 'source' of attentional modulation may be frontal cortex (Buchel & Friston, 1997; Rowe, Friston, Frackowiak, & Passingham, 2002). The **bottom-up** 'source' may be GABAergic thalamic reticular nucleus (**TRN**) (Baars, 1995; Crick, 1984; Kinsbourne, 1995; Mitrofanis & Guillery, 1993; Scheibel & Scheibel, 1966; Yingling & Skinner, 1977), serotonergic dorsal and medial raphe nucleus (**RN**) (Harrison, Everitt, & Robbins, 1997), noradrenergic locus coeruleus (**LC**) (Coull, 1994; Delagrange, Canu, Rougeul, Buser, & Bouyer, 1993; Selden, Robbins, & Everitt, 1990; Sturm et al., 1999), and dopaminergic substantia nigra (**SN**) (Milton, Marshall, Cummings, Baker, & Ridley, 2004). The arousal signal from brainstem reticular formation (of pons and medulla) inputs to thalamic intralaminar nucleus (ILN) (Bogen, 1995a; Kaufman & Rosenquist, 1985; Royce, Bromley, & Gracco, 1991). ILN sends signal to TRN that mediates selective attention (Baars, 1995; Crick, 1984; Kinsbourne, 1995; Mitrofanis & Guillery, 1993; Scheibel & Scheibel, 1966; Yingling & Skinner, 1977). This arousal signal triggers the bottom-up attentional processing (Sarter et al., 2001). Reticular nucleus (and possibly adjoining perigeniculate nucleus: PGN) receives excitatory signals from LGN and V1 and sends inhibitory signal to LGN (Baars, 1995; Crick, 1984; Pinault, 2004; Scheibel & Scheibel, 1966; Uhlrich, Manning, & Feig, 2003). This signal presumably suppresses irrelevant information in retino-LGN-cortical pathway for stimulus salience. LGN↔V1 loop (involving TRN) further selects and amplifies the feed-forward signal (Baars, 1995; Crick, 1984; Pinault, 2004). In other words, the bottom-up signals from TRN in selective attention appear to be reentrant. This is because LGN and V1 excite TRN cells and TRN cells inhibit LGN cells. That is, TRN signals reenter LGN to suppress irrelevant not-target signals in selective attention. We do not know if RN, LC, and SN modulating signals are also reentrant signals, which needs further investigation.

Hamker assumed that V4 is the key area for location processing (Hamker, 2005). However, posterior parietal cortex (PPC) is assigned for encoding spatial location (Andersen, 1995). Cells in the dorsolateral cortex show maintained activity for object location whereas cells in the ventral cortex show maintained activity for object identity (Wilson, Scalaidhe, & Goldman-Rakic, 1993). Location switching produced activations at anterior and medial to other types of switches in both anterior and posterior right intraparietal sulcus (IPS) (Wager, Jonides, & Reading, 2004). The location ('where') area may be parietal cortex and the identification ('what') area may be IT (Baars, 1999). In other words, one could argue that PPC may play important role in addition to V4 for location signal, and the reentrant signal from FEF to PPC could also bind location and feature (indirectly from V4 to FEF) attributes similar to the reentrant signal from FEF to V4 for binding location and feature attributes. Both top-down attention and reentry signals may be involved in the binding process. If we consider attention as a mental entity that emerges in brain, then it's one of the neural correlates (for spatial selective attention in visual search) is the reentrant neural signal that feedbacks from FEF to V4, which enhances the sensitivity of feed forward stimulus related signals in V4 and binds the location and features of the stimulus. There might be other neural correlates of attention such as FEF↔PPC neural network. For example, the signal via faster route (retina → superior colliculus → parietal lobe → FEF) might generate this attentional signal in frontal cortex (for example some salient event has occurred and system should 'attend' it).

Furthermore, visual attention tasks can be grouped into five forms, namely, (i) foveal short-sustained, long-sustained, and vigilance attention tasks, (ii) covert attention task, (iii) divided attention task, (iv) selective (or focused) attention task, and (v) switching attention task; these five aspects of visual attention are detailed in (Vimal, 2008a).

One could also argue that 'experienced self' is a part of the 'stream of consciousness', which provides the background for the central focus of attention (Stapp, 2005). Awareness during dream may have degraded attention (Sarter & Bruno, 1999). Attention is *necessary* but not *sufficient* for *access* awareness (Kentridge, Heywood, & Weiskrantz, 2004). Attending one visual stimulus may lead to temporary blindness to other unattended stimuli (Perry & Hodges, 2003). There seems to be no (report of) awareness in the absence of attention (Lamme, 2003). Thus, '*no attention* means *no (reportable) awareness*' appears to be valid statement. However, top-down selective attention and awareness can be dissociated; for example, subjects can be aware of the pop-out in visual search or the gist of a scene without or very little top-down selective attention; on the other hand, in aftereffect and priming, subjects can attend but are not aware of invisible objects (Koch & Tsuchiya, 2007). This needs further elaboration and qualification to make it more precise. For example, as discussed in Section 1, there are two types of awareness: (i) *Phenomenal* awareness is not reportable, which presumably occurs during less than 50 msec stimulus presentation such as in Sperling type experiments (Sperling, 1960). For this attention is not needed. (ii) *Access* awareness is reportable, for which attention is necessary; it takes longer time than *phenomenal* awareness. In PE-SE framework (Vimal, 2008c), attention is defined as neural signal that modifies the feed forward stimulus dependent main signal. Attention could be top-down (such as fronto-parietal signal) or bottom-up (such as thalamic reticular signal in selective attention). In other words, *phenomenal* awareness can occur without top-down attention and top-down attention can occur without *phenomenal* awareness; for example, subjects can attend to perceptually invisible objects.

Furthermore, Prefrontal cortex (PFC) is involved in attention tasks (Wager et al., 2004). However, subjects with bilateral removal of PFC appear to be both subjectively aware and volitional (Bogen, 1995b). Therefore, attentional-modulation must involve additional areas (such as TRN (Crick, 1984; Pinault, 2004) for stimulus-salience based bottom-up attentional signal). The overlap between attention, working memory, episodic memory, and awareness appeared in the bilateral parietal cortex (BA 7 and BA 40; close to IPS), and dorsolateral PFC (DLPFC: right BA 9 and left BA 6) (Naghavi & Nyberg, 2005).

In our PE-SE framework (MacGregor & Vimal, 2008; Vimal, 2008c), neurotransmitters/neuromodulators, involved in attention and arousal systems, play important role by regulating (visual) awareness; they are detailed in (MacGregor & Vimal, 2008).

To sum up, there are two types of reentry processes, one related to attention and other that is not related to attention (such as binding process). These two types of reentry processes should be separated using appropriate psychophysical tasks and fMRI. For example, attention related reentry areas could be separated first and then areas related to non-attentional reentry could be investigated by subtraction method (see Section 4). Furthermore, areas common to all five attention tasks and areas specific to a specific task should be investigated (see Section 4). From the meta-analysis of above studies and the consistency among studies, we argue that attention is another *necessary* ingredient for awareness.

2.4. Memory: There are three types of memory: (i) Iconic (or sensory) memory refers to the visual image a subject holds onto after briefly looking at an object. Iconic memory is by nature fleeting. The site of visual iconic memory might be visual areas (Lamme, 2003), which appears to be essential for retaining information for *phenomenal* awareness (Rowlatt, 2009) because there is not enough time for the top-down attention to act on it. (ii) Short-term (or working) memory stores information that is needed to recall in the subsequent seconds, minutes, or hours. The site of visual short term memory might be frontal (such as PFC), parietal, and also visual areas (Lamme, 2003; Pasternak & Greenlee, 2005). The working memory (WM) maintains internal representations to guide actions. This memory appears to be essential for retaining information for *access* (reportable) awareness (Rowlatt, 2009). "Working memory refers to an active system for maintaining and manipulating information in mind, held during a short period, usually of seconds" (Deco & Rolls, 2005). Short-term memory for figure-ground organization was found in the visual area V2 (O'Herron & von der Heydt, 2009). (iii) Long-term memory (LTM) stores salient information that is recalled after a day to years. Attention plays an important role in the formation of LTM; LTM is useful but does not appear to be necessary for *access* awareness. The site of LTM might be medial temporal lobe system and hippocampal area (Frankland & Bontempi, 2005).

Attention and working memory are closely related cognitive processes (Kastner & Ungerleider, 2000). For example, if we search for a familiar face in a crowd, we hold the information required to identify the face 'on-line' in WM. We selectively attend to different people in the crowd until we find the face matching our internal template in WM. In other words, selective attention process actively holds a location or object as the attentional target in WM and modulates earlier cortical processing (Deco & Rolls, 2005). The close relationship between WM and selective attention suggests that they may share common neural mechanisms (Desimone, 1998). The overlap between WM and attention is most prominent in DLPFC and bilateral parietal cortex (Naghavi & Nyberg, 2005). The WM-encoding is done in PFC WM-cells, and the matching of the incoming pattern with the memorized pattern is done in PFC match cells (Bledowski, Prvulovic, Goebel, Zanella, & Linden, 2004; Hamker, 2005). When both (incoming and WM) patterns match, IT cells can drive PFC match cells (Hamker, 2005). When PFC match cells are activated, (a) the target is detected in visual search, (b) input into the fixation cell of frontal eye field (FEF) is removed, which then disinhibits the movement cells of FEF, and (c) an eye movement is executed towards the target for further scrutiny (Hamker, 2005). In visual search, *overt* eye movement is necessary because IT represents mostly what is close to the fovea (Deco & Rolls, 2005). Attention appears to play an essential role in transferring stimuli from iconic memory (250-500 ms)(Chow, 1986) to visual short-term memory or WM (duration <= 30 s for the spatial frequency of grating patterns (Magnussen et al., 1991)) (Yeh et al., 2005). Attention switching among perceptual items and stored items in WM is needed in (a) manipulating information in WM, (b) maintaining information in WM while processing other information, and (c) selecting which information should be stored in WM.

Furthermore, the sensory memory for the *phenomenal* awareness and the working memory for the *access* awareness and perhaps the working memory for *reflexive (or reflective)* awareness (Block, 2001; Rowlatt, 2009) is consistent with the principle of *structural*, *functional* and *experiential* cohesion (Chalmers, 1995).

Reentry, attention, memory, and awareness: In general, reentry interactions can be grouped in two categories: attention related reentry (or simply 'attention') and awareness related main reentry (or simply 'reentry') signals. Attention signals could be top-down (such as FEF ↔ V4) and bottom-up (LGN ↔TRN) reentry signals; the effect of attentional reentry as a gain control mechanism would be to modulate the feed-forward stimulus related signal. The awareness related main reentry signals will include stimulus related thalamocortical signals in ventral pathway (retina → LGN ↔ V1 ↔ V2 ↔ 'V8/V4/VO' ↔ IT ↔ GF) and dorsal pathway (retina → LGN ↔ V1 ↔ V2 ↔ V5/MT/MST ↔ IPL/PPC) along with lateral interaction. Visual attention and visual WM may be closely related: DLPFC may support spatial WM and could be a 'source' of spatial attention that modulates the location signal in PPC, whereas VLPFC may support object WM and could be the 'source' of attention signal that modulates the target object signal in IT. The interaction of visual feed-forward (bottom-up), attentional fronto-parietal feedback (top-down) signal, and reentrant signals in awake extrastriate higher visual and/or parietal areas results in visual awareness (Crick & Koch, 2003; López, 2003; Sarter et al., 2001; Wray & Edelman, 1996) by the matching and selection mechanisms in the dual-aspect-dual-mode PE-SE framework (Vimal, 2008a, 2008c, 2009b) (Section 2.7). Reentry process is necessary for the emergence of consciousness/awareness (Friston, ononi, Sporns, & Edelman, 1996; Wray & Edelman, 1996), attention modulates the consciousness/awareness (Edelman, 2003), and memory retains the information for consciousness/awareness. Though attention and WM are closely related, areas for attention and memory should be separated using appropriate psychophysical tasks combined with fMRI (Section 4). From the meta-analysis of above studies and the consistency among studies, we argue that working memory is another *necessary* ingredient for awareness.

2.5. Stimulus level

Stimuli could be external or internal. For detection, discrimination and recognition, the contrast of external stimulus should be at or above threshold contrast. Here, threshold level is defined as the critical stimulus-contrast at which the percent correct response is 50%; one could raise it to 75% depending on methods used (Vimal, 1997, 1998a, 1998b, 2000, 2002a). Suprathreshold contrast is obviously better for awareness. Our psychophysical experiments related to detection and discrimination (Vimal, 1997, 1998a, 1998b, 2000, 2002a) validates this hypothesis. Internal stimuli could be endogenously generated such as in thought processing, day-dreaming, imagery, dreams, phosphenes (Vimal & Pandey-Vimal, 2007), and so on. The states of mind/brain other than wakefulness (such as in dream, alternated states, and so on) are beyond the scope of this article and are deferred for future investigations. From the meta-analysis of above studies and the consistency as described in Section 1, we argue that 'stimulus at or above threshold' is also *necessary* ingredient for awareness; below threshold, a system is considered as subconscious.

2.6. Executive functions

Executive functions (EFs) — the 'CEO', 'orchestra conductor' or 'central command and control station' in our brain — include (i) the initiation of and the overall control of goal directed behavior, such as suppressing the activation of irrelevant information, creating and maintaining goal-related behaviors, and temporally sequencing behavior, (ii) the initiation of and the overall control of the execution of deliberate actions, (iii) strategic planning, (iv) decision making, (v) effortful and flexible organizational skill, (vi) future-oriented behavior, (vii) self-regulation, (viii) attention, and (ix) working memory (Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Fine, Lumsden, & Blair, 2001). It is critical to recognize that most of these functions are phenomena of distributed neural processing. Some of areas involved in EFs are (i) DLPFC for initiation and execution of deliberate actions, (ii) anterior cingulate cortex (ACC) for monitoring the consequences of actions (Ito, Stuphorn, Brown, & Schall, 2003), and (iii) cerebellum for coordinating movement. Attention and WM, which are *necessary* for awareness, are also the parts of EFs. Areas PFC and ACC are also activated in attention tasks. One can ask the following questions: Are other components of EFs also *necessary* for awareness? Is motor action (for generating reports for *access* awareness) also *necessary* element for awareness? Do we need to redefine awareness to include EFs and motor action? If so, then fMRI experiments should be designed to isolate the components of EFs, such as (i) to (vii) and motor action, similar to attention and working memory. Furthermore, some areas are activated by multiple processes. For example, DLPFC supports EFs such as attention, memory, planning, and possibly other functions. DLPFC is a large area; some part of DLPFC may be assigned to WM, some to attention, and some to planning function. Alternatively, whole of DLPFC may support multiple functions; if so, the underlying mechanism for each of them could be separated. Otherwise, one can ask if mechanisms are also the same for the functions that a group of neurons support. These need further research.

2.7. Neural-network proto-experiences

What are the proto-experiences (PEs), exactly? PEs are precursors of SEs.[d] SEs are those experiences that satisfy the necessary ingredients of SE (such as wakefulness, attention, reentry, working memory, stimulus at or above threshold, and so on), and that are expressed (i.e., that are not covert or unexpressed). In (Vimal, 200x), the three competing hypotheses of the dual-aspect-dual-mode PE-SE framework (Vimal, 2008c, 2009b) are summarized: "(i) *superposition* based hypothesis $\mathbf{H_1}$, (ii) *superposition-then-integration* based $\mathbf{H_2}$, and (iii) *integration* based hypothesis $\mathbf{H_3}$ where the superposition is not required. In $\mathbf{H_1}$, the fundamental entities and inert matter are the *carriers* of superimposed fundamental subjective experiences (SEs)/proto-experiences (PEs). In $\mathbf{H_2}$, the fundamental entities [strings or elementary particles] and inert matter are the *carriers* of superimposed fundamental PEs (not SEs), which are *integrated* by *neural-Darwinism* (co-evolution, co-development, and sensorimotor co-tuning by the evolutionary process of adaptation and natural selection). […] In $\mathbf{H_3}$, a string has its own string-PE; a matter is not a *carrier* of PE(s) in superposed form as it is in $\mathbf{H_2}$, rather it is a proto-experiential entity and has two aspects at every level; $\mathbf{H_3}$ is a dual-aspect panpsychism. These two aspects are rigorously *integrated* together by *neural-Darwinism*. […] In hypothesis $\mathbf{H_1}$, PEs are precursors of SEs in the sense that PEs are superposed SEs in unexpressed form in the mental aspect of every entity, from which a specific SE is selected via matching and selection process. In hypotheses $\mathbf{H_2}$ and $\mathbf{H_3}$, PEs are precursors of SEs in the sense that SEs *somehow* arise/emerge from PEs". A specific SE is selected from neural-network PEs using matching process as described in (Vimal, 2008c, 2009b), and then this selected SE becomes 'expressed-SE'.

2.7.1. The dual-aspect-dual-mode PE-SE framework

In materialism, SEs are emerged entities from neural-networks; however, emergentism leads to the problem of explanatory gap. Therefore, these material entities must have some trace of mental entities (such as elemental Proto-experiences (PEs)). In other words, matter must have associated elemental PEs in physicalism (materialism + experiences). PEs are proposed to close the psychophysical or explanatory gap (Levine, 1983): how subjective experiences (SEs) can emerge from non-experiential matter, such as neural-networks. Here, this is called Type-1 explanatory gap.

The dual-aspect-dual-mode PE-SE framework is detailed in (Vimal, 2008c, 2009b), which is concisely described as follows. We hypothesized that string or elementary particles (fermions and bosons) have two aspects: (i) mental aspect such as elemental proto-experiences (PEs) and (ii) material aspect such as mass, charge, spin, and so on (Vimal, 2008c). Elemental PEs are a group of irreducible fundamental SEs/PEs that are in superimposed (or superposed) form in the mental aspect of string or elementary particles (Vimal, 2008d). Since SEs/PEs are superposed, strings or elementary particles are not specific to any SE/PE; rather, they (and all inert matter) are *carriers* of SEs/PEs. Therefore, elementary particles and all inert matter act as non-experiential material entities (Vimal, 2008c). In the dual-aspect-dual-mode PE-SE framework (Vimal, 2008c, 2009b), the *neural Darwinism* is referred to the hypothesis that matter and associated elemental PEs co-evolved, co-developed, and co-tuned via sensorimotor interaction into neural-networks and associated neural-network PEs, respectively. The feed-forward signals interact with that feedback signals in a neural-network; this interaction leads to the selection of neural-network PEs via matching process (Vimal, 2008c, 2009b). The neural-network PEs are a set of SEs embedded and stored as memory traces in the neural-network by the processes related to *neural Darwinism*. In addition, the non-specificity of elementary particles is transformed into the specificity of neural-networks via *neural Darwinism*. For example, a specific SE *redness* is selected from the embedded neural-network color PEs in visual 'V4/V8/VO' neural-network by the

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[d] The terms 'experience', 'subjective experience', and 'phenomenal experience' are interchangeably used. Strictly speaking, the term 'experience' refers to PEs/SEs superposed in the mental aspect of all entities; the term 'subjective experience' refers to experience that is experienced by a subject; the term '*phenomenal* experience' refers to experience in *phenomenal* awareness where attention-related feedback signals do not get time to interact with feed-forward signals and hence these experiences cannot be reported. In *access* awareness, an experience can be reported.

matching process (Vimal, 2008c, 2009b) when the network is activated either by external stimulus such as a long wavelength light or by endogenously generated internal signals such as that from memory.

Moreover, the matching process activates the 'state space' (Churchland, 1988) in dynamical systems theory (DST: continuous time-varying systems with energy exchange and information processing). The DST-state-space (Churchland, 1988) can explain (i) unity of consciousness, (ii) qualia/SEs, (iii) spectrum of consciousness (deep sleep to meditative states), (iv) personality (slowly varying pattern of thought and behavior but consistent over time), (v) knowledge (memory), and (vi) intentionality (the content of every mental phenomenon, such as belief and desire, is directed at an object) as discussed in (Skrbina, 2009). In addition, "spatiotemporal processing emerges from the interaction between incoming stimuli and the internal dynamic state of neural networks, including not only their ongoing spiking activity but also their 'hidden' neuronal states, such as short-term synaptic plasticity" (Buonomano & Maass, 2009).

In addition, the specificity of a SE increases when feed-forward and feedback signals interact in the neural-network. The *necessary* ingredients for SEs are wakefulness, attention, re-entry between neural populations, working memory, stimulus at or above threshold, and neural-network PE signals. The matching and selection process (Vimal, 2008c, 2009b) for a specific SE could be accomplished classically by matching the signal due to external stimulus in feed-forward pathway with the signals related to the embedded neural-network PEs (as memory traces) in a specific neural-network leading to the selection of the specific SE. In addition, orchestrated objective reduction (Orch OR) model (Hameroff & Penrose, 1998), based on quantum coherence in dendritic microtubule-network (Engel et al., 2007), might also be involved in the selection of the specific SE from a set of many neural-network PEs (embedded in microtubule-network). In this network, the quantum conjugate matching (Globus, 2005) might also be involved (Vimal, 2008a, 2009b). The collapse of many states (or PEs) into a specific SE may depend on the stimulus. One could argue that the neural-network PEs embedded in neural-networks can be considered as neural-correlates of Penrose Platonic values encoded in fundamental space-time geometry (Hameroff & Penrose, 1998). The number of possible SEs for Orch OR, however, can be reduced by sensorimotor tuning during development in a neural-network (*neural Darwinism*). For example, the X-linked red-green V4/V8/VO-neural-network embeds only red-green color related SEs as neural-network PEs.

According to (Vimal, 2008d), the material aspect of the behavior of system in string theory remains invariant with the introduction of SEs/PEs in superposed form. This requires that SEs/PEs in superposed form might be present in one space and one time 'hidden' dimensions of F-theory to satisfy the condition of minimum action, and the Neumann and Dirichlet boundary conditions. The introduction of SEs/PEs in superposed form in the mental aspect of string unifies consciousness with all four fundamental material forces. This leads to the theory of everything (Vimal, 2008d).

The term 'superimposition' or 'superposition' refers to the process in which all kinds of SEs are laid over on say in the mental aspect of electron. This means that an electron is not specific to any specific SE; and the electron acts as if it is a non-experiential material entity. In the dual-aspect-dual-mode PE-SE framework (Vimal, 2008c), an electron is a *carrier* of experiential entities (SEs/PEs), and hence it is not proto-conscious. This is because (a) electron cannot have SEs and (b) to have SE the entity/system needs to have *necessary* ingredients of having SEs such as wakefulness, attention, re-entry, and memory (that is possible in neural-networks). One could argue that nature took billions of years to evolve from elementary particles to neural-networks. Thus, although SEs are irreducible entities, they cannot be experienced at various levels. It is only when observation is made via matching process (Vimal, 2008c, 2009b), a specific SE is experienced by a specific neural-network after objective-reduction (or collapse) of many neural-network-PEs into to one specific SE say *redness* when stimulus say long wavelength light is presented. A neural-network is necessary to have experience. Therefore, all (from quantum electrons to classical neural-networks) are considered to have PEs rather than SEs, except when necessary ingredients for having SEs are satisfied. In other words, elemental-PEs and PEs at other levels can be considered as they have *potentialities* or *possibilities* for actualizing SEs when neural-networks are formed. The term 'superimposition' is used (more or less) in the same sense as the term 'superposition' used in the quantum mechanics. For example, "**In the first process**, a physical system constantly evolves into a <u>superposition</u> of possibilities or tendencies, […] for actual events to occur. […] **In the second process**, the transition from the "possible" to the "actual" takes place […] when observation is made, in which one of states <u>superimposed</u> in the probability function is selected and becomes real in the ordinary sense" (underline mine) (Schäfer, 1997). For example, if Red-Green 'V4/V8/VO'-neural-network can have SEs *redness, orangeness, yellowness, yellowish-greenness,* and *greenness*, then these SEs can be embedded in this neural-network in superposed form: $\alpha_{redness}\,|redness\rangle + \alpha_{orangeness}\,|orangeness\rangle + \ldots + \alpha_{greenness}\,|greenness\rangle = \Sigma\alpha_i\,|SE_i\rangle$, where α is a coefficient related to probability distribution of SE in the network during embedding process (Vimal, 2008d). In quantum physics, the probability is defined as the square of the coefficient of the superposition. When a stimulus is presented, then a specific SE is selected from many embedded SEs and the coefficient α corresponding to the specific SE takes the values of 1 and all other coefficients change to zero.

According to Vimal (Vimal, 2008a), the PE-SE framework consists of four hypotheses, namely, co-evolution and co-development of mind and brain, internal-representation, sensorimotor interaction, and dual-aspect model to link *structure, function,* and *experience*. (Vimal, 2008a).

The co-evolution and co-development need further elaboration. They are based on the evolution and development of brain, mind, environment, and culture, which need variations for the natural selection to act on. For example, (Jablonka & Lamb, 2007) described four different types of heritable variation: (i) genetic (DNA-based), (ii) epigenetic (self-sustaining feedback loops, chromatin marking, structural and RNA-mediated inheritance), (iii) behavioral (socially mediated learning), (iv) symbolic/cultural (associated with human, symbol specific processes involving language, mathematics, music, visual arts). Variations which may influence behavior can be transmitted between individuals through the soma, by-passing the germ line, and ecological legacies may lead to the transmission of behavioral, symbolic and developmental legacies. Each inheritance system can provide variations on which natural selection can act, and the organism's developmental history can influence some of them. Cultural changes may often construct new selection regimes and hence lead to the selection of variants in new contexts, which change in the genetic composition on populations. Epigenetic, heritable variations, however, can be directly induced when the environment changes (Jablonka & Lamb, 2007). Interactions between different mechanisms have played important roles in sensorimotor tuning and the evolution of human behavior (Jablonka & Lamb, 2007). For organism-environment interaction and sensorimotor tuning (*neural Darwinism*), see (Bridgeman, 2007) related to the tuning of eye-lens-focus and receptive fields: "The high-resolution information comes from the world, not the genes".

According to (Vimal, 2009a), "The dual-aspect-dual-mode framework of consciousness, based on neuroscience, consists of four components: (1) dual-aspect primal entities; (2) *neural-Darwinism*: co-evolution and co-development of subjective experiences (SEs) and associated neural-nets from the mental aspect (that *carries* the SEs/proto-experiences (PEs) in *superposed* and unexpressed form) and the material aspect (mass, charge, spin and space-time) of fundamental entities (elementary particles), respectively and co-tuning via sensorimotor interaction; (3) matching and selection processes: interaction of two modes, namely, (a) the non-tilde mode that is the material and mental aspect of cognition (memory and attention) related feedback signals in a neural-network, which is the cognitive nearest past approaching towards present; and (b) the tilde mode that is the material and mental aspect of the feed forward signals due to external environmental input and internal endogenous input, which is the nearest future approaching towards present and is a entropy-reversed representation of non-tilde mode; and (4) the *necessary* ingredients of SEs (such as wakefulness, attention, re-entry, working memory, stimulus at or above threshold level, and neural-net PEs)."

The above hypotheses and components of the PE-SE framework (a) lead to structural and functional coherence between mind and brain, (b) link *structure, function,* and *experience*, and (c) bridge the explanatory gap (Vimal, 2008c).

2.7.2. *Formation of neural-network and the selection of SE: neural Darwinism*

In materialism/emergentism, the hypothesis is that SEs *somehow* emerge in neural-networks (Vimal, 2008a); but, precisely how SEs emerge is not clear. The dual-aspect-dual-mode PE-SE framework (Vimal, 2008c, 2009b) hypothesizes that a specific SE is selected by a matching process during the interaction between feed-forward and feedback signals in neural-networks. The selection of SE *redness* can be qualitatively unpacked as follows (Vimal, 2008c): (i) there exist a 'virtual reservoir' (detailed in (Vimal, 2008c)) that *stores* all possible fundamental SEs/PEs in superposed form, (ii) the interaction of long wavelength light-stimulus dependent feed-forward and feedback signals in the 'V4/V8/VO' Red-Green color neural-network creates a specific neural-network state, (iii) this specific state is assigned to a specific SE, *redness*, from the virtual reservoir during *neural Darwinism* (co-evolution, co-development and sensorimotor co-tuning by the evolutionary process of adaptation and natural selection), (iv) this specific SE, *redness*, is embedded as a memory trace of neural-network-PE, (v) similarly, all SEs get embedded in appropriate neural-networks, and (vi) when, for example, a specific *redness*-related stimulus (such as long wavelength light) is presented to the 'V4/V8/VO' Red-Green color neural-network, the associated specific SE, such as *redness*, is selected by the matching and selection process (Vimal, 2008a, 2008c, 2009b) and experienced by this network. Let us call the steps (i)-(vi) **hypothesis H_1**. The generation of specificity involved in premises (iii)-(vi) can be further unpacked using *neural Darwinism* (Vimal, 2008c). In the dual-aspect-dual-mode PE-SE framework (Vimal, 2008c), the embedding process and matching-selection process (Vimal, 2008a, 2009b) for generating specificity of SE, can be achieved using *neural Darwinism*. As specific neural-network is formed via *neural Darwinism*, the specificity of the neural-network for SEs/PEs also increases. One could argue that the parvocellular pathway is specific to color vision because its lesion leads to the loss of color vision (Merigan, 1989; Merigan, Katz, & Maunsell, 1991; Schiller, Logothetis, & Charles, 1990). The mechanisms such as retinal tiling ("to provide a complete representation across the entire visual field of the attributes it conveys to the brain"), hierarchical processing, parallel processing (to overcome neural limited spatial bandwidth and "the anatomical bottleneck of the optic nerve"), and modularity ("defined spatially and by cell type-specific connections") are used for visual perception (Nassi & Callaway, 2009) (see also (Zeki & Shipp, 1988)). One could hypothesize that (a) they are necessary for generating specificity in specific visual neural-networks for both functions (such as discrimination of red from green patterns) and experiences (such as *redness*), and (b) the hierarchical processing may lead to novel *emergent* properties, such as novel *functions* and perhaps *experiences* as in hypotheses **H_2** and **H_3**. For example, the specificity of Reddish-Greenish color opponent channel (L – 2M) (Krauskopf, Williams, & Heeley, 1982; Krauskopf, Wu, & Farell, 1996) related neural network containing (L – M) and (M – L) color opponent neurons is higher than the specificity of L- or M-cone signals.[e] This is because (L – M) and (M – L) color opponent neurons represent color SEs between *redness* and *greenness*: *redness, orangeness, yellowness, yellowish-greenness,* and *greenness* and all just-noticeable differences (JND) between them. Whereas, L- or M-cone signals represent significant large number of SEs such as all color SEs of Reddish-Greenish color opponent channel plus part of SEs involved in Yellowish-Bluish color opponent and luminance channels (Krauskopf et al., 1982; Krauskopf et al., 1996), and other vision related SEs such as shape, depth, and so on. According to (Vimal, 1998b), "the R-G [Red-Green] channel used here is very close to the Reddish-Greenish cardinal axis … but may be different from the L-M channel, … however, all these channels are due to the transformation of cone signals. … Cone-weightings for chromatic and achromatic channels are not clear; they depend on the models and the methodologies used by the investigators. For example, L, M, and S cone-weightings for respective R-G, Yellow-Blue, and achromatic channels are (1) [L - 2M, S - (L + M), 2L + M = V_λ], … (2) [L - 2M, S - (L + M), L + M] (Krauskopf et al., 1982; Krauskopf et al., 1996), (3) on average [0.74L - 0.67M- 0.02S, 0.39L + 0.39M - 0.83S, 0.96L + 0.28M - 0.05S]"; Cone weightings [L - M, S, 2L + M + S] (Krauskopf et al., 1982; Krauskopf et al., 1996) and [L - M, S - (L + M), L + M] (Chaparro, Stromeyer, Kronauer, & Eskew, 1994; Stromeyer, Kronauer, Ryu, Chaparro, & Eskew, 1995) are also reported. These channels are calibrated during co-development and sensorimotor co-tuning as discussed in (Vimal, 2008c). The calibration of Reddish-Greenish color opponent channel suggests that a specific SE (such as *redness*) is selected in the related Reddish-Greenish 'V4/V8/VO'-neural-network. This happens when long wavelength light in 'isolation' (such as dark background/surround without any context related to color induction and color assimilation) is presented to the neural-network and when the network satisfies the *necessary* ingredients of SEs. Further details are given in (Vimal, 2008c, 2009b).

It is known in psychophysics (D'Antona & Shevell, 2006; Engel, Zhang, & Wandell, 1997; Kaiser, Ayama, & Vimal, 1986; Kaiser & Boynton, 1996; Kaiser, Vimal, Cowan, & Hibino, 1989; Pokorny, Shevell, & Smith, 1991; Ruttiger et al., 1999; Schier, 2007b; Shevell & Cao, 2006; Sun, Pokorny, & Smith, 2001; Vimal, 2000; Vimal, Pandey, & McCagg, 1995) that SE/appearance of color depends both on the spectral attribute of the target and on the spectral, spatial, temporal and figural attributes of the surround or entire visual field, as in

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[e] L, M, and S represent long wavelength sensitive cone, middle wavelength sensitive cone, and short wavelength sensitive cone sensitivities, respectively.

the SE/appearance of color in color induction or simultaneous color contrast and color assimilation. In other words, if one manipulates these attributes appropriately then just about any surface can appear red; this implies that there does not appear to be any simple mapping from a specific color SE, say *redness*, to some objective property of surfaces (Schier, 2007b). Nevertheless, illumination-independent and background-independent color constancy is still approximately achieved in our daily lives (Schier, 2007b). This provides a strong evidence for *neural Darwinism* because once a specific neural-network is formed during 'co-evolution, co-development, and sensorimotor co-tuning' (i. e., *neural Darwinism*) for say *redness*, then SE *redness* will be experienced by any means that activates the *redness*-related neural-network. For example, even if other methods —such as electrical stimulation or meditation-induced cortical phosphenes and pressure-on-eye-balls induced retinal phosphenes (Vimal & Pandey-Vimal, 2007)— activate the already developed *redness*-related neural-network, SE *redness* will be experienced.

As mentioned before, in the dual-aspect-dual-mode PE-SE framework with **hypothesis H_1**, irreducible fundamental SEs/PEs are superimposed in the mental aspect of all fundamental entities (strings, or fermions such as electron and bosons such as photon) as elemental-PEs. This entails that external objects also have experiences superimposed in their mental aspect and act as a *carrier* of SEs/PEs. In other words, photons have experiences superimposed in their mental aspect; however, 650 nm spectral light may have higher specificity because less number of experiences may be superimposed in its mental aspect, such as *redness* and nearby color experiences but not experiences related to blueness, audition, taste, olfaction, somatosensory and so on. This makes *neural Darwinism*, and matching and selection processes simpler. In addition, 'red-color' that is the property of object (Byrne & Hilbert, 2003) may also play role in *neural Darwinism* for generating specific color related SEs, such as *redness*. This view is sympathetic to radical externalism (Honderich, 2006), sensory-motor account of vision ('seeing is a way of acting') (O'Regan & Noë, 2001), fractal catalytic theory ("experience arises as an organism mediates (catalyzes) the transitions in its surround") (Carpenter, Davia, & Vimal, 2009), and brain as a decoder (Robbins, 2007).

Furthermore, the two complementary mechanisms for the matching and selection of a specific SE are as follows (Vimal, 2008a, 2009b): (i) In classical axonal-dendritic mechanism, a specific SE is selected from SEs **embedded in neural-network** based on the stimulus-dependent signals by matching process during the interaction of feed forward stimulus-dependent signals with fronto-parietal attentional feedback signals. (ii) In quantum dendritic-dendritic mechanism, quantum Orch OR occurs in MT network (Hameroff & Penrose, 1998), where SE say *redness* is selected from SEs **embedded in spacetime geometry** by objective reduction (collapse) of superimposed SEs in the mental aspect of neural-network to the specific SE say *redness* when stimulus say long wavelength light is presented. The coherence between feed-forward incoming and reentrant feedback signals is necessary for SEs. Therefore, both classical and quantum mechanisms may involve matching process during the interaction of feed forward stimulus-dependent signals with fronto-parietal attentional feedback signals, where the SEs embedded in neural-network/spacetime geometry match with the experiences superimposed in the mental aspect of external and/or internal stimulus-related signal for the selection of a specific SE (Vimal, 2008a, 2009b).

Furthermore, SEs superimposed in the mental aspect of stimulus-dependent neural signals after phototransduction in photoreceptors (for example) plays important role in *neural Darwinism* that helps the selection of a specific SE *redness* (for example) in the red-green 'V4/V8/VO'-neural-network. In addition, stimulus-dependent neural signals raise their specificity via appropriately formed neural circuits during co-development and sensorimotor tuning (neural Darwinism), such as via the three-channel model of color vision, namely two color-opponent channels and one luminance channel (Kaiser & Boynton, 1996; Krauskopf et al., 1982; Vimal, 1998b, 2002b) as discussed above. In other words, the embedding of SEs *redness-greenness* closely follows the formation of its functional Red-Green color opponent psychophysical channel (Vimal, 1998b, 2002b) in its neural correlates V4/V8/VO Red-Green neural-network (Bartels & Zeki, 2000; Hadjikhani et al., 1998; Tootell et al., 2003; Wandell, 1999).

Since one can have *access* (reportable) awareness in the range of 75-500 msec depending on the complexity of scene (Beeckmans, 2007), it is hypothesized that some of specific SEs for specific neural-network states might have been 'stored' (for having SE faster) in the respective neural-networks during co-development and sensorimotor tuning (*neural Darwinism*).

Neural Darwinism is consistent with the hypothesis that when Jackson's Mary (Jackson, 1986), although expert in color vision, did not have SE *redness* when she was in her black-white room since birth; however, when she leaves the room and interacts with red color objects she will have SE *redness* after appropriate sensorimotor tuning .

Alternative hypothesis is as follows. According to the principle of *emergence*, the physical property of salt (NaCl) *emerges* from the interaction of its constituents Na^+ and Cl^- ions because the property of salt is not present in its constituents (Vimal, 2008a). In analogy to this, a specific SE, such as *redness*, can emerge in a neural-network from interaction of its constituent neural-PEs in 'V4/V8/VO'-color neural-network: call it **hypothesis H_2**. For example, the reportable SE *redness* might have emerged during the interaction of two types of signals: (i) feed-forward long wavelength (say 600 nm) stimulus dependent PE-carrying-neural-signal from retina to LGN to V1 to 'V4/V8/VO' color area (call it FF_{600}) and (ii) feedback fronto-parietal attention related re-entrant PE-carrying-neural-signal (call it FB), i.e., *redness* related to 600 nm light is SE *redness*$_{600}$ = $(FF_{600})*(FB)$, in analogy to $NaCl = (Na^+)*(Cl^-)$. Another analogy is that water emerges from the interaction of hydrogen and oxygen; water is entirely new entity that is not in any way the sum of its parts. This is consistent with Schier, who argued, "the colour visual facts are structurally emergent" (Schier, 2007a). However, the mind-dependent-reality (MDR) vs. mind-independent-reality (MIR) (Müller, 2007) and how they are related to SEs need to be addressed. It should be noted that $FF_{600} = \Sigma\alpha_i\ [FF_{600}]_i$ and $FB = \Sigma\beta_k\ [FB]_k$ where i and k represent i^{th} and k^{th} neural-signal, and α and β are weighting factors; for non-reportable *phenomenal* SE, FB = 0. Further research is needed to investigate if hypotheses H_1 and H_2 are complementary to each other or one of them needs to be rejected.

To sum up, the two hypotheses H_1 and H_2 can address the two types of explanatory gaps (Vimal, 2008a). Type-1 explanatory gap is the famous Levine's explanatory gap (Levine, 1983): how SEs can emerge from non-experiential matter. We encountered Type-2 explanatory gap, which is how it is possible that our SEs (such as happiness, sadness, painfulness, and similar SEs) were already present in primal entities, whereas there is no shred of evidence that such SEs were conceived at the onset of universe. In hypothesis H_1**,** string, elementary particles, and inert matter are considered as the *carriers* of fundamental (not derived) SEs/PEs superimposed in their mental aspect. The *neural Darwinism* and matching and selection processes (Vimal, 2008a, 2009b) assist in generating and selecting a specific SE in a neural-network. We used the concept of fundamental and derived SEs/PEs. SEs/PEs that can be derived from the irreducible fundamental SEs/PEs are called 'derived' or 'secondary' SEs/PEs. For example, happiness, sadness, and similar emotional SEs might have been derived from irreducible fundamental emotional-type proto-experience(s) interacting with the context of emotional stimuli. In hypothesis H_2, string, elementary particles, and inert matter are the *carriers* of fundamental PEs (not SEs) superimposed in their mental aspect. There is a PE attached to every level of evolution, such as atomic-PE, molecular-PE, genetic-PE, neural-PE, and so on. A specific SE emerges in a neural-network from the interaction of its constituent neural-PEs, such as in the interaction between feed-forward stimulus-dependent neural signals and fronto-parietal feedback attentional signals; this is in analogy to the emergence of physical property of salt from the interaction of sodium and chlorine ions. In both hypotheses, SEs occur when *necessary* ingredients of SEs (such as wakefulness, attention, re-entry, working memory and so on) are satisfied. Perhaps, hypothesis H_2 is closer to neuroscience because it does not have Type-2 explanatory gap, which is, however, implicit in hypothesis H_1. In hypothesis H_2, since PE co-evolves with matter, PE (the mental aspect of an entity) is inter-dependent on the *structure* and *function* of material aspect of that entity. For example, the water-PE (liquidity/liquidness) is inter-dependent on structure and function of the liquid water, ice-PE (solidity/solidness) on that of ice, steam-PE on that of steam. Similarly, the SE *redness* is inter-dependent on the *structure* and the *function* of *redness*-related 'V4/V8/VO' Red-Green neural-network and is selected (in H_1) or emerges (in H_2) during the interaction of two types of signals (feed forward and feedback neural signals). Thus, neural-network PE should also be considered as a *necessary* condition for awareness; otherwise, the explanatory gaps cannot be addressed. In other words, the formation of specific neural-networks for specific functions and related specific experiences is necessary; otherwise, specific SE will never be experienced.

From the methodology of meta-analysis of various authors' studies in Sections 2.1-2.7 and consistency methods, we argue that wakefulness, reentry, attention, working memory, stimulus at or above threshold, and neural-network PEs are *necessary* ingredients for awareness. It is not clear if other executive functions (listed in Section 2.6) are also *necessary* for awareness. According to Feigl (Feigl, 1967), "Inductively it is plausible that sentience requires complex organic processes." If this is true then 'complex organic process' is another *necessary* ingredient. Once all *necessary* ingredients are investigated then one could ask if they are *sufficient*. This needs further research.

Critique: One could critique that strings or elementary particles are not specific to any SE/PE; rather, they (and all inert matter) are carriers of SEs/PEs would require extraordinary evidence, given that the particles are at least eight orders of magnitude smaller than the chemical events that characterize brain function, and the strings are ten orders of magnitude smaller yet. However, no evidence is given for this assertion.

The evidence is that they (strings, elementary particles, inert matter, molecules, proteins, neurotransmitters and so on) behave as if they are non-experiential entities. This behavior is consistent with materialism on which all our physical science is based. It is only when a neural-network is formed and when this network satisfies the necessary ingredients of experiences, it has a specific experience via matching and selection mechanisms, for example, V4/V8/VO-neural-net for color. Furthermore, there is evidence that experiences (such as *redness*) are irreducible, fundamental and inherent; for example, one cannot reduce *redness* to any other entity. Our hypothesis is that all experiences are superposed in the mental aspect of matter (such as strings, elementary particles, molecules, proteins, neurotransmitters and so on) in unexpressed form because matter behaves as if it is non-experiential entity. Most neuroscience models that employ materialism/emergentism directly or indirectly have serious problem of explanatory gap (Levine, 1983): how experiences can emerge from non-experiential matter like brain's neural-networks. This is addressed by the dual-aspect-dual-mode PE-SE framework in the current article.

3. Red-Green Channel and Visual Awareness

There are three aspects in a conscious system, which need to be linked: structure, *function*, and *experience* (awareness, SE, qualia); this is elaborated in this section. A computational framework or a framework based on other standard models of neuroscience and cognition correlates structure and function well. However, they fail to link experience with structure-function. It is indeed 'hard' to generate SE via computational model; that is why Chalmers classifies SE as a 'hard problem', and structure and function as easy (tractable) problems (Chalmers, 1995) . The dual-aspect-dual-mode PE-SE framework (a novel concept in neuroscience) (Vimal, 2008c, 2009b), concisely described in Section 2.7, links all these three aspects and addresses the 'hard problem', which is a major contribution of this article. Thus, the dual-aspect-dual-mode PE-SE framework and the standard neuroscience frameworks are complementary to each other, which are further discussed here.

3.1. Psychophysics of color vision

A *psychophysical* entity is an abstract mathematical construct derived by modeling the experimental data related to psychophysics and neurophysiology. For example, there are 3 psychophysical visual (cardinal (Krauskopf et al., 1982)) channels (such as the Red-Green, the Yellow-Blue, and the achromatic or luminance channels) derived from psychophysical and physiological data (Hurvich & Jameson, 1957; Kaiser & Boynton, 1996; Krauskopf et al., 1982). In this article, we focus on the Red-Green channel (Hurvich & Jameson, 1957; Vimal, 1998b, 2002b) or Reddish-Greenish cardinal channel (Krauskopf et al., 1982); other psychophysical entities can be unpacked in a similar way. The genuine first-person measurements lead to the subjective experience of color qualia such as *redness* to *greenness* (see also (Dennett, 2003)). The third-person measurements will reveal the physical attributes such as neural activities in related neural-network that includes visual red-green (R-G) color area 'V4/V8/VO'. In addition, the experience of hue, saturation and brightness (first-person data) (Vimal, Pokorny, & Smith, 1987) correlates with the activity of its neural-network and the properties of associated color stimuli (third-person data). This *psychophysical* entity (such as the R-G channel) provides a link between first-person data (*phenomenal or mental aspect,* such as *redness* to *greenness*) and third-person data (*physical aspect,* such as 'V4/V8/VO R-G color neural-network'). In other words, a *psychophysical entity* acts like a mental entity during first-person measurements and a physical entity during third-person measurements. Subjective experiences (SEs) *redness* to *greenness* and 'V4/V8/VO R-G color neural-network' are causally related via the Red-Green channel. That is, active 'V4/V8/VO R-G color neural-network' causes SEs *redness* to *greenness* upon the presentation of equiluminant red-green patterns via the spatial frequency tuned mechanisms of the Red-Green channel (Vimal, 1998b, 2002b); these are external stimulus driven SEs. Subjective experience of color can also occur by internal activation, such as electrical stimulation, transcranial magnetic stimulation (TMS), and 'meditation-induced cortical phosphenes with eyes closed' (Vimal & Pandey-Vimal, 2007).

Using psychophysical orientation masking technique, we found that the orientation tuning curves of the spatial frequency (SF) tuned mechanisms of the Red-Green channel are broader than those of the achromatic mechanisms (orientation half-bandwidths: 68^{o}-30^{o} for color vs. 32^{o}-15^{o} for luminance channel) (Vimal, 1997). Using oblique and orthogonal masking techniques, we found five SF tuned bandpass mechanisms (peak SF's 0.13, 0.5, 2, 4, and 8 cycles per degree; bandwidths: 4, 3.1, 2.1, 1.1, and 1.3 octaves) and one lowpass mechanism of the Red-Green channel (Vimal, 1998b, 2002b). Orientation gains are one of the factors involved in the transformation of information from nonoriented to oriented mechanisms (Vimal, 2002b). The crossed (color-test/luminance-mask and luminance-test/color-mask) tuning curves are bandpass functions of mask-SF, which are mostly narrower than their respective uncrossed (color-test/color-mask and luminance-test/luminance-mask) SF tuning curves (Vimal, 1998a). In general, color and luminance channels interact at suprathreshold contrasts; color masks luminance mildly more than luminance masks color for SFs >= 0.5 cpd; the opposite seems to prevail for lower SF, such as 0.13 cpd (Vimal, 1998a). The color-contrast-constancy is partly achieved at high contrasts and the information processing at suprathreshold levels is different from that at the threshold levels (Vimal, 2000). Color and luminance SF discrimination thresholds have a different SF dependence; while color appears to perform better than luminance vision at low SFs, this effect is lost or even reversed at high SFs; color and form interact, but color and motion are largely segregated (i.e. they weakly interact) (Vimal, 2002a). These reports elucidate spatial properties of the Red-Green channel.

Furthermore, in a divided attention task (with near-absence of peripheral attention), subjects were able to discriminate the gender of peripheral faces with high performance whereas their performance of color discrimination (peripheral red-green vs. green-red disk) was very low (Reddy, Wilken, & Koch, 2004). Moreover, the fusiform gyrus (GF: for face recognition) is at higher level in ventral pathway than 'V4/V8/VO' and/or IT (for red-green vs. green-red discrimination). In other words, the effect of divided attention is less at GF level than that at 'V4/V8/VO' level in their dual-task paradigm. Thus, *phenomenal* awareness could also be associated with higher stages of ventral system. This hypothesis can be tested using fMRI.

3.2. Neural-network for function and experience

The dual-aspect-dual-mode PE-SE framework predicts that the formation of a specific neural-network for a specific function (such as red-green color detection and discrimination) and for a specific experience (such as redness or greenness) is necessary; otherwise the specific SE will never be experienced.

As reviewed in (Nassi & Callaway, 2009) (see also (Dacey, 2004; Milner & Goodale, 2008)), (i) there are at least 80 different neuron-populations and 20 distinct neural-networks in the retina for processing visual input signals, which constitute at least a dozen parallel pathways that project to visual cortex for further processing. (ii) The two separate but interconnected parallel processing streams of the extrastriate cortex are the dorsal pathway for the visual control of skilled actions and navigation, and the ventral stream for the recognition of objects and their spatial relationships. (iii) In the ventral stream, the midget ganglion cells (70% of the total population of cells) project to the parvocellular layers of the LGN, which in turn project to layers 4Cβ and 6 of V1 and eventually to 'V4/V8/VO' color area. This is related to the Red-Green color opponent psychophysical channel.

(iv) Both the blobs and interblobs project to the thin stripes (Xiao & Felleman, 2004); this is an improvement on the original proposal of highly segregated functional streams that blobs of V1 → thin stripes of V2 → V4 (for color), interblobs of V1 → pale stripes of V2 → V4 (for form/pattern), and 4B of V1 → thick stripes of V2 → V5/MT (for motion and depth) (Albright, 1984; DeAngelis, Cumming, & Newsome, 1998; Livingstone & Hubel, 1988; Shipp & Zeki, 1985, 1989; Zrenner et al., 1990).

(v) According to (Nassi & Callaway, 2009), "cell type specific connectivity allows for systematic combinations of early parallel pathway inputs despite the misleading appearance of indiscriminate intermixing at the laminar or compartmental level … it seems that early parallel pathways of the retina and the LGN are recombined in V1 into both spatial and cell type-specific modules to form multiple output channels that project to specific areas of the extrastriate cortex." This is consistent with (Sincich & Horton, 2005a, 2005b). One could hypothesize that the pathway 4Cβ → interblobs (layer 2/3) of V1 → thin stripes of V2 ↔ 'V4/V8/VO' might play role perhaps in the processing of the saturation and brightness aspects of color, whereas 4Cβ → blobs → thin stripes of V2 ↔ 'V4/V8/VO' may be for the hue aspect of color processing; this hypothesis needs to be tested.

(vi) The visual area 'V4/V8/VO' processes color information (Bartels & Zeki, 2000; Conway, Moeller, & Tsao, 2007; Hadjikhani et al., 1998; Tootell et al., 2003; Wandell, 1999); "V4 neurons develop direction-of-motion selectivity after adaptation" (Tolias, Keliris, Smirnakis, & Logothetis, 2005) and "strong extraretinal signals for direction matching were found in V4" (Ferrera, Rudolph, & Maunsell, 1994); V4 & IT process color and form (pattern, shape) discrimination (Distler, Boussaoud, Desimone, & Ungerleider, 1993; Nakamura, Gattass, Desimone, & Ungerleider, 1993) and binocular disparity (Janssen, Vogels, & Orban, 1999; Uka, Tanaka, Yoshiyama, Kato, & Fujita, 2000; Watanabe, Tanaka, Uka, & Fujita, 2002), and IT processes color and pattern/shape (Desimone, Albright, Gross, & Bruce, 1984; Komatsu & Ideura, 1993).

(vii) The visual area V4 contains separate modules (DeYoe, Felleman, Van Essen, & McClendon, 1994; Xiao, Zych, & Felleman, 1999; Zeki & Shipp, 1989), which are perhaps related to segregated color processing (Conway et al., 2007): (a) "The cells projecting from V2 to V4 are arranged in bands and the number of bands per cycle of cytochrome oxidase stripes varies (one cycle consists of a thin stripe, a thick stripe and two interstripes). In the Type 1 connectivity pattern, there is just one band per cycle, centred over the thin stripes but normally spreading into the neighbouring interstripes. In the Type 2 connectivity pattern there are two bands per cycle, generally rather narrower and centred over the interstripes. Thick stripes are mostly free of labelled cells. The return projection from V4 to V2, whilst being concentrated in the vicinity of the labelled cells, is more diffusely distributed and invades the territory of all the stripes"(Zeki & Shipp, 1989). (b) "V4 and the ventral posterior inferotemporal cortex, each contain anatomical subdivisions that have distinct input and output projections. … modularity and multistream processing within individual cortical areas are widespread features of neocortical organization" (DeYoe et al., 1994). (c) "A small iontophoretic injection, either in a thin stripe or an interstripe, labeled a large primary and several secondary foci in V4. The primary foci from the thin stripe and interstripe were spatially segregated by a gap of approximately 1 mm. Furthermore, less dense regions within the primary foci were often 'filled-in' by secondary foci from the opposite V2 compartment. When two injections were made both at interstripes, their projections to V4 were almost entirely overlapping. These anatomical patterns indicate that segregation and convergence of intercortical pathways are both important features of V4 organization. Furthermore, the size of cortical modules increases considerably from the blobs of V1, through the stripes of V2, to the afferent domains of V4" (Xiao et al., 1999). (d) "Almost all cells located in globs showed strong luminance-invariant color tuning and some shape selectivity. [A glob is a large region (several millimeters wide) encompassing V4, PITd, and posterior TEO, which is distributed within posterior inferior temporal (PIT) cortex.] Cells in different globs represented distinct visual field locations, consistent with the coarse retinotopy of this brain region. Cells in "interglob" regions were not color tuned, but were more strongly shape selective. Neither population was direction selective. These results suggest that color perception is mediated by specialized neurons that are clustered within the extrastriate brain" (Conway et al., 2007).

The above is helpful in proposing that the neural correlate of color related subjective experiences is 'V4/V8/VO'-color-neural-network. One could hypothesize that this network consists of: (a) the main color processing network in the ventral pathway (retina → parvocellular layers of the LGN ↔ cytochrome oxidase-rich blobs (and also interblobs) of the layer 2/3 of V1 ↔ thin stripes of V2 ↔ 'V4/V8/VO') ↔ IT ↔ GF; (b) the attentional network such as [fast (retinotectal: retina → SC → pulvinar → intraparietal lobule (IPL)/parietal cortex) and slow (geniculostriate: retina → LGN → V1 → V2 → 'V5/MT/MST' → IPL/parietal cortex)] → frontal cortex/PFC (such as FEF) ↔ 'V4/V8/VO';[f] (c) other auxiliary networks such as emotion, face, and color related network such amygdala system ↔ GF ↔ IT ↔ 'V4/V8/VO', location and color related dorsal network such as parietal cortex ↔ FEF ↔ 'V4/V8/VO', and so on; (d) the ARAS arousal system that sends projections to thalamocortical neural-networks to bring them to wakefulness as a baseline for awareness to occur; (e) the memory related areas such as PFC, parietal and visual areas (Lamme, 2003; Pasternak & Greenlee, 2005); and (f) Self related areas (Bruzzo & Vimal, 2007; Northoff et al., 2006). The areas

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[f] See Section 2.3 and (Chambers et al., 2004; LaBerge, 1997; LaBerge et al., 2000; Rossi, Pessoa, Desimone, & Ungerleider, 2009).

up to V2 are involved in processing local aspects of color vision (Lennie, Krauskopf, & Sclar, 1990). The visual area V4 is involved in more global processing such as contextual information in color constancy, color induction, and color discrimination (Hurvich & Jameson, 1957; Kaiser & Boynton, 1996; Wray & Edelman, 1996; Zeki, 1983a, 1983b). The IT is involved in color vision (Komatsu, Ideura, Kaji, & Yamane, 1992), but its functional role is not clear.

3.3. Computational color vision

The **computational model** of Wray and Edelman (Wray & Edelman, 1996), that links structure and function (but not SE), consists of three reentrant pathways mediated by the long-range intrinsic connections (i) within V1/V2, (ii) within V4, and (iii) the backward connections from V4 to V1/V2. Color is represented as the ratio between the firing levels of four populations of cells (red, green, yellow, and blue) in V4. The IT is assumed to provide a spatially organized map that explicitly represented a given color by specific firing patterns within one population of cells. The implicit representation of hue and saturation in V4 is remapped onto explicitly represented color as a population vector in IT. Their (Wray & Edelman, 1996) findings are as follows: (i) Long-range intrinsic connections within V4 have the greatest effect on both constancy and induction. (ii) Long-range intrinsic connections within V1/V2 have a smaller but significant effect on color constancy. The color induction effects depend on the size of the stimulus surround: V1/V2 and V4 have equivalent effects with small surrounds. (iii) The backward connections from V4 to V1/V2 have insignificant effect on color constancy but have measurable effect on color induction. They concluded that long-range reciprocal reentrant connections within and between cortical areas could mediate a dynamic process of reentry, which could integrate contextual cues into the color percept. This is consistent with psychophysical and physiological data on color constancy and color induction (Hurvich & Jameson, 1957; Kaiser & Boynton, 1996; Singer & D'Zmura, 1994; Wray & Edelman, 1996; Zeki, 1983a, 1983b).

Furthermore, to link structure, function and SE, ventral stream (retina → LGN ↔ V1 ↔ V2 ↔ 'V4/V8/VO' ↔ IT → GF) (Bar et al., 2001; Kanwisher, 2001; Moutoussis & Zeki, 2002; Zrenner et al., 1990) with neural-network PEs (Vimal, 2008c) can be implicated for visual awareness, but it is also activated by unperceived stimuli (Driver, Vuilleumier, Eimer, & Rees, 2001; Moutoussis & Zeki, 2002); therefore the ventral system is not sufficient for visual awareness. Fronto-parietal attentional areas with neural-network PEs are also involved in *access* awareness (Lumer & Rees, 1999).

3.4. Event-related brain potential measurements and awareness

The event-related brain potential (ERP) measurements in EEG study showed that visual *phenomenal* awareness initially emerged independent of selective attention and earlier than selective attention (Koivisto, Revonsuo, & Salminen, 2005): The earliest part of visual awareness negativity (VAN) (130–200 ms) at occipital sites was independent of attention, suggesting *phenomenal* awareness. However, attention independent VAN of 130-320 ms (peaking at ~260 ms) was also reported at posterior sites (Koivisto, Revonsuo, & Lehtonen, 2006). This difference may be because in the latter study attentional modulation was different (global vs. local attention). Further research is needed. The later part of visual awareness negativity (200–260 ms) was affected (enhanced) by selective attention at posterior temporal sites, which may correspond to the formation and recall of coherent object representations (Wolfe, 1999). The late positive amplitude enhancement (LP) (290-700 ms, peaking around 400 ms) at parietal sites, representing late stages of conscious processing, seem to depend strongly on attention that modulates awareness (Koivisto et al., 2006; Koivisto et al., 2005). The LP is associated with *access* (reportable) or *reflective* awareness, which includes updating of working memory, reporting, identification, categorization, naming the stimulus (Block, 2001; Donchin & Coles, 1988). The selective attention, independent of visual awareness, was observed for target stimuli; it can affect the processing of a target stimulus that does not enter visual awareness (Koivisto et al., 2005). In general, VAN is related to *phenomenal* awareness and LP is related to *access* or *reflective* awareness.

To sum up, for subjective experiences (SEs) (such as *redness* to *greenness*) related to the Red-Green channel, the internal representation of color stimulus is needed in 'V4/V8/VO R-G neural-network'. This neural-network needs to be awake, attentive, and re-entrant and needs to have working memory and stimulus should be at or above threshold level for having a SE of color.[g] For color, the feed-forward stimulus dependent signal needs to interact at 'V4/V8/VO' color area with fronto-parietal attentional feedback signal to generate visual awareness of color. Moreover, there are three main levels for unfolding the attributes of the Red-Green channel: (i) psychophysical level (such as spatial frequency, temporal frequency, orientation, and wavelength-tuned mechanisms), (ii) neurophysiological level (such as 'V4/V8/VO'-neural-network, and (iii) awareness level (such as the subjective experiences *redness* to *greenness*). I have tried to integrate psychophysical, neurophysiological, and consciousness research for the Red-Green Channel; however, further research is needed to clearly link all these levels. In general, one could argue that the psychophysically derived three channels and mechanisms in each channel have two aspects: (i) mental aspect, such as visual awareness or subjective experiences *redness* to *greenness* related to the Red-Green channel, and (ii) physical aspect, such as its neural correlates 'V4/V8/VO-neural-network'.

Thus, the goal (B) is accomplished by linking the three aspects of a conscious system, namely, structure, function, and SE as discussed in Sections 2.7 and 3, which is further detailed in our previous articles in the following order: (Vimal, 2008c), (Vimal, 2009b), (Vimal, 2008d), (Vimal, 2008a), (MacGregor & Vimal, 2008), and (Bruzzo & Vimal, 2007).

4. Future directions

For goal (C), a few simple experimental designs related to the Reddish-Greenish cardinal color channel are proposed (a) to separate areas for attention, reentry, wakefulness, and memory, (b) to separate *access* and *phenomenal* awareness, and (c) to investigate the *necessary* and *sufficient* attributes of visual awareness. To define equiluminant Reddish-Greenish cardinal color channel for each subject, one needs to isolate (a) the chromatic channels from the achromatic channel by estimating equiluminance ratios (Vimal, 1997, 1998a, 1998b, 2000, 2002a, 2002b) and (b) the Reddish-Greenish cardinal from Yellowish-Bluish cardinal channel (Krauskopf et al., 1982; Webster & Mollon, 1994). The Reddish-Greenish pattern is generated by making the greenish pattern in spatial antiphase with the reddish pattern using the result of this isolation process. One could use simple stimuli with luminance contrast, but then the experimental design will address the luminance channel; for chromatic channels, we need to do extra work in setting up proper stimuli.

(a) Separating areas for attention, reentry, wakefulness, and memory: In order to investigate neural correlates of consciousness (NCC), activities in thalamocortical dynamic core need to be measured at various level of consciousness (such as deep sleep, deep anesthesia, dream, and conscious wakeful state). In addition, activity correlated with stimulus needs to be separated from that with conscious percepts (such as in binocular rivalry) at both cortical and thalamic levels (Edelman, 2003). Furthermore, we need to separate the areas for the *necessary* ingredients of *access* awareness: areas for attention, areas for reentry processes excluding attention, areas for wakefulness, and areas for memory. The test stimulus can be color pattern for the Red-Green channel (such as reddish-greenish equiluminant pattern) (Vimal, 1997, 1998a, 1998b, 2000, 2002a, 2002b). Attention could be at high and low levels. The 'targets' of attentional signal depend on the test stimulus. For example, the 'targets' of attention may be the visual area 'V4/V8/VO' for color test stimulus.

In Vimal (Vimal, 2008a), we have detailed a fMRI experimental protocol to separate attentional areas from '*other*' areas. Here, we will concisely describe it. '*Other*' areas consist of those areas that not the attentional areas, but they are also activated by visual attention tasks depending on the stimuli used. For example, '*other*' areas may include (i) visual areas (such as V1 and V2) for both color and luminance contrasts, (ii) visual areas (such as 'V8/V4/VO') for 'only color contrast' and color identification, (iii) areas involved in working memory (such as PFC), (iv) areas for iconic memory, long term memory, task performance, thought processing, perceptual categorization, reasoning, planning, evaluation of alternatives, decision-making,

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[g] The retina (a) does not appear to have projections from ARAS system, (b) does not have reentry from LGN and higher level, and (c) does not have attentional feedback; therefore, the retina is not awake, not reentrant, and not attentive and cannot create visual awareness. However, the retina participates in the essential stimulus related feed forward visual processing for all three psychophysical visual entities: Red-Green, Yellow-Blue and luminance channels. Without retina, normal visual system and its awareness will be completely shut down.

rational control of action, (v) areas for wakefulness, (vi) areas involving non-attentional reentry, and (vi) remaining areas as detailed in (Vimal, 2008a). Some of these areas may be involved in reentry process and other executive functions (Section 2.6).

For separating attentional areas from non-attentional or '*other*' area, we need three conditions (Vimal, 2008a):

(1) Fixation condition (**F**): 'looking at white fixation light on dark background', (2) non-attentional condition (**N**): 'fixation at the center without attention to the test stimulus', and (3) attentional condition (**A**): 'fixation at the center and high level of attention to the test stimulus'. Our psychophysical studies (Vimal, 1997, 1998a, 1998b, 2000, 2002a, 2002b) were performed with high degree of attention. The activated areas for these three conditions are adapted from the Eqs. (1)-(3) of (Vimal, 2008a) as follows:

$$\mathbf{F} = \mathbf{A_f} + \mathbf{O_f} \quad (1)$$

$$\mathbf{N} = \mathbf{A_f} + \mathbf{O_f} + \mathbf{A_n} + \mathbf{O_n} \quad (2)$$

$$\mathbf{A} = \mathbf{A_f} + \mathbf{O_f} + \mathbf{A_h} + \mathbf{O_h} \quad (3)$$

In the left side of above equations, **F**, **N**, **A**, represent fixation, non-attentional, and attentional conditions, respectively; in the right side, 'A' and 'O' indicate attentional and '*other*' areas, respectively. The subscripts 'f', 'n', and 'h' on the right side represent foveal, *no*-attention, and high-attention conditions, respectively. One can assume that the activation A_n is small, $A_n << A_h$, and $O_n \sim O_h$. The attentional areas can be separated from the subtraction map $(A - N) \sim (A_h - A_n) \sim A_h$. The '*other*' areas can be separated from the subtraction map $[(A - F) - A_h] \sim O_h$. We have used subtraction method successfully in (Vimal et al., 2009; Vimal et al., 2006).

Furthermore, if we need to separate color area as well, then '*other*' areas will include areas mentioned in (i) and (iii)-(vii). Accordingly, more conditions need to be included in above equations leading to tasks that are more complex for subjects. One can simplify if multiple sessions with simple tasks are included in the design. For example, Eqs. (1)-(3) will separate attentional areas from non-attentional areas; another set of three conditions can be set up for separating memory areas from non-memory areas in another session, and so on. In other words, experimental designs should balance between subject-difficulty and long tiring sessions versus a number of short sessions with different tasks. Furthermore, the areas involved in wakefulness may include ARAS system such as brain stem reticular formation peribrachial nuclei and hypothalamus as discussed in Section 2.1. This can be verified using whole brain sagittal scan that includes brain stem areas. John's work (John et al., 2001) may be useful in separating the areas involved in wakefulness. Moreover, neural network model, such as extension of Hamker's model, can be useful in detailing how the mechanisms of wakefulness, reentry, attention, and memory lead to visual awareness.

(b) Separating areas for *access* and *phenomenal* awareness: The above groups of experiments can be extended to address the separation of *phenomenal NCC* from *access NCC* (Block, 2005; Lamme, 2003; Sperling, 1960). Attention is necessary for *access* (reportable) awareness but not for *phenomenal* awareness (Lamme, 2003), although they are still controversial (Baars & Laureys, 2005; Fell, 2004; Kentridge et al., 2004; Tallon-Baudry, 2004). One can test the hypothesis that (a) *phenomenal NCC can be separated from the access NCC and (b) access NCC = phenomenal NCC + attention* (Block, 2005; Lamme, 2003). The iconic memory (not durable and erased quickly) does not need attention, so it may be related to *phenomenal* NCC (Block, 2001; Sperling, 1960). Therefore, the above attention experiments can be performed with short (Block, 2001; Sperling, 1960) test-stimulus duration of 1 frame (16.7 msec for LCD projector or color monitor with the frame rate of 60 frames per sec). The test pattern in conditions N and A can be 16.7 msec ON and 2983.3 msec OFF (for TR = 3000 msec), which can be repeated for 10 times. At the end of experiment, subjects can be asked about their subjective experiences (such as color, shape, contrast, brightness, sharpness and anything else they can tell) during N and A conditions. Although subjects can be instructed not to attend in condition N, some residual attention may still be present. With this limitation, one can test the possibility that the subtraction maps (N – F) for '*no*-attention' condition does not involve attentional-modulation areas but subjects may have *phenomenal* awareness, whereas (A – N) may involve some transient attentional-modulation areas even though it is of short duration (Sperling, 1960). For this purpose, subtraction maps (N – F) and (A – N) for both short (Block, 2001; Sperling, 1960) (16.7 msec) and long (30 sec) stimulus-durations can be compared and examined further for testing the above hypothesis. As discussed in Section 3, the ERP methods are useful for separating *phenomenal* awareness and *access* awareness in temporal domain (Koivisto et al., 2006; Koivisto et al., 2005) and should be investigated further.

The data of above groups of experiments can also test the hypothesis that a part of *common* attentional areas will always be activated. This is because a conscious subject by definition has to be awake and hence must always be attending on 'something' (Fell, 2004) whether it is 'attention' or '*no* attention' condition. This can easily be rejected if one can find a single fMRI session (in which a subject is conscious) that does not activate this common area. Otherwise, this area must be a part of 'neural correlate of consciousness' (NCC) (Crick & Koch, 2003). Self related areas can be investigated using Northoff's paradigms (Northoff et al., 2006).

(c) Investigation of *necessary* and *sufficient* ingredients of visual awareness: Future research should address whether the *necessary* ingredients of visual awareness are *sufficient* for awareness. If not, then other components of executive functions (EFs), motor action, and other plausible ingredients should be included one at a time to address this question. Functional MRI experiments should be designed to isolate the other components of EFs, such as (i) to (vii) of Section 2.6 and motor action, similar to attention and working memory.

According to Merker (Merker, 2007), the neural correlates of consciousness might include brainstem mechanisms in addition to the thalamocortical system because there is some evidence of consciousness without a cerebral cortex. In that case, fMRI study may separate brainstem areas from thalamocortical areas for the *necessary* ingredients of visual awareness.

These types of experimental design could test the hypothesis that the *necessary* ingredients are also *sufficient* for awareness. This could be an interesting area of research related to awareness.

5. Conclusions

This article presents in detail the aspects of the nervous system and neural function that contribute to the subjective experience (SE) aspect of consciousness related to the red-green distinction in color vision. It is based on the idea that physical objects are the *carriers* of SEs/PEs, as presented in a previous papers (Vimal, 2008c), (Vimal, 2009b), and (Vimal, 2008a).

A simple working hypothesis is as follows: "Visual awareness is *the result of dynamic interactions between widely distributed neuronal groups* (Edelman, 2003) in the visual neural-network of thalamocortical (that includes dorsal and ventral visual pathways and frontal cortex) system. The *necessary* ingredients for *access* (reportable) awareness are wakefulness, reentry, attention, and working memory. In addition, for awareness, stimulus should be at threshold level for detection, and above threshold for discrimination and recognition. Moreover, neural-network proto-experiences (a set of SEs embedded in a neural-network) are also essential for SEs to emerge, but it needs further research. Attention and ability to report are not *necessary* for *phenomenal* awareness. The neural source for the arousal system is the ascending reticular activating system (ARAS) in the brain stem. Reentry process in a neural network binds various stimulus attributes such as location and features (color, motion, and orientation). Attention could be the results of reentry and competitive interactions. Attentional signal is a (reentrant) neural signal (such as FEF ↔ V4) that modulates the stimulus related feed forward signal. This modulating signal could be in forward (bottom-up) direction or mostly in backward (top-down) direction. Attention could be at foveal or peripheral targets for long (sustained) or short (transient) duration. The 'sources' of attention may be thalamic reticular nucleus for bottom-up or frontal cortex for top-down direction. The 'target' of visual attention is 'V4/V8/VO' for the Red-Green channel."

The areas for the 'targets' of attention (where attentional signal modulates the main signal) need to be carefully separated from that for 'sources' of attention (where attentional signal is generated) (Vimal, 2008a) to make attention research more rigorous and simple. Attention along with reentry process may solve the binding problem by linking together different features at the attended location and may play an essential role in transferring stimuli from iconic memory to working memory and then to long-term memory.

We conclude that arousal system brings the thalamocortical neural networks to wakefulness as a baseline for awareness to occur, reentrant interactions among neural populations entails awareness, attention modulates the awareness, and memory retains information for awareness. We ask if these *necessary* ingredients of visual awareness are *sufficient* for awareness, this certainly needs further research. The dual-aspect-dual-mode PE-SE framework (Vimal, 2008c, 2009b) links/integrates the three aspects of a consciousness system, namely, structure, function, and SE. An experimental design is proposed to investigate the *necessary* and *sufficient* ingredients for visual awareness. Thus, we accomplish all three goals specified in Section 1.

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Research Report

SELF: AN ADAPTIVE PRESSURE ARISING FROM SELF-ORGANIZATION, CHAOTIC DYNAMICS, AND NEURAL DARWINISM

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In this article, we establish a model to delineate the emergence of "self" in the brain making recourse to the theory of chaos. Self is considered as the subjective experience of a subject. As essential ingredients of subjective experiences, our model includes wakefulness, re-entry, attention, memory, and proto-experiences. The stability as stated by chaos theory can potentially describe the non-linear function of "self" as sensitive to initial conditions and can characterize it as underlying order from apparently random signals. Self-similarity is discussed as a latent menace of a pathological confusion between "self" and "others". Our test hypothesis is that (1) consciousness might have emerged and evolved from a primordial potential or proto-experience in matter, where inert matter is the *carrier* of subjective experiences; and (2) "self" arises from chaotic dynamics, self-organization and selective mechanisms during ontogenesis, while emerging post-ontogenically as an adaptive pressure driven by both volume and synaptic-neural transmission and influencing the functional connectivity of neural nets (structure).

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1. Introduction

Investigations into questions of "self" are clearly controversial. In fact, some might wish to argue that it is ill defined and too early or perhaps even inappropriate to undertake empirical investigations of "self". For example, within the traditional cognitive framework, it has been relatively easy to dismiss the "self" as epiphenomenal because of work showing that many, if not most, changes in behavior can be accounted for by externally caused automatic processes rather than conscious control (i.e., a "will" or "self").[a]

However, such questioning of an "efficacious" self presumes that there is a functional separation between perception and action (e.g., between "seeing" and "doing") that requires some kind of mediation.[b] It has been suggested that several aspects of the traditional framework of cognitive science, within which the "self" is generally modeled as a monitoring (or "executive") function that mediates between perception (an input function: input to "self") and action (an output function), are based more on folk-psychological assumptions than derived on the basis of empirical data [40].

As an alternative view, it has been argued that it may be more appropriate to regard the perception and action planning systems as inherently coupled. An evidence for such a "coupling" in instances of shared neural mechanisms is the existence of "mirror neurons". They are the population of cells identified in monkeys' premotor cortex that become active both when a monkey performs a given action and when he perceives a similar action being performed by an experimenter [25].

Such a conceptual reframing does not address whether or not the "self" exists as a causal mechanism, but rather permits conceptual emphasis to be shifted to what might be referred to as empirical regularities that individuals identify as "self" [40]. Jordan has elaborated a model in which such regularities may be characterized at the different levels of scale at which they are specified. These range from the level of particular effector systems (e.g., limbs and their movements), to more distal effects (e.g., particular tasks or goals), to even more distal, so called "virtual" effects (e.g., thoughts about goals, principles).

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[a] C. J. Davia (personal communication) commented, "I believe that the "self" emerges as a dichotomy – self/other. [. . .] the "self" is implicit in the similarities that we perceive between ourselves and other people. This set of implicits become explicit as "self" at quite a young age".

[b] According to C. J. Davia (personal communication), there is no fundamental difference between perception and action because all living processes are catalytic [22]. For example, The basilar membrane gives rise to the robust Von Bekesey traveling wave when sound stimulus is presented. This wave can be considered an action as well as an aspect of the perception suggesting perception and action are actually very closely related if not identical processes.

Thus, one's sense of "self" may vary depending upon the task at hand at any particular moment, ranging from identification with more proximal effector systems as in the case of a novice musician at the moment of attempting to control his/her finger movements during a task performance to that of an expert musician whose more automated finger movements permit attention to and identification with the control of emotions or cognitions during performance of a piece. In this view, an individual's acknowledged "self" at any particular moment is regarded as that one which is prepotent in and constrained by the circumstances of a behavioral context. However, as also noted by Jordan, there are certain levels of event control that seem more "appropriately" referred to by means of the term "self", since they are more conventionally referred to as such. Such levels of event control include those events that may be performed with an *other* and require specifying, monitoring and producing one's events in relation to those anticipated from an *other*, i.e., the more commonly construed social conceptions of the self.

The considerations of self by neurophysiologists are relatively few. Llinas and co-workers [50, 51], however, have, like Jordan, come to endorse the self as an abstraction arising from regularities in nature that have useful and important influences on intelligent organisms' (and particularly humans') behavior. In their view, the brain is largely a closed-system that is modulated by the senses (rather than driven by sensory input), with perception and action-planning systems intrinsically coordinated (and, thus, inherently intentional).[c]

In Llinas' formulation [50], the brain is primarily a self-activating system, which derives from the intrinsic oscillatory capabilities of neurons organized within the thalamo-cortical system. This "self activation" is "geared toward the generation of intrinsic (sensori-motor) images" [50] (that can control prediction of events in the environment in addition to controlling responsivity to coordinated commands for motor execution [50, 51].

Numerous other investigators are now exploring issues related to consciousness itself and asking the extent to which young children, as well as nonhuman primates, may have a sense of self, as well as self-reflective or metacognitive capacities, thoughts and representations. Significantly, investigators from research traditions as diverse as ethology and social psychology have converged on the notion that self awareness fundamentally involves processes of discrimination and evaluation in the service of guiding and optimizing certain behaviors. Self-awareness at the level of consciousness of a body image, for example, has been attributed to arboreal higher primates, and has been proposed to arise in order to enhance the planning and reduce the risk of clambering through the trees by such animals, who have a significantly larger body size than smaller monkeys and non-primates [68].

At the human level, social psychologists have long noted the significance of self-awareness in influencing planning, decision making, and behavioral control [17, 46].

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[c] According to Adrian Klein (personal communication), in the sub quantum (SQ) framework, "Self emphatically does NOT emerge IN THE BRAIN but modulates its Quantum activity".

Thus, despite the obvious complexity of the concept and the diverse ways in which the term self has been used in folk psychological discourse and scientific circles, serious empirical investigation with regard to aspects of self, clearly have been and continue to be undertaken.

Furthermore, one could argue that the emergence of self could be addressed using integrative neuroscience framework, where the continuity in hierarchically based neural organization allows modeling biophysical neural networks. One could argue (quotes are from [69])[d] that, (i) "dynamic chemical modulation alters the intrinsic properties of neuronal excitability and synaptic efficacy", which "indirectly affects synaptic connectivity by modulating functional connectivity serving as an adaptation mechanism by producing a new dynamic process"; (ii) this functional productivity creates adaptive pressures assisted by modulatory environments and provides flexibility and adaptability [33, 69]; (iii) "the role of microtubules in generating consciousness via a quantum mechanical effect [37, 64] could be an example of functional productivity based on traditional reductionism"; "such quantum effects need not traverse across the synaptic barrier ["selective" process] but possibly through the extracellular fluid via the ["wireless"] volume transmission mode of electrochemical communication"; (iv) neural Darwinian process [16] (i.e., ontogenesis in the life span of an individual organism, Darwinian process through selectional self-organization and adaptation during embryonic development, or selection through variance in neuroanatomy and through neural dynamics) may be "capable of recursively bootstrapping random novelties into something of quality"; (v) "during ontogenesis, the dynamics are less stable and may appear to be driven randomly by pure self-organization processes, but post-ontogenically the analysis of dynamic complexity may involve chaos"; (vi) "after ontogenesis in which *both* structural and functional modules are continually modified, new groups form through the so called experiential selection process" [27]; (vii) "functional productivity is an adaptive pressure [...] the process during post-ontogensis is productive rather than selective [...] After ontogenesis, self organization is non-random, and selectivity no longer modifies functional connectivity along pre-existing structural connections".

According to [82, 83], "there could be three types of explanatory gaps, namely the gap between (i) subjective experience (SE) and the object of SE; (ii) SE and the subject of SE; and (iii) subject and object, where "object" is internal representation.

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[d] Definitions of terms used here are adapted from Poznanski [69]: "*Darwinian process during ontogenesis* — self organizing process which is non-computational and based on selection of random variation. *Functional Productivity* — adaptability of dynamical pressures selected from either environmental influence (i.e., stimuli), past experience or behavior (i.e., a form of learning) leading towards the formation of a functional trait (e.g., as a result of a change in the electrochemical signature) at an appropriate hierarchical level. *Integrative neuroscience* — a representation of all traits that lead to a hierarchical integration of functional neural organization. *Re-entry* — refers to the inter connectivity and exchange of signals between neuronal groups. *Self organization* — process where random or non-algorithmic changes manifest themselves into a coherent organized activity (i.e., synergetics). *Volume transmission* — conduction of signal along a leaking pathway characterized by the absence of physical constraints linked to the wiring of neurons (i.e., synapses). Example include, nonsynaptic transmission, ephaptic transmission, paracrine and endocrine transmission".

The hypothesis is that SE, its subject, and its object are the same neural activity in a neural-net, where a neural activity is a proto-experiential entity in our framework. In this context, neural-net also includes self related brain areas [62, 63]. This is true because re-entry binds all the neural signals of areas specialized for a particular attribute, such as visual areas V4/V8/VO for color and V5 for motion. Re-entry represents "dynamic connectivity between neuronal groups of strongly connected neuronal assemblies" [69]. In re-entrant framework [26, 39, 80], signals re-enter repeatedly in a neural-net and bind all the features. We are referring this re-entrant signal related to the triad (subject, object, and their SEs) being the same neural activity. These gaps are actually closed if the above hypothesis is not rejected; this triad appears distinct in our daily lives, but it is a sort of illusion because internally they are same neural-activity. When information related to "subject experiencing objects" projected (mentally) outside [47], objects appear in three-dimension with respect to reference subject (self). Alternatively, one could argue that the internal reality of the triad being the same neural-activity in a neural-net is an illusion with respect to the external reality of the triad being distinct (and *vice versa*). Moreover, the subjective experience of objects could be (a) *phenomenal* awareness that is mostly related to feedforward stimulus dependent processing in primary and association sensory cortical areas and subcortical areas, where attention is not necessary, or (b) *access* (reportable) awareness where frontoparietal attentional feedback is needed to interact with feedforward stimulus dependent signals".

Our working definition of self is the subjective experience of subject, "which can operate in three levels hierarchically or in parallel depending of various conditions: (i) *proto*, *bodily, or physical* self is related to sensory processing in sensory cortical and subcortical activations, (ii) *core*, *minimal*, or *mental* self is related to self-referential processing in cortical midline structures via deactivation, and (iii) *autobiographical, emotional, spatial, verbal, narrative, or spiritual* self is related to higher order processing in lateral (ventrolateral PFC: VLPFC, dorsolateral PFC: DLPFC) cortical activations [62, 63]. Cortical midline structures (CMS) include MOFC (medial orbital prefrontal cortex: Brodman areas or BA 11, 12), VMPFC (ventromedial prefrontal cortex: BA 10, 11), PACC (pre- and subgenual anterior cingulate cortex: BA 24, 25, 32), SACC (supragenual anterior cingulate cortex: BA 24, 32), DMPFC (dorsomedial prefrontal cortex: BA 9), MPC (medial parietal cortex: BA 7, 31), PCC (posterior cingulate cortex: BA 23), and RSC (retrosplenial cortex: BA 26, 29, 30) [63]. This first-person-perspective is consistent with [59] that reported involvement of medial cortical and parietal areas. For the construction of body image of subject (to which it is related) in the brain, somatosensory cortex, posterior parietal lobe, and insular cortex (its lesion or electrical stimulation leads to illusion of feelings of being outside one's own body) are involved [9, 58, 61].

Self awareness may be related to the higher order processing; *self-referential* processing is only conscious processing whereas *self-related* processing includes both unconscious and conscious processing of stimuli in relation to the self; unconscious processing of *self-related* stimuli (*implicit self*) may involve subcortical and anterior cortical midline area such as VMPFC and the OMPFC [62].[e] Since areas of all levels interact with each other, self *encompasses* different levels of *self-related* processing and is associated with the *equilibrium* within the whole *embodied* brain that is *embedded* in the environment [62, 83]. "The subjective experience of objects could be (a) *phenomenal* awareness that is mostly related to feedforward stimulus dependent processing in primary and association sensory cortical areas and subcortical areas, where attention is not necessary, or (b) *access* (reportable) awareness where frontoparietal attentional feedback is needed to interact with feedforward stimulus dependent signals" [83].

What we have attempted to point out here is that there is some modicum of emerging consensus as well on the utility of investigations on self that are based on the functionality that a sense of self may confer. In particular, self-awareness (or access to representational content of self) may participate in the elaboration of control structures, which may be necessary for loosening the rigid stimulus-response bond in higher animal species.

2. Chaos and Order in Human Beings

Most people hearing the words "chaos" and "order" would tend to think of them as opposites. This is no surprise, since we have been programmed to think that way from the very foundations of civilization. Creation myths from many cultures describe the universe as an original formless mass from which the creator molded the ordered universe. Order is generally equated with "good" and "progress"; disorder, with "evil" and "decay". In the history of science, we could generally say that human beings have been striving to understand the regularities in nature and the laws behind the complexities of the universe — to bring order out of chaos.

The scientific thinking that culminated in Isaac Newton's "*The Mathematical Principles of Natural Philosophy*" led to a vision of the universe as a gigantic mechanism, functioning like clockwork [60]. This vision provided a sense of security. However, this ordered clockwork view started to break down as twentieth century scientists discovered, with more sophisticated measuring devices, the inherent unpredictability in the order of the universe. They also have been discovering that our bodies are far from clockwork mechanisms. This point of view is provided by a famous book: *Order Out of Chaos, Man's Dialogue with Nature* [72].

The human brain is the junction point of the body and the mind; both intuition and science say that our brain is complicated. It is an epistemic system that interacts with itself and its environment [28]. There is a natural background of chaos in the

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[e] In general, the term 'consciousness' may include self (subjective or first person experience of subject), subject experience (SE) of object, processing of SE, thought processing, memory, attention, access and phenomenal awareness, will, qualia, initiation of activities, and/or other cognitive processing. However, in PE-SE framework [82, 83], consciousness and SE are interchangeably used. Therefore, the term NCC (neural correlates of consciousness) initiated by [20, 21] may differ from the use of term consciousness in this article. NCC may also differ from the term self referential processing used [63]; however, our use of the term "self" for SE of subject may be somewhat closer to [63].

body — for example, in brain activity — which performs useful functions. The loss of chaos can actually be dangerous. The seizure in epilepsy, for example, may appear as an attack of chaos, but it is in fact due to loss of chaos: it is the result of an abnormally periodic order in the brain. Epilepsies involve the synchronization of large areas of the brain cortex, and so an epileptic EEG appears much more ordered than a normal one [77] and the permutation entropy decreases [13, 14].

In addition, our normal heartbeat is slightly irregular; when it becomes too regular, we could be in danger of cardiac arrest. Why is this? Analyses of healthy hearts reveal the presence of long range correlations in heart dynamics that appear to be an *emergent property* of complex physiology. For *emergent property*, we refer to the behavior of complex systems unpredictable accurately beyond a limited period because of their sensitivity to initial conditions. Consequently, the subsystems in a complex system may interact according to known rules, such as those pertaining to physiological states and environment for human body, but the coherent overall behavior of the system cannot be predicted from the rules because the number of subsystems is always too numerous and their self-organizing interactions too promiscuous. The slightest change in rules or interaction leads to emergent behavior and outcomes. The resulting balance of coherence is subtle, but it means that the heart avoids being locked into any dominant frequency that might prevail under particular patterns of an individual's behavior. In general, a loss of physiological variability (and hence chaos) in a variety of systems in our bodies seems to be characteristic of the aging process.

3. Self-organization in Dynamic Systems

The basic instability of such systems actually enables them to adapt to changing conditions. A famous example of this process is known as "Bénard convection" (after the French physicist who first studied it). If we take a large shallow container, fill it with water and then heat it evenly from below, soon the water begins to move as warmer water rises from the bottom and cooler, denser water sinks. Eventually, and spontaneously, this motion organizes itself into a regular pattern of cells, looking something like a honeycomb. The pattern does not reflect the way in which the water was heated nor the shape of the container. It is an emergent property arising out of the dynamic of the system itself. We could say that it is latent in the nature of the system. This process is known as self organization. The capacity for self organization enables complex systems to develop or change their internal structure spontaneously and in order to cope with their environment. The environment does not create the form of the system but it generally influences it by affecting which of the system's potential forms is actually realized.

Self organization also occurs in the development of organisms; it is most easily seen in the formation of patterns such as the coats of animals and the arrangements of feathers on birds.

This suggests that the brain is likely to exhibit self organization and we can expect to observe it in mental processes.

The main features of self organizing systems are as follows:

1. They are "open" and intimately connected with their environment. Because they exist in far from equilibrium conditions, they are able to develop and maintain their structure and organization. The second law of Thermodynamics does not inexorably drive them towards increasing disorder as it does "closed" systems.
2. They can create novel new structures and new modes of behavior. Therefore, we can say that they are "creative". This suggests that complex subjective experiences (such as *redness*) might have been created by the self organization process of brain to cope with its environment during coevolution [83].
3. Their parts are so numerous (in all but the simplest of examples) that there is no way in which a causal relationship between them can be established. Their components are interconnected by a network of feedback loops.

4. An Epigenetic View of Self

To illustrate these concepts further, we would like to bring in an illustration from biology, which might help us to see the parallels between our psychological journey through life and what we know about physical self organizing systems. This model is called the epigenetic landscape and was introduced by the embryologist Waddington CH [84] who first used the epigenetic landscape to illustrate the process of canalization, or the increasing differentiation of tissues and organs during embryogenesis. As development proceeds, the initial undifferentiated embryo becomes canalized into more specific body tissues and organs. As the embryo is stable — the embryo does not need a perfect environment and it can survive many small disturbances and even some fairly large ones — in the same way the self, through life, is stable over space and time during awareness.[f] This stability, however, does not mean that if an embryo is perturbed it will return to its previous state. Instead, if it can recover at all, it will continue to develop and eventually reach more or less the state it would have attained if it had been left alone. What is important here is that it is not the state of the embryo at any one time but its path of development.

The organism is a complex, non-linear dynamical system. Linear systems can be modeled by simple equations where the variables appear only to the power of one. Linear relations can be easily expressed as a straight line on a graph and we know where the line is going. Nonlinear relationships involve powers other than one and are much harder to analyze.

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[f] In this article, self is defined as the subjective experience of subject; awareness could be phenomenal or access type [10, 44]. Therefore, self can exist both in phenomenal awareness (such as in less than 50 ms stimulus-presentation [78], where attention is not necessary) and access (reportable) awareness. For the latter, wakefulness, re-entry, attention, and memory are necessary. However, self sleeps in deep sleep and is unconscious under deep anesthesia or coma. The temporospatial continuity of self may be due to temporospatial long range correlation (temporo-spatial entanglement/non-locality). See Sec. 6 for further detail.

It is difficult to predict what is going to happen. Familiar examples are abrupt climate changes and the proverbial straw that broke the camel's back. Almost all real systems are nonlinear. Linear models are much easier to analyze than nonlinear ones, and quite often, they are good approximations to real nonlinear systems. Therefore, we can learn a lot from them, but we must not let this success fool us into thinking that the only things real systems can do are what we see in linear models. Their repertoire is a lot bigger and more interesting than that and one of the most active and exciting areas in present day mathematics, dynamical systems theory, is devoted to learning about it.

Returning now to the epigenetic landscape, where we will use an example of a boll rolling down the topography of a valley. We know that the stability of development is very important for evolution. Therefore, in this model, the valleys are deep enough that neither minor changes in topography nor small random disturbances to the ball are likely to divert it from its normal course. The guy ropes, representing the influence of the genes, are so complex that changing the position or tension of any one rope is unlikely to alter the landscape very much and most such changes will have little or no influence on the end result. The majority of exceptions will be near the end of the process, where the sides of the valleys are flattening out and where the ball may not have enough time to return to its original trajectory [74]. Therefore, the landscape is a series of potential valleys, where the steepness of the sides indicates the amount of push the system needs to escape. In dynamical systems terminology, the behavioral modes represented by the valleys are attractor states, as the system, under certain conditions and at a particular phase of development, has an affinity for that state. Remember that in a dynamical systems view, development is a function of the interaction of internal components and their sensitivity to external conditions.

The attractor regime is only determined as the system is assembled: there are no codes, prescriptions, schemata, or programs orchestrating the nature of the attractor or its trajectory. While some attractor states are so unstable that they are almost never observed, others are so stable that they look like they are inevitable. Because of this, it is easy to believe that they are hard wired structures or programs within the system. As an example, think of the simple pendulum. If the workings of a pendulum were not so transparent, we could easily believe a little clock were hidden somewhere making it swing regularly. Very stable attractors take very large pushes to move them from their preferred positions, but they are nonetheless dynamic and changeable. Many patterns in development that seem like permanent programs or structures are actually stable attractors.

Here, we emphasize that the attractor develops and is not preordained! These stable attractors can be shifted, however, given the appropriate circumstances. For example, object permanence and walking are attractors of such strength and stability that only the most severe perturbations can disrupt them. Other abilities, such as many sports skills and playing the piano, have attractors whose stability is easily upset by contextual manipulations such as the like lack of practice or not paying attention.

If we extend this model to a general description of self, we could say that the landscape itself is an icon for the background of our individuation process composed of our real life experiences. If we are like the ball rolling down the hill then we could imagine our development existing on a fairly stable developmental pathway, but there may be jolts from the environment which knock the ball off course. Mostly, we will fall back on course and survive. If the perturbations are too great, however, we may be diverted into an alternative pathway, which may or may not allow us to function normally. What is not obvious from the landscape model but follows if you think in terms of the dynamic (i.e., the reality), is that if one is knocked off the normal course, even at a relatively early stage, the path that is followed may be in many respects not too different from the usual development.

On the epigenetic landscape, we could imagine this as the ball needing to go back up the mountain to be able to take a different turning. Psychologically, this is similar to the idea of regression of the self. If we imagine another scenario where the ball actually goes over a mountain and into another valley, this would be where we psychologically go through a transition that is not one of the inevitable ones. And of course, this would be much harder than moving over to another valley when the landscape is flat.

5. Metastability in the Self

In light of above discussion, we propose that phases of the constitution of the self could broadly be compared to the different possible structures or states of a self organizing system. We could say that each phase represents a phase space in which certain developmental processes form powerful attractor states.

However, although the self seems to depend on the appearance of the earlier human functions, nothing in the earlier functions implies that self needs to emerge from these. Since this event indeed occurs (self emerges), the emergence of a specific subjective experience (SE) depends on the neural-net proto-experiences, context, stimuli, and a specific neural-net [82, 83]. In this framework, the emergence of a specific SE is the selection process, i.e., selecting it from the set of neural-net PEs (that are embedded in the neural-net) possibly by orchestrated objective reduction of these PEs, i.e., collapse of wavefunctions when a specific stimulus is presented to a subject [82, 83]. The emergence of neural-net proto-experiences depends on sensorimotor interaction and tuning with external stimuli during embryonic development in addition to the interaction of neural-PE signals of feedforward stimulus dependent pathways with that of feedback frontoparietal attentional signals in neural-nets [82, 83]. The emergence of self is the emergence of the subjective experience of subject.

Furthermore, according to [41], we need a collation of earlier experiences. Only in this sense, the self is a secondary phenomenon in the ontogenetic theory because it does not involve the acquisition of a new ability: it is merely the deployment of an earlier function upon a wider range of objects. However, it should be noted that in the framework of [82, 83], internally the triad (subjective experience, subject, and object) are the same neural-activities in a neural-net, which also includes self-related brain areas [61–63]. However, when projected outside, they appear distinct with subject being the reference point. Therefore, self is the subjective experience of this reference point, the subject.

Moreover, the self seems to be constituted by a collection of transient images, a constructed self, and a condensation of related experiences. This feature helps it to appear both as a singular entity and, at the same time, as something that contains our transient states.

Metastability is the function of the constitution of the self where the individual constituting parts exhibit tendencies to function autonomously at the same time [42]. Specifically, this function allows such a system to operate in an intermediate regime between complete stability, which would lack flexibility, and complete plasticity, which would lack useful organization. More precisely, a metastable system can manifest a state that is quasi-stable, and it can also flexibly switch to another such state. In the terminology of nonlinear dynamics, the metastable system trajectory can visit the vicinity of quasi-stable attractors but never settles into a stable attractor because stable attractors do not actually exist in the energy landscape.

One may note that the metastability principle extends the Haken's synergetics rules, which aim to compress the effective number of degrees of freedom in complex systems to a few order parameters or variables that adequately approximate system dynamics at large scales [35]. Metastability extends them to situations where there are neither stable nor unstable states, rather there are only coexisting tendencies [42]. Metastability refers to transient, non stationary processes and differs from synergetics in this respect.

Because the constructed self-image is a condensation of related ideas, it seems likely that certain of our ideas, which normally appear when we think of ourselves are such that they bear little relation to other ideas that also appear in the same instant. Consequently, any attempt at condensing these ideas into a composite idea will tend to fail. To enter a state of the self in these circumstances would be to have one's awareness divide itself between two objects competing for the same phenomenological status. The constructed self just is an instant of consciousness. What happens is this: the consciousness throws itself into a certain configuration that is structured in a condensed form, which diffuses over our phenomenal world at that instant. In this situation, we can begin to see how parts of own experience, which are neither assimilable nor repressible, might fissure themselves off to become a separate sphere of consciousness [24].

Here, the problem of having more than one self would be dealt with by producing a schism in awareness that would subsequently be attended by the appearance of two or more personalities, each of which would be matched to the appropriate image. We now have to ask what it is that leads someone into perceiving the constructed self and what is it that leads a subject to this fictitious identification?

When we come to believe that we are the same subject across time, it is because of the smooth and uninterrupted progress of thought that is produced in our imagination when we reflect on the succession of related ideas. When, on the other hand, we believe that we perceive our self in an instant of self awareness, such as when we experience a self oriented emotion, what is happening is that our awareness is being directed to an object that is merely a condensed version of extracts from the succession of related ideas. This is the *constructed* self, which is a rare and secondary aspect of consciousness.

6. Chaos Theory for the Emergence of Subjective Experiences and Self

According to [76], "Chaos" in the oldest sense means the formless void from which order springs. The term is now commonly applied to disorderly, unpredictable happenings that give an observer no sense of regularity. It describes a kind of activity that appears to be random or stochastic by every standard statistical test, but is not. It is deterministic, in the sense that it can be reliably simulated by solving sets of coupled nonlinear partial differential equations or generated by building a system to certain specifications and putting energy into it. It is pseudorandom noise that can be reproduced with high precision if the initial conditions are identical on repeated runs, but which is unpredictable if new initial conditions are used. In contrast to noise, chaos has fewer degrees of freedom and is said to be low-dimensional. Chaos is indistinguishable from random noise in appearance and in statistical properties but it is deterministic and not stochastic.

Chaos theory has following attributes: (i) deterministic systems can display behavior that appears random, and (ii) chaos in these systems is controlled, bounded, and has a small number (4–7) of independent contributors, and has definite qualitative form [32]. Chaotic systems are not as predictable as the cause-and-effect based linear system. According to chaos theory, order can emerge from chaos in two ways: (i) a narrow spectral peak can emerge that could represent high temporal coherence, and (ii) the local amplitudes of oscillation may be related to particular stimuli [30]. In addition, chaos theory suggests, "the evolution of life on Earth has been achieved economically by random mutation and not in any formal deterministic predetermined pattern" [49]. Chaos theory may be useful in describing certain chaotic attributes of consciousness, such as free will, by finding middle ground between straightforward materialism and separative dualism [48].

Some of the chaotic systems are (i) thought processing attribute of self, (ii) free will attribute of self for which the notion of quantum mechanics and brain uncertainty may also be useful [52, 53], (iii) relationship such as in family [15] and work, and (iv) future prediction such as what will happen to a subject tomorrow, a month from now and so on. These systems may be mutually interacting. In chaotic systems, there may be many random initial inputs, many random inputs may be added later, and results are unpredictable.

Chaos theory and the concept of fractals were previously applied to embryonic development successfully. Chaos theory describes the behavior of the complex nonlinear dynamical systems and finds the underlying order in apparently random data. A fractal is a rough geometric shape that can be subdivided in parts, each of which is a reduced size copy of the whole. Objects in the phase space of a chaotic dynamical system can be fractals. We wish to investigate if the notions of chaos and fractals can address the emergence of self (subjective experience of subject)[g] in brain.

Chaos theory for the development of proto-experiences might be the same as that for the embryonic development; the only difference is that the former is experiential and the latter is material aspect of physics. In our framework, physics includes both aspects [82, 83]. Thus, our approach is simple: we extend the chaos theory of embryonic development [84] by appropriately recognizing the various factors related to self. For example, the initial conditions in chaos theory for the emergence of subjective experiences are genetic proto-experiences (PE) because a little change in initial conditions has significant effects. It is well known that a small change in genes from a normal state results in significant abnormalities after birth. The attractors are the same as in embryonic development in addition to neural-net proto-experiences embedded in neural-nets. The path of development involves sensorimotor interaction and tuning as in embryonic development, which also leads to the development of subjective experiences and self. This implicitly means that there is codevelopment of subjective experiences and their neural-nets. We have assumed that coevolution processes of elemental proto-experiences and matter (mass, charge, and space–time) to genetic proto-experiences and genes, respectively, are already complete before our model based on chaos theory is applied. It would be interesting to investigate if these neural proto-experiential feedforward signals interacting with feedback attentional signals in awake re-entrant neural-nets lead to the emergence of subjective experiences. If chaos theory can elucidate the emergence of subjective experiences of objects and the subject, the emergence of self is explained because self is defined as the subjective experiences of subject.

For example, let us investigate how SE *redness* emerges. In chaos theory, initial conditions make a significant difference. For example, if we consider the initial conditions in terms of genetic disposition of both parents who are protanopes (red-green color blindness: inability to see the color red or to distinguish red and bluish-green) then children will be protanopes (assuming both X-chromosomes of mother are abnormal). The guiding developmental path is sensorimotor interaction and tuning with environmental color stimuli which is also important. For example, if new born is blind folded and hence does not receive visual stimuli, then development of visual system will be abnormal [86]. Striking reorganization of orientation

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[g] Since self is defined as the subjective experience of subject, self organization and chaos theory should first explain how subjective experiences of objects emerge and then explain how self emerges. They all fall under the umbrella of both higher and lower order information processing. The term neural-net in our framework includes all neurons that participate directly or indirectly, implicitly or explicitly, consciously, subconsciously, or unconsciously.

maps in early life was induced by orientation-restricted continuous visual exposure [79]. "Normal red-green genetic information and normal sensorimotor interaction with red-green stimuli will set up appropriate red-green color neural-net that will have all red-green color SEs (such as redness, greenness, and all the intermediate just-noticeable-differences) embedded in it. When long wavelength light keeps on stimulating the V4/V8-color-neural-net repeatedly since birth to its critical period, SEs such as redness will emerge in it due to re-entrant interactions between feed forward and feedback signals. This is because neural signals are proto-experiential signals in our framework" [83]. Each stimulation leaves a trace of a specific neural-net PE in the neural-net in terms of memory; this memory trace is potentiated by repeated stimulation [83]. This is consistent with the self-organization[h] of neural-nets: "the organic structure of the (connection) matrix (of the brain) facilitates particular patterns of energy flow, which in turn affect the subsequent development of the matrix" [75].

According to [83], "At every level of evolution, a relevant physical entity has its associated PEs: from elemental PEs to neural-net PEs. For example, one possible source of PE might be the proto-experience related to ions that rush across neural membrane during spike generation, which can be called neural-PE. Signals related to neural-PEs interact in a neural-net and neural-net PEs somehow emerge, which are then embedded in the neural-net during development". According to MacGregor, "the localization of basic neural PE is likely larger than simply the possibility of the ionic fluxes of spiking. In addition to many deeper levels of neural activity, there is suggestive evidence that consciousness may associate with astroglial cells, and possibly through this with the metabolic energization of the brain, which would seem an elegant and highly strategic foundation" (personal communication see also [48, 52–54, 71]).

According to [4], "life-long self-optimization process, epigenetic information remodels the cognitive, behavioral and emotional reactivity of an individual to meet the environmental demands". Genetic programs the basic wiring pattern of the brain, whereas the experience does the fine tuning throughout life [67]. According to [70], "higher brain function arises from both synaptic and extrasynaptic integration in the neuropil where information on environmental changes are represented dynamically through a discourse of semantics". Self organization process specifies neuronal interconnections and continuously reshapes the brain using the epigenetic information obtained from microenvironment (such as biochemical signals generated by local neurons and glial cells) during early development and sensory experiences during late development and post-development or adulthood [4, 5, 18]. "Although we do not precisely know how, but since brain is nonlinear dynamic system, *somehow* SEs emerge in neural-nets, which are then embedded in it as neural-net PEs (or

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[h] In self organization (or self control), "the control parameters of a system are influenced by the state of the system itself", i.e., "control parameter of one scheme being under the control of another" [1]. For example, groups of neurons in a neural-net can self organize into a firing pattern in response to changes in experience [11, 56].

latent SEs)[i]" [83]. Later, whenever long wavelength light is presented to a normal subject, the SE *redness* is selected out of set of neural-net color PEs [83].

Awareness, subjective experience, and/or self has five essential elements: (a) wakefulness, (b) re-entry, (c) attention, (d) a provisional buffer of working memory, and (e) proto-experiences [83].

Self has the following characteristics or aspects [73]: (i) **continuity**: self appears to be continuous along time line from birth to death and has a sense of past, current, and future; (ii) **unity or coherence** of self: one experiences oneself as one person in spite of the diversity of sensory experiences, memories, beliefs and thoughts; (iii) **embodiment or ownership**: self appears to be anchored to body; (iv) agency or **free will**: one's sense of being in charge of one's own destiny. Some of these aspects of self can be disturbed in brain disorders, which may lead to appearance of multiplicity in self [73]. We can also add (v) **personal nature**: self is defined as the SE of subject and hence self appears to be personal, (vi) **sensory realism** and (vii) **sense of presence** to the above list.

The autogenesis of the self is a bifurcation sequence of increasing order and complexity; in this dynamical system, self organization is the creation of new information with the development of increasing complexity [1, 75]. The development of the self could be in four stages during ontogenesis: (i) the self organization of neural nets (nn), where nn facilitates particular patterns of energy flow, which in turn affect the subsequent development of nn, (ii) the selective capture of information by the body for evaluating self created information with respect to environment, (iii) the self organization of impulses by imagery that can modify itself or produce new imagery, and (iv) the self organization of imagery by language that controls imagery and self representation [1, 75].

A *sensory realism* is subsumed within a broader perspective of our model, as one of the means that contributes to the experience of presence. A *sense of presence* derives from feeling as if we exist within but as a separate entity from the world (that also exists). It is reasonable that the differentiation and experience of self may be enhanced if other beings (not self) exist in the world and if they appear to recognize that we exist. Many features of that sensorimotor system provide to convincing someone that we *are* there. But what could enhance our sense of presence? Even though social presence is a subset of personal presence, the description of its extent is beyond the scope of this article. Responsiveness tries to maintain an efficient sense of continuity and coherence as in [73]. The experience of *oneself as one person* requires continuous serial reactivation and refreshing of the dynamic identity location bindings. If these bindings are not periodically refreshed, they are lost with the risk of a morbid *derailment* of sense of experience.

Sense of coherence is guaranteed by a *global stability* but this does not mean that self stays stable in all conditions. But each point of trajectory of the system of self

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[i] Emergence of SEs may involve the chaotic process of self organization.

could diverge to infinite of the trajectory. We further argue that self emerges by a slight perturbation, as a consequence of activity dependent synaptic fluctuations, which continuously destabilize the attractor and induce irregular hopping to other possible attractors, generating the occurrence of spatialtemporal homogeneous patterns.

A complexity drop occurs when some sensors become suddenly active, making the activity of redundant sensors dispensable in the description of the system's state. Emergence corresponds to a negative discontinuity of structural complexity through time. Hence, we assume that the nature of the self depends in principle on the intensity of the synaptic noise and the number of sites of the neural-net, which are synchronously updated at each time step [2, 3, 39]. But how to explain the evolution from a state to a further state of self, without the risk to create a *derailment* of sense of experience? We must hypothesize a self system that returns to the basal state even if it evolves along the life of a person. In the absence of stimuli, self is in a high dimensional state of spatially coherent basal activity. The basal state could be described by an aperiodic (chaotic) global attractor. In response to external stimuli, the system self goes from the basal state into a local memory section. This wing could be of much smaller/bigger dimension than the basal state. It shows coherent and spatially patterned amplitude-modulated fluctuations. The system self resides in this localized section for the duration of the stimuli and it returns to the basal state when the stimuli cease.

In normal subjects, self is invariant with time as self is preserved until death, although it is interrupted during sleep, anesthesia, and when subject is unconscious. The invariance of the dynamics of self, thus, requires assigning a conserved entity over time. This time invariant entity could be long range spatiotemporal correlations, which is like collective modes, such as Nambu-Goldstone (NG) boson modes in quantum field theory (QFT), that are wave-like and generated dynamically [65]. They can propagate over the whole brain spatiotemporally; they are the carriers of the order in terms of long range spatiotemporal correlations to maintain continuity of self until disintegration during death. QFT is the quantum field theory of electromagnetic fields induced during neuronal firing and signal transmission in neurons. In our framework, the fundamental units of the brain are basic field variables (such as electric dipole field), not necessarily the neurons [65]. Therefore, although there is no evidence of orchestrated objective reduction (Orch OR: collapsing of wavefunction or many states into one specific observable state; used for explaining consciousness) in a neuron [37, 43], quantum mechanics can still be applied in brain via QFT for memory, subjective experiences, and self; whereas, electrochemical synaptic dynamics can still be considered classically; the coupling between quantum and classical processing is possible [65].

7. The Functional Nature of Self

Even if both functionalism and reductionism are the two positions that we might admit to conceptualize the self, these alone are not enough. We need to keep in mind the nonlinear concept of fractals, which is defined as *objects* with non-integer dimension and statistical self similarity at all resolutions. Fractals are generated by an infinitely recursive process. One could still argue that the difficulty in defining the self could stem primarily from the lack of this chaotic feature,[j] where *identity* is conceptualized multivalent in terms of *self similar* processes repeating on multiple size and event scales. Let us consider that self alternates in periodic states of integration and disruption [88]. With this assumption, it is clear that Jung's arguments concerning the operational definition of self as psychosomatic entity are denied.

Therefore, in complete agreement with Fordham [29], we acclaim that the experience of wholeness is not a reliable basis on which to construct a definition of the self. From the *intrapsychic* to the *universal*, we believe each level of analysis to be equally as valid and useful to tell about self. Each folds into the next, displaying recursively embedded dynamics that recur on multiple levels of observation.

Using these fractal lenses, we conceptualize the self as an open, multileveled system coupled to other dynamical systems of different scales, from biological, physiological levels through intrapsychic, social, cultural, and even transpersonal ones. A *personal* self exists in the interior phenomenological space of our heads; a *family* self supplies the uniqueness of each person's relational dynamics; a *regional* self refers to the local garb of particular geographical areas; a national identity forms the butt of international jokes and stereotypes. A *global* self may even struggle to emerge and bring geographical differences into harmony. In general, such multivalent existence is highly suggestive of fractal dynamics.

Fractals also come into play within the internal attractor structure of self, which organizes *self* similar patterns of behavior at various scales of observations. We assume a perspective of self as open, dynamical system and fractally constellated, sympathetically with Francisco Varela's framework of autonomy in biological systems [81]. In a few words, Varela's model involves endless feedback loops which allow biological systems to re-enter themselves continuously.

This results in paradoxical dynamics when biological systems are characterized in opposite terms, as being functionally closed yet structurally open. We claim that self follows the same pattern. All subaspects of self too are "closed" in that, when we are healthy, we retain a cohesive, coherent, ongoing sense of identity. Yet, self is clearly unlocked via interaction with the others. Likewise, Marks-Tarlow *et al.* [55] have modeled the emergence of "identity" through endless cycles of re-entry, in which, consciousness arcs away the self, in order to enter into the perspective of another and then circles back again. This model conforms nicely to social *mirror* theory [6, 19, 57, 85], which posits the development of self and the perception of others to arise hand in hand. Contrary to popular lore, which maintains that it takes huge, traumatic events to shape basic self, it is increasingly evident to most clinicians that the tiny falls, tweaks and mishaps are equally, if not more, significant in the

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[j] However, given the neurobiological motif in previous sections, it should no longer be difficult to elaborate.

formation of basic personality. Like endless waves on a shoreline, ever similar yet ever changing at a minute-to-minute level, day in and day out, mother, caretakers and their children are embedded in paradoxical, feedback cycles of subtle nuance. Tiny events, like the toddler's stumble, form endless feedback loops in both directions, from self to other and other to self. Over time, these cycles shape both people (caretaker and toddler) by building a repertoire of memory and experience. Out of this foundation, at the next level of complexity, self image emerges to form self referential loops in consciousness. By requiring the ongoing presence of others to become *present* to our selves, this model of development emphasizes the paradoxical dimensions by which self and other, observer and observed are inseparable. Self retains a paradoxical quality because the truth of a fixed identity i.e., its functional closeness, rests precisely on its underlying falsity, i.e., its structural openness.

8. The Space Between Self and Other

The idea of self arising in the *paradoxical space between people* was articulated elegantly by British object relations psychoanalyst, Winnicott, whose most important contribution was the notion of the transitional object [87]. This consists of baby's first possession, such as a blanket or teddy bear, which occupies the fertile space *between* mother and baby. The transitional object is the first symbolic object that serves to both connect and separate baby and mother. This object is partly discovered and partly created, neither wholly of the one nor of the other, yet it partakes of both.

Out of the nebulous space of the transitional object, Winnicott envisions the creative emergence not only of symbol and play, but also most broadly of culture at large. Winnicott came to his idea of transitional objects after returning repeatedly to a Tagore poem, "On the seashore of endless worlds, children play". Like a barnacle, this fragment lodged in his psyche upon first encounter. Over the years, wave after wave of meaning washed over him. At first the poem represented endless association between man and woman with the child emerging from their union. Then the sea represented the mother's body and the land her ego, with the baby spewed upon the land like Jonah from the whale. Finally, out of a long, chaotic state of not-knowing, the notion of "transitional object" crystallized in Winnicott's mind. The creativity of Winnicott emerged through contemplation of a fractal image, similar to that of psychoanalyst Stuart Pizer, a pioneer who conceptualizes psychotherapy in nonlinear dynamical terms [66]. Because fractals inhabit the nebulous territory of the "space between", their borders provide endlessly fertile, endlessly deep frontiers. Self might arise in the paradoxical space between people and events as an ongoing, cocreative, interactive, and iterative process. Just as with any fractal, internal structure is added or removed through the ongoing negotiation of boundaries. This complex border area, where inner and outer, self and other are melded, can be conceptualized in terms of fractal separatrices. The ordinary conception of a boundary is literally a bounded or fixed area whose resolution is easily detectable, e.g., the door of our houses or edge of our desks. By contrast, fractal separatrices can never be resolved. Instead, they form endless, infinitely complex zones of articulation and negotiation. Here, between any two points, e.g., of self and other, inside and outside, exist infinitely many other points. The image of fractal separatrices can be viewed in terms of intrapsychic dynamics, such as the dilemma of a person with obsessive-compulsive personality disorder in an ice cream store. Each color, or basin of attraction, represents a different flavor, and the complex fractal boundary between the four choices illustrates the obsessive nightmare of attempting to use intellect or logic to figure out the "right" choice when rightness is not the issue at all. In order to understand the complex, nether zone of a fractal separatrix interpersonally, it is useful to examine the psychopathology of the borderline personality.

People with this character disorder display chaotically organized psyches, which includes intense, shifting affect and highly unstable relationships. These individuals tend to oscillate between subjective poles of engulfment and abandonment, often harboring central issues of rage and shame. They repeatedly express confusion between self and other. At times, interpersonal confusion reaches a crescendo to the point denying psychological existence altogether. That is, the borderline is wont to claim that she has no self, to assert in essence "I don't exist". This is the ontological equivalent of the Liar's paradox: "This statement is false". In both cases, if it is true, then it is false; and if it is false, then it is true. Because of such intense confusion, extreme defensiveness, and rigidly closed boundaries, interaction with a borderline personality frequently results in what anthropologist and scientist Gregory Bateson, identified as the double bind [7, 8]. The double bind that Bateson postulated as the cause for schizophrenia consists of seemingly impossible paradoxical demands made on relationships which involves contradiction at multiple levels of communication. When it comes to borderline personality disorder, paradoxical demands often center upon the issue of blame. For example, "You're to blame for my hurt. If you don't think so, you're wrong, because I know you better than you know yourself. But even if you're right, you're still to blame, because you're always trying to be right at my expense". In this closed feedback loop that serves to keep contradiction in place, which is what Ben Goertzel calls "chaotic logic" [34], we see that engagement with a borderline easily becomes a paradoxical morass, including the potential for endless recursion.

Attempts to ignore multiple realities and ambiguity by always being right while making others wrong results in failure to recognize the fractal quality of boundaries along with their irresolvable openness. People with borderline personality disorder have often been so hurt or abused by letting others in emotionally, they now feel entirely threatened. Yet the more they fight the open contradictory nature of psychological boundaries, ironically the more everyone is sucked into the endless vortex in the space between. Fractal separatrices between inside and outside mean we all carry the potential for confusion between self and world, projections, delusions, hallucinations or self and other, e.g., introjections, projective identification, delusions and borderline double binds. Yet, except under extreme conditions of stress, most of us resist these vulnerabilities. We can usually let this seam alone, because in ordinary daily functioning, it proves irrelevant.

By contrast, psychopathology is characterized by either excessive rigidity or too much chaos that causes us to deny, fight, reject, ignore, or repress this potentially scary, disheartening condition. The major difference between psychological health and psychopathology is not so much the possession of clearer or cleaner boundaries. Rather, it is more that in health, we possess the wherewithal and flexibility to recognize, to tolerate, and if we are lucky even welcome, the vagueness, uncertainty, and ambiguity inevitable with fractal separatrices. We do not need to lose ourselves in infinitely complex, irresolvable boundaries as long as we understand them. Along with a source of psychopathology, open boundaries are a fount of aliveness, creativity, and even higher consciousness. They preserve the mystery and wonder of life. We grow through our ability to tolerate *ambiguity*, to hold opposites without succumbing to the tension of reducing one side to the other, and to understand ambivalence. All these emotional skills relate to embracing rather than rejecting underlying fractal dynamics, along with their paradoxical elements.

9. General Conclusions

In our framework, self is neither a *substance* nor a *function*. Self is experiential entity because it is subjective experience of subject. The main thrust of the article is to investigate how self emerges in neural-nets that contains *self related* areas [62] using the PE-SE framework [82, 83].

According to Poznanski [69], self organization (at the molecular level) during ontogenesis invokes a non-computational or non-algorithmic process (such as chaotic dynamics) together with selective mechanisms (neural Darwinism) to produce an adaptive pressure. This adaptive pressure can be considered to be a neurobiological substrate of the self. In other words, self arises from chaotic dynamics, self organization and selective mechanisms during ontogenesis, while emerging post-ontogenically as an *adaptive pressure* driven by volume transmission and influencing the functional connectivity of neural nets (structure).

We take self as intimately associated with subjective experience or consciousness, the neurobiological basis of which is obscure [48, 52]. Generically, Lashley *et al.* [45] suggested that consciousness might be associated with neural action potentials ("spikes"). More recently, Poznanski [69] has cogently argued that the volume transmissions of the brain (ionic currents, regulator and "second messenger" fluxes, and the like) are a more likely substrate for consciousness because of their global and continuous (non-discrete) character. Our own view, in PE-SE framework, is that consciousness (including self) might be best seen to have emerged and evolved from a primordial potential or proto-experience in matter, where inert matter is considered as the *carrier* of subjective experiences; this is described in a companion paper currently in review [81, 82]. The PE-SE framework is consistent with both (a) non-computational[k] extracellular wireless volume transmission [69] for non-specific or less specific consciousness (such as thought processing), and (b) synaptic-neural signal transmission in neural-nets for specific SEs (such as SE of *redness* via V4/V8-neural-net when long wavelength light is presented). This is because both types of transmissions involve ionic PEs.

Our definition of self (subjective experience of subject: [81, 82]) is consistent with three concepts of self: *proto* or *bodily* self (related to sensory processing in sensory cortex and subcortical areas), *core*, *mental*, or *minimal* self (related to self-referential processing in cortical midline structures), and *autobiographical*, *emotional*, *spatial*, and *verbal* self (related to higher order processing in lateral cortex) [63].

We have not absolutely described self as a substratum of psychological and/or physical properties, spatially located and causally active. In so doing, we have demonstrated that using *fractals* and the nonlinear attribute of *self similarity* is possible providing a parsimonious account on the *function* of self. Principally, we have rejected the self as an *object* among others in the world, compatibly with some interpretations of the Buddhist no-soul theory, as well as with Kant's claim.

Finally, we have explained the potentialities of fractals bound to a prior differentiation between oneself and the other, without taking into account other specific systems of self attribution (e.g., "who" system into the brain, [23]). Punctually, three principles have been applied to discuss the self.

(1) the presence of the phenomenon of self on different scales of observation;
(2) its fractal growth in both phylo- and ontogenesis;
(3) its appearance and disappearance (elusiveness) on different *structure* levels by contrast its constancy as *subjective experience of subject.*

In a few words, the role of the self-as complex system, likely the brain, is determined by its interaction with the states created by self. It is clear that, on one hand, it can open the possibility of restabilizing itself at another level or, on the other hand, the self can fall victim of regression. It possible to provide several anecdotes confirming that the danger, anxiety, and stress produced during a confrontation with "the Other" can create *chaos*, usually leading to what is called a *bifurcation* or splitting of the energy in two different directions. We know in this regard that the experience may be shattering. However, sometimes regression serves the process of evolution of self and leads to creative transformation and its renewal. Therefore, the potential benefit makes the risks worthwhile.

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[k] According to Poznanski [69], a non-computational process implies (a) an inability of the neural system to process information symbolically at the molecular level [64], and (b) a continuous evolution of nonlinear dynamical systems at the cellular/network level is a process of "differing and deferring" [33].

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