Electroencephalographic field influence on calcium momentum waves

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Abstract. Macroscopic electroencephalographic (EEG) fields can be an explicit top-down neocortical mechanism that directly drives bottom-up processes that describe memory, attention, etc. The top-down mechanism considered are macrocolumnar EEG firings in neocortex, as described by a statistical mechanics of neocortical interactions (SMNI), developed as a magnetic vector potential \( A \). The bottom-up process considered are Ca\(^{2+} \) waves prominent in synaptic and extracellular processes that are considered to greatly influence neuronal firings. Here, the complimentary effects are considered, i.e., the influence of \( A \) on Ca\(^{2+} \) momentum, \( p \). The canonical momentum of a charged particle in an electromagnetic field, \( \Pi = p + qA \) (SI units), is calculated, where the charge of Ca\(^{2+} \) is \( q = -2e \), \( e \) is the magnitude of the charge of an electron. Calculations demonstrate that macroscopic EEG \( A \) can be quite influential on the momentum \( p \) of Ca\(^{2+} \) ions, in both classical and quantum mechanics. Molecular scales of Ca\(^{2+} \) wave dynamics are coupled with \( A \) fields developed at macroscopic regional scales measured by coherent neuronal firing activity measured by scalp EEG.

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1. Introduction

1.1. Multiple Scales

There is a growing awareness of the importance of multiple scales in many physical and biological systems, including neuroscience [1, 2]. As yet, there do not seem to be any explicit top-down mechanisms that directly drive bottom-up processes that describe memory, attention, etc. Of course, there are many top-down type studies demonstrating that neuromodulator [3] and neuronal firing states, e.g., as defined by electroencephalographic (EEG) frequencies, can modify the milieu of individual synaptic and neuronal activity, which is still consistent with ultimate bottom-up paradigms. However, there is a logical difference between top-down milieu as conditioned by some prior external or internal conditions, and some direct top-down processes that direct cause bottom-up interactions specific to short-term memory (STM).

This study crosses molecular (Ca$^{2+}$ ions), microscopic (synaptic and neuronal), mesoscopic (minicolumns and macrocolumns), and macroscopic (regional scalp EEG) scales. Calculations support the interaction between synchronous columnar firings large enough to be measured by scalp EEG and molecular scales contributing to synaptic activity: On one hand, the influence of macroscopic scales on molecular scales is calculated via the evolution of Ca$^{2+}$ quantum wave functions. On the other hand, the influence of Ca$^{2+}$ waves is described in the context of a statistical mechanics model that already has been verified as calculating experimental observables, aggregating and scaling up from synaptic activity, to columnar neuronal firings, to regional synchronous activity fit to EEG while preserving an audit trail back to underlying synaptic interactions.

1.2. Magnetism Influences in Living Systems

There is a body of evidence that suggests a specific top-down mechanism for neocortical STM processing.

An example of a direct physical mechanism that affects neuronal processing not part of “standard” sensory influences is the strong possibility of magnetic influences in birds at quantum levels of interaction [4–6]. It should be noted that this is just a proposed mechanism [7].

The strengths of magnetic fields in neocortex may be at a threshold to directly influence synaptic interactions with astrocytes, as proposed for long-term memory (LTM) [8] and STM [9, 10]. Magnetic strengths associated by collective EEG activity at a columnar level gives rise to even stronger magnetic fields. Columnar excitatory and inhibitory processes largely take place in different neocortical laminae, providing possibilities for more specific mechanisms.

Note that magnetic fields generated by axons, about $10^{-7}$ T, are generally small relative to the Earth’s magnetic fields on the order of $3 \times 10^{-5}$ T ($T = \text{Telsa} = \text{kg-A}^{-1}\cdot\text{s}^{-2}$). This is often cited as a reason that magnetic fields due to firing neurons are not
influential in brain processes. However, this paper calculates the oscillatory magnetic vector potential $A$ due to many synchronous minicolumns from many macrocolumns, not the magnetic field of a single axon or minicolumn. The effects of this oscillatory $A$, synchronized to $Ca^{2+}$ waves which contribute to this process, are the issue.

1.3. SMNI Context of $Ca^{2+}$ Waves

Since 1981, 30+ papers on a statistical mechanics of neocortical interactions (SMNI) applied to columnar firing states, have detailed properties of short-term memory — e.g., capacity (auditory $7 \pm 2$ and visual $4 \pm 2$), duration, stability, primacy versus recency rule, Hick’s law — and other properties of neocortex by scaling up to macrocolumns across regions to fit EEG data [11–17]. SMNI not only details STM, testing SMNI at columnar scales, but also scaled-SMNI at relatively macroscopic scales has very well modeled large EEG databases, testing SMNI at regional scales.

Experimental research reported in 2012 supports information/memory processing by coherent columnar firings across many neurons [18, 19]. This new experimental confirmation greatly enhances the importance the SMNI approach.

The influence on the momentum of a $Ca^{2+}$ ion from macrocolumnar EEG fields as measured on the scalp, is thereby considered as the processing of information. SMNI calculates the influence of these regional synchronous firings at molecular scales that drive most influential $Ca^{2+}$ waves across synapses. The roles of $Ca^{2+}$ in neocortex, while not completely understood, are very well appreciated as being quite important. It also is possible that $Ca^{2+}$ waves may be instrumental in tripartite synaptic interactions of astrocytes and neuronal synapses [20–22], although the role of tripartite synapses in the adult brain has been disputed [23]. The $Ca^{2+}$ waves considered here arise from a nonlinear cooperative regenerative process from internal stores, complementary to $Ca^{2+}$ released through classic endoplasmic reticulum channels and voltage-gated and ligand-gated $Ca^{2+}$ transients [22].

Columnar EEG firings calculated by SMNI lead to electromagnetic fields which can be described by a vector potential. This is referred to as the SMNI vector potential (SMNI-VP). An early discussion of SMNI-VP contained in a review of short-term memory as calculated by SMNI was simply suggested [17], and a previous paper outlined the approach taken here, but only in a classical physics context [24]. Current research is directed to more detailed interactions of SMNI-VP firing states with $Ca^{2+}$ waves.

1.4. Outline

The next Section calculates the influence of $A$, derived using current experimental data, on $Ca^{2+}$ momenta $p$. Since $Ca^{2+}$ waves are influential in synaptic interactions, this demonstrates the influence of $A$ in synaptic interactions.

In the Section following, SMNI is scaled to regional EEG activity, e.g., as measured on the scalp, and similar to previous studies that fit synchronous columnar firings to the electric potential $\Phi$ to EEG data, here such synchronous columnar firings are scaled
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to the vector potential \( \mathbf{A} \). In either case, developing \( \Phi \) or \( \mathbf{A} \), SMNI provides an audit trail back to columnar averaged synaptic parameters which are fit to EEG data, with parameters constrained to their experimentally determined ranges. In fitting \( \mathbf{A} \), the prior established dependence of synaptic interactions on \( \mathbf{A} \) provides justification to include coefficients as parameters to test and detail the dependence and sensitivity of EEG on \( \mathbf{A} \).

The Conclusion summarizes the calculations.

2. Classical and Quantum Considerations

In these calculations, the Lagrangian formulation will be used. In descriptive terms, for classical physics calculations the Lagrangian \( L \) is defined by the argument of a short-time conditional probability distribution \( P \) over a vector of variables \( x \) and time \( t \),

\[
P[x(t)|x(t - \Delta t)] = \bar{N} \exp(-L\Delta t)
\]

where \( \bar{N} \) is a normalization prefactor. This conditional probability evolves the initial distribution, e.g., as expressed by the path integral over all variables at all intermediate times. In quantum physics the Lagrangian is similarly defined in terms of the evolution of the wave function \( \psi \) whose absolute square is a probability distribution. As demonstrated in many disciplines as well as in many SMNI papers, the Lagrangian formulation often offers intuitive, algebraic and numerical advantages to its equivalent partial and stochastic differential representations. E.g., this approach affords the use of powerful derivations based on the associated variational principle, e.g., Canonical Momenta and Euler-Lagrange equations. This is all rigorously derived in many preceding SMNI papers, and has required developing powerful numerical algorithms to fit these algebraic models to data, such as Adaptive Simulated Annealing (ASA) [25,26], to calculate numerical details of the propagating probability distributions using PATHINT [27] and PATHTREE [28].

2.1. Effective Momentum \( \Pi \)

The effective momentum, \( \Pi \), affecting the momentum \( p \) of a moving particle in an electromagnetic field, is understood from the canonical momentum [29–32], in SI units,

\[
\Pi = p + qA
\]

where \( q = -2e \) for Ca\(^{2+} \), \( e \) is the magnitude of the charge of an electron = \( 1.6 \times 10^{-19} \) C (Coulomb), and \( A \) is the electromagnetic vector potential. (In Gaussian units \( \Pi = p + qA/c \), where \( c \) is the speed of light.) \( A \) represents three components of a 4-vector [32,33]. In the standard gauge, the 3-vector components of this 4-vector potential related to magnetic fields are of interest.

\( \Pi \) can be used in quantum as well as in classical calculations. Quantum mechanical calculations including these effects are likely important as it is clear that in time scales
much shorter than neuronal firings Ca$^{2+}$ wave packets spread over distances the size of typical synapses [34]. The gauge of $\mathbf{A}$ is not specified here, and this can lead to important effects especially at quantum scales [35].

2.2. Quantum Calculation

The Lagrangian $L$, the argument of the exponential defining this probability distribution, includes the canonical energy $\Pi^2/(2m)$. The momentum representation of a Gaussian wave function is developed in this context. The magnetic vector potential field $\mathbf{A}$ is shown to be quite insensitive to a reasonable spatial location, so we just have to consider the expectation of momentum $p$, which essentially gives back the classical value. This is made more explicit as follows:

The 3-dimensional Gaussian wave function in $r$-space of a Ca$^{2+}$ ion is derived as follows. (Further analysis is required of an initial many-bode wave function for a Ca$^{2+}$ wave.) The normalized wave function at time $t = 0$ in momentum space for a wave packet centered with momentum $p$ is

$$\phi(p, 0) = (2\pi(\Delta p)^2)^{-3/4} e^{-(p-p_0)^2/(4(\Delta p)^2)}$$

where squared vectors represent inner products, e.g., $(\Delta p)^2 = \Delta p \cdot \Delta p$. There is as yet no experimental evidence as to how this kind of wave packet is developed by Ca$^{2+}$ waves in vivo. $\phi$ develops in time as $U = \exp(-iHt)$ with Hamiltonian/Energy $H$,

$$U(p, t) = e^{-i((p+q\mathbf{A})^2/2m\hbar)}$$

$$\phi(p, t) = \phi(p, 0)U(p, t)$$

The normalized wave function in coordinate space is given by a Fourier transform in $k$-space, which can be taken in $p$-space using $p = \hbar k$,

$$\psi(r, t) = (2\pi\hbar)^{-3/2} \int_{-\infty}^{\infty} d^3p \phi(p, t)e^{ipr/\hbar}$$

This integral yields

$$\psi(r, t) = \alpha^{-1} e^{-\beta/\gamma-\delta}$$

$$\alpha = (2\hbar)^{3/2}(2\pi(\Delta p)^2)^{3/4} \left( \frac{it}{2m\hbar} - \frac{1}{4(\Delta p)^2} \right)^{3/2}$$

$$\beta = \left( \frac{r - q\mathbf{A}t}{m} - \frac{i\hbar p_0}{2(\Delta p)^2} \right)^2$$

$$\gamma = 4 \left( \frac{it\hbar}{2m} + \frac{\hbar^2}{4(\Delta p)^2} \right)$$

$$\delta = \frac{p_0^2}{4(\Delta p)^2} + \frac{iq^2\mathbf{A}^2t}{2m\hbar}$$
In coordinate space $\psi$ exhibits a direct dependence on $A$ in the displacement $r \rightarrow r - qAt/m$. This is not the phase-dependence of $A$ at work here, recognized as the Aharonov-Bohm effect [36].

Note that

$$(\Delta p)^2(\Delta r)^2 \geq (\hbar/2)^2$$

where $((\Delta r)^2)^{1/2}$ is the spatial 1/2-width of the packet. With the variance of $\psi$ in terms of $1/\Delta p$ instead of $\Delta r$, a factor of $\hbar^{-3/2}$ is introduced into $\psi(r, t)$ in order that the wave function in coordinate space be properly normalized. The dispersion of the wave packet in time can be seen in the factors and terms in $\psi(r, t)$, $\{\alpha, \beta, \gamma, \delta\}$, above.

If just the effects of $A$ on the wave function is required, using $p$-space is more straightforward than a typical $p \cdot A$ calculation that does a partial integration to get $\partial A/\partial t$, giving $-r \cdot E$, in terms of the coordinate $r$ and electric field $E$, but $r$ is not as directly observed as is $p$. Also note that the quantum expected value of $p$ from $\int \phi^* \phi p$ returns just $p_0$, the same as the classical value.

### 2.3. A of Wire

For a wire/neuron carrying a current $I$, measured in $A$ (not bold $A$) = Amperes $= C/s$,

$$A(t) = \frac{\mu}{4\pi} \int \frac{dr}{r} I$$

where the current is along a length $z$ (a neuron), observed from a perpendicular distance $r$ from the line of thickness $r_0$. Neglecting far-field retardation effects, this yields

$$A = \frac{\mu}{4\pi} I \log\left(\frac{r}{r_0}\right)$$

Similar formulae for other geometries are in texts [33]. The point here is the insensitive log dependence on distance. The estimates below assume this log factor to be of order 1. However, especially in this neocortical EEG context, the (oscillatory) time dependence of $A(t)$ derived from $I(t)$ is influential in the dynamics of $Ca^{2+}$ waves.

The magnetic field $B$ derived from $A$,

$$B = \nabla \times A$$

is still attenuated in the glial areas where $Ca^{2+}$ waves exist, and its magnitude decreases as inverse distance, but $A$ derived near the minicolumns will be used there and at further distance since it is not so attenuated. The electrical dipole for collective minicolumnar EEG derived from $A$ is

$$E = \frac{ic}{\omega} \nabla \times B = \frac{ic}{\omega} \nabla \times \nabla \times A$$

$\mu_0$, the magnetic permeability in vacuum $= 4\pi10^{-7}$ H/m (Henry/meter), where Henry has units of kg-m-C$^{-2}$, is the conversion factor from electrical to mechanical variables. In neocortex, $\mu \approx \mu_0$ [37, 38].
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The contribution to $A$ can be viewed as including many such minicolumnar lines of current across 100’s to 100’s of macrocolumns that typically contribute to large synchronous bursts of EEG [39], e.g., within a region not large enough to include many convolutions.

2.4. Numerical Effects of $A$ on $p$

The momentum $p$ at issue is calculated for comparison to the vector potential. In neocortex, a Ca$^{2+}$ ion with mass $m = 6.6 \times 10^{-26}$ kg, has speed on the order of 50 $\mu$m/s [40] to 100 $\mu$m/s [22]. This gives a momentum on the order of $10^{-30}$ kg-m/s. A study of molar concentrations gives an estimate of a Ca$^{2+}$ wave as comprised of tens of thousands of free ions representing about 1% of a released set (the bulk being buffered), with a range of about 100 $\mu$m, duration of about 500 ms, and concentrations ranging from 0.1-5 $\mu$m [22].

$qA$ can be calculated at several scales:

In studies of small ensembles of neurons [41], an electric dipole moment $Q$ is defined as $Iz\hat{r}$, where $\hat{r}$ is the direction unit-vector, leading to estimates of $|Q|$ for a pyramidal neuron on the order of 1 pA-m = $10^{-12}$ A-m. Multiplying by $10^4$ synchronous firings in a macrocolumn gives an effective dipole moment $|Q| = 10^{-8}$ A-m. Taking $z$ to be $10^2 \mu$m = $10^{-4}$ m (a couple of neocortical layers) to get $I$, this gives an estimate $|qA| \approx 2 \times 10^{-19} \times 10^{-7} \times 10^{-8}/10^{-4} = 10^{-28}$ kg-m/s.

Estimates at larger scales [42] give a dipole density $P = 0.1 \mu$A/mm$^2$. Multiplying this density by a volume of mm$^2 \times 10^2 \mu$m (using the same estimate above for $z$), gives a $|Q| = 10^{-9}$ A-m. This is smaller than that above, due to this estimate including cancellations giving rise to scalp EEG, while the estimate above is within a macrocolumn (the focus of this study), leading to $|qA| = 10^{-29}$ kg-m/s.

The estimates for $Q$ come from experimental data, which therefore include all shielding and material effects expected in other theoretical treatments that would derive $Q$. In the context of coherent activity among many macrocolumns, correlated with STM [19], $|A|$ may become orders of magnitude larger than these conservative estimates. Since Ca$^{2+}$ waves play an important role in synaptic activity inherent in this coherent macrocolumnar activity, of course there is direct coherence between these waves and the activity of $A$.

The above calculations show how important the effect of $qA$ from macroscopic EEG, on the order of $10^{-28}$ kg-m/s can be on the momentum $p$ of a Ca$^{2+}$ ion, on the order of $10^{-30}$ kg-m/s. The EEG effect on the displacement of the $r$ coordinate in the $\psi$ wave function, $qAt/m$, is on the order of $1.5 \times 10^{-2} t$ m which within 100 ms is on the order of $1.5 \times 10^{-3}$ m. If we assume the extent of $\Delta r$ can be on the order of a synapse [34], then this spatial extent is on the order of about $\mu$m = $10^4$ Å (Å = Angstrom = 10x10$^{-10}$ m). (Typical synaptic gaps are on the order of a few nm.) If this is correct, then the displacement of $r$ by the $A$ term is much larger than $\Delta r$. While Ca$^{2+}$ are observed to remain in waves for durations up to 500 ms [22], this example invokes extremely long
quantum coherence times of 100 considerations discussed below on how long quantum coherence times may be achieved may not support these long times. However, in any case, it should be noted that $A$ exerts strong quantum influences on $r$ via its relative influence on $p$.

If the uncertainty principle is close to saturation, we can take $\Delta p \geq \hbar (2\Delta r) = 1.054 \times 10^{-34}/(2 \times 10^{-6}) = 5 \times 10 - 29$ kg-m/s. This would make $\Delta p$ about the same as $p$.

### 2.5. Quantum Coherence of Ca$^{2+}$ Waves

It is now understood that standard arguments, that quantum coherence cannot be maintained at high temperatures [43], simply may not apply to many complex biological systems where other interactions may take precedence [44–48]. Quantum coherence in potassium ion channels has been proposed [49].

Here, waves of free Ca$^{2+}$ ions [22], the ions being synchronized into coherent waves by phase coordination in this columnar coherent firing context [50], may introduce pulsed-dynamical decoupling, a generalization of the quantum Zeno effect (QZE) and “bang-bang” (BB) decoupling, of ions from their environment, promoting long coherence times [51,52], as the system receives $n$ “kicks” during time $t$,

$$U_n(p,t) = [U_k U(p,t/n)]^n \tag{12}$$

where the kicks $U_k$ may include interactions with other quantum systems, e.g., other Ca$^{2+}$ ions in the same wave. Such mechanisms for maintaining coherence are currently investigated in the context of quantum computation [53,54].

In the context of of quantum Ca$^{2+}$ waves interacting with $A$, while it is straightforward to model many-body Hamiltonians/Lagrangians and wave functions, this issue can only be resolved by experimental verification, e.g., to ascertain the degree of quantum coherence among ions in a Ca$^{2+}$ wave. There is as yet no experimental evidence as to how this long-time coherence is developed by Ca$^{2+}$ waves in vivo.

### 3. Coupled SMNI-VP Ca$^{2+}$-Waves

#### 3.1. SMNI Dipoles

A dipole model for collective minicolumnar oscillatory currents is considered, corresponding to top-down signaling, flowing in ensembles of axons, not for individual neurons. The top-down signal is claimed to cause relevant effects on the surrounding milieu, but is not appropriate outside these surfaces due to strong attenuation of electrical activity. However, the vector potentials produced by these dipoles due to axonal discharges do survive far from the axons, and this can lead to important effects at the molecular scale, e.g., in the environment of ions [30,55].

The SMNI columnar probability distributions, derived from statistical aggregation of synaptic and neuronal interactions among minicolumns and macrocolumns, have
established credibility at columnar scales by detailed calculations of properties of STM. Under conditions enhancing multiple attractors, detailed in SMNI with a “centering mechanism” effected by changes in background synaptic activity, multiple columnar collective firing states are developed. These minicolumns are the entities which the above dipole moment is modeling. The Lagrangian of the SMNI distributions, although possessing multivariate nonlinear means and covariance, have functional forms similar to arguments of firing distributions of individual neurons, so that the description of the columnar dipole above is a model faithful to the standard derivation of a vector potential from an oscillating electric dipole.

Note that this is not necessarily the only or most popular description of electromagnetic influences in neocortex, which often describes dendritic presynaptic activity as inducing large scale EEG [56], or axonal firings directly affecting astrocyte processes [57]. This work is only and specifically concerned with electromagnetic fields in collective axonal firings, directly associated with columnar STM phenomena in SMNI calculations, which create vector potentials influencing ion momenta just outside minicolumnar structures.

3.2. SMNI Lagrangian

A short summary of the relevant SMNI Lagrangian in terms of its scaled synaptic parameters enables an explicit presentation of coupling the SMNI-VP with Ca^{2+} waves.

The SMNI Lagrangian, $L$, was derived as

$$L = \sum_{G,G'} (2N)^{-1}(\dot{M}^G - g^G)g_{GG'}(\dot{M}^{G'} - g^{G'})/(2N\tau) - V'$$

$$g^G = -\tau^{-1}(M^G + N^G \tanh F^G)$$

$$g_{GG'} = (g_{GG'})^{-1} = \delta_{GG'}^{-1} N^G \sech^2 F^G$$

$$g = \det(g_{GG'})$$

(13)

where $G = \{E, I\}$ represents excitatory $E$ and inhibitory $I$ processes, the aggregated relaxation time $\tau$ is on the order of 10 ms, $N = N^E + N^I$, and $N^E = 80$, $N^I = 30$ has been used the number of $E$ and $I$ neurons in a minicolumn, with twice these numbers for visual cortex, in previous calculations. $V'$ are derived mesocolumnar nearest-neighbor (NN) interactions.

The threshold factor $F^G$ is derived as

$$F^G = \sum_{G'} \frac{\nu^G + \nu^{AE'}}{((\pi/2)[(\nu_{G'}^G)^2 + (\delta_{G'}^G)^2](\delta^G + \delta^{AE'})^{1/2}}$$

$$\nu^G = V^G - a_{G'}^G v_{G'}^G N^G - \frac{1}{2} A_{G'}^G v_{G'}^G M^{G'}$$

$$\nu^{AE'} = -a_{E'}^E v_{E'}^E N^{AE'} - \frac{1}{2} A_{E'}^E v_{E'}^E M^{AE'}$$

$$\nu^{AE'} = -a_{E'}^E v_{E'}^E N^{AE'} - \frac{1}{2} A_{E'}^E v_{E'}^E M^{AE'}$$
where $A_{G'}$ and $B_{G'}$ are minicolumnar-averaged inter-neuronal synaptic efficacies, $v_{G'}$ and $\phi_{G'}$ are averaged means and variances of contributions to neuronal electric polarizations. $M_{G'}$ and $N_{G'}$ in $F_{G}$ are afferent macrocolumnar firings, scaled to efferent minicolumnar firings by $N/N* \approx 10^{-3}$, where $N*$ is the number of neurons in a macrocolumn, about $10^5$. Similarly, $A_{G'}$ and $B_{G'}$ have been scaled by $N*/N \approx 10^3$ to keep $F_{G}$ invariant. $V'$ is mesocolumnar NN interactions. Other values taken are consistent with experimental data, e.g., $V_{G} = 10$ mV, $v_{E'} = 0.1$ mV, $\phi_{E'} = 0.03^{1/2}$ mV.

The numerator of $F_{G}$ contains post-synaptic parameters, and that the denominator of $F_{G}$ contains pre-synaptic parameters, a result that drops out of the derivation of the mesoscopic derivation from the statistics of synaptic and neuronal interactions in and across minicolumns. Afferent contributions from $N_{E'}$ long-ranged excitatory fibers, e.g., cortico-cortical neurons, are included, where $N_{E'}$ might be on the order of 10% of $N*$: Of the approximately $10^{10}$ to $10^{11}$ neocortical neurons, estimates of the number of pyramidal cells range from 2/3 up to 4/5 [58]. Nearly every pyramidal cell has an axon branch that makes a cortico-cortical connection; i.e., the number of cortico-cortical fibers is of the order $10^{10}$. This development is used in the SMNI description of scalp EEG across regions.

3.3. Coupling Ca$^{2+}$-Waves with SMNI Lagrangian

The SMNI approach is a bottom-up mesoscopic aggregation from microscopic synaptic to columnar scales, and then scaled to relatively macroscopic regional scales of neocortex, which has been further merged with larger non-invasive EEG scales — all at scales much coarser than molecular scales. Here it is calculated how an SMNI vector potential (SMNI-VP) constructed from magnetic fields induced by neuronal electrical firings, at thresholds of collective minicolumnar activity with laminar specification, can give rise to causal top-down mechanisms that effect molecular excitatory and inhibitory processes in STM and LTM.

While many studies have examined the influences of changes in Ca$^{2+}$ distributions on large-scale EEG [59], future work will examine the complimentary effects on Ca$^{2+}$ ions at a given neuron site from EEG-induced magnetic fields arising from other neuron sites. Here, sufficient calculations claim the importance of macroscopic EEG $A$, arising from microscopic synchronous neural activity, on molecular momenta $p$ in Ca$^{2+}$ ions.

The time dependence of Ca$^{2+}$ wave momenta may be calculated with rate-equations [60] as a Hodgkin-Huxley model [61], including contributions from astrocytes in the vicinity of synapses [62,63]. In this study, the resulting flow of Ca$^{2+}$ wave momenta will
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be further determined by its interactions in Π, the canonical momenta which includes A.

One influence of Ca$^{2+}$ is likely regulating synaptic interactions [64]. The SMNI Lagrangian explicitly describes where the Ca$^{2+}$ affect the columnar-averaged synaptic parameters $A^G, B^G, A^E, B^E$. In this context Ca$^{2+}$ wave activity can affect the A, B synaptic parameters in these equations, while the A EEG fields affect the Ca$^{2+}$ waves.

In SMNI papers, the “centering mechanism” is invoked by fine-tuning B parameters to bring maximum multiple minima in firing space $M$, by adjusting background $B^G$ to set $ν^G = 0$ when $M^G = 0$, similar to the control of spontaneous synaptic background observed during selective attention [65]. The B parameters are a logical first choice to include influences from columnar Ca$^{2+}$ activities. These minima tend to lie along a line in a trough in M space, essentially $A^E M^E − A^I M^I ≈ 0$, noting that in $F^I I − I$ connectivity is experimentally observed to be very small relative to other pairings, so that $(A^E M^E − A^I M^I)$ is typically small only for small $M^E$. This model gives rise to all the successful SMNI calculations describing various STM phenomena.

This trough also supported previous SMNI work fitted to EEG data [16], developing a scaled macrocolumnar electric potential $Φ_ν$ at scalp region $ν$ derived with first and second moments of the SMNI Lagrangian, the argument of the associated distribution $P_ν$, at each (interconnected) region $ν$,

$$P_ν[Φ_ν(t)|Φ_ν(t − Δt)] = \frac{1}{(2πσ^2Δt)^{1/2}} \exp(-L_νΔt)$$

$$L_ν = \frac{1}{2σ^2} (\dot{Φ}_ν − m)^2$$

$$m = <Φ_ν − φ> = a <M^E > +b <M^I >= ag^E + bg^I$$

$$σ^2 = <(Φ_ν − φ)^2> = c^2 g^{EE} + d^2 g^{II}$$

in terms of $M^G$-space drifts $g^G$, diffusions $g^{GG}$, and an averaged reference $φ$.

The same process supports the similar parameterization of A in these studies, i.e.,

$$A = cM^E \dot{r} + dM^E \dot{r}$$

where c and d are scaled to the order of $10^4$ pA, as discussed above. This results in a Lagrangian $L$ for the combined EEG-Ca$^{2+}$ system,

$$L = \frac{1}{2σ^2} (\dot{A}_ν − m')^2$$

$$m' = <|A|_ν − φ'> = c <M^E > +d <M^I >= cg^E + dg^I$$

$$σ'^2 = <|A|_ν − φ'|^2> = c^2 g^{EE} + d^2 g^{II}$$

where now $m'$ and $σ'$ are nonlinear functions of $A$. This Lagrangian is the argument of the exponential defining the conditional probability density for developing from a state at time $t − 1$ to time $t$. The variational principle obeyed by this Lagrangian permits optimization of parameters to find most likely states that best fit EEG data, i.e., including macrocolumnar parameters within regions, long-ranged connectivity and time delays across regions [16].
3.4. Experimental Verification

The duration of a Ca\(^{2+}\) wave can be on the order of 500 ms, so that the momenta of such ions can be importantly influenced during relatively long EEG events like N100 and P300 potentials, reflecting latencies on the order of 100 ms and 300 ms, common in selective attention tasks which span these events [39]. Similar to procedures used in previous SMNI fits to EEG data [16, 66], here the influence of Ca\(^{2+}\) waves may be tested by parameterizing the \(B\) synaptic parameters to include their influence in data sets where subjects have had simultaneous recording of scalp EEG and samplings of Ca\(^{2+}\) wave activity at synaptic scales. These parameters are then fit to a portion of the EEG data, the in-sample set. The trained parameters can be used in out of sample EEG data, to test if the included Ca\(^{2+}\) wave activity correlates with the observed Ca\(^{2+}\) wave data.

The interaction of \(A\) and Ca\(^{2+}\) waves can be detailed using SMNI-scaled synaptic parameters which include a term dependent on \(A\), with coefficients measuring the convergence of synaptic interactions from many local minicolumnar and regional long-ranged fibers. The waves clearly depend on aggregates of their \(\Pi = p + qA\) dynamics. E.g., this can be modeled as a Taylor expansion in \(|A|\),

\[
\begin{align*}
B_{G'}^{G} &= B_{0G'}^{G} + |A|B_{1G'}^{G}, \\
B_{E'}^{IE} &= B_{0IE}^{IE} + |A|B_{1IE}^{IE} \\
\end{align*}
\tag{18}
\]

Eventually, the functional form of these dynamics should be established by models fit to molecular dynamics data, but for now at least their parameterized influences can be included. Since \(\Phi\) is experimentally measured, not \(A\), but both are developed by currents \(I\), when fitting to EEG data, it is reasonable to consider \(A\) as proportional to \(\Phi\) with a simple scaling factor, and now the additional parameterization of \(B_{G'}^{G}\) and \(B_{E'}^{IE}\) are to be included to modify previous work.

Another experimental test, just at the molecular scale to verify the influence of \(A\), can be made using the information that since the current lies along \(\hat{z}\), then \(A\) only has components along \(\hat{z}\), and

\[
\Pi = p_{x}\hat{x} + p_{y}\hat{y} + (p_{z} + qA_{z})\hat{z}
\tag{19}
\]

The influence of time-dependent Ca\(^{2+}\) waves is introduced in the post-synaptic and pre-synaptic SMNI parameters, which here also are time-dependent as functions of changing Ca\(^{2+}\) ions. Such parameters are present at neuronal scales and are included in microscopic ordinary differential equation calculations. However, as in the original development of SMNI, these parameters are developed to mesocolumnar scales, and the prediction here is that there is a predominance of Ca\(^{2+}\) waves in directions closely aligned to the direction perpendicular to neocortical laminae during strong collective EEG.

4. Conclusion

A model has been developed to calculate and experimentally test the coupling of molecular scales of Ca\(^{2+}\) wave dynamics with \(A\) fields developed at macroscopic regional
scales measured by coherent neuronal firing activity measured by scalp EEG.

For several decades biological and biophysical research into neocortical information processing has explained neocortical interactions as specific bottom-up molecular and smaller-scale processes [67]. It is clear that most molecular approaches consider it inevitable that their approaches at molecular and possibly even quantum scales will yet prove to be causal explanations of relatively macroscopic phenomena.

This study crosses molecular, microscopic (synaptic and neuronal), mesoscopic (minicolumns and macrocolumns), and macroscopic regional scales. Over the past three decades, with regard to STM and LTM phenomena, which themselves are likely components of other phenomena like attention and consciousness, the SMNI approach has yielded specific details of STM not present in molecular approaches [17]. The SMNI calculations detail information processing capable of neocortex using patterns of columnar firings, e.g., as observed in scalp EEG [19], which give rise to a SMNI vector potential $\mathbf{A}$ that influences the molecular $\text{Ca}^{2+}$ momentum $\mathbf{p}$, and thereby synaptic interactions. Explicit Lagrangians have been given, serving as cost/objective functions that can be fit to EEG data, as similarly performed in previous SMNI papers.

This study predicts a predominance of $\text{Ca}^{2+}$ waves in directions closely aligned to the direction perpendicular to neocortical laminae ($\mathbf{A}$ is in the same direction as the current flow, typically across laminae, albeit they are convoluted), especially during strong collective EEG (e.g., strong enough to be measured on the scalp, such as during selective attention tasks). Since the spatial scales of $\text{Ca}^{2+}$ wave and macro-EEG are quite disparate, an experimenter would have to be able to correlate both scales in time scales on the order of tens of milliseconds.

The basic premise of this study is robust against much theoretical modeling, as experimental data is used wherever possible for both $\text{Ca}^{2+}$ ions and for large-scale electromagnetic activity. The theoretical construct of the canonical momentum $\Pi = \mathbf{p} + q\mathbf{A}$ is firmly entrenched in classical and quantum mechanics. Calculations demonstrate that macroscopic EEG $\mathbf{A}$ can be quite influential on the momentum $\mathbf{p}$ of $\text{Ca}^{2+}$ ions, in both classical and quantum mechanics.

A single $\text{Ca}^{2+}$ ion can have a momentum appreciably altered in the presence of macrocolumnar EEG firings, and this effect is magnified when many ions in a wave are similarly affected. Therefore, large-scale top-down neocortical processing giving rise to measurable scalp EEG can directly influence molecular-scale bottom-up processes. This suggests that, instead of the common assumption that $\text{Ca}^{2+}$ waves contribute to neuronal activity, they may in fact at times be caused by the influence of $\mathbf{A}$ of larger-scale EEG. Such a top-down effect awaits forensic in vivo experimental verification, requiring appreciating the necessity and due diligence of including true multiple-scale interactions across orders of magnitude in the complex neocortical environment.
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