Influence of Macrocolumnar EEG on Ca Waves

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Abstract

A “smoking gun” for explicit top-down neocortical mechanisms that directly drive 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, \(\mathbf{p} = \mathbf{p} + q\mathbf{A}\) (SI units), is calculated, where the charge of Ca\(^{2+}\) is \(q = 2e\), e is the magnitude of the charge of an electron, valid in both classical and quantum mechanics. It is shown that A is large enough to influence p. This suggests that, instead of the common assumption that Ca\(^{2+}\) waves contribute to neuronal activity, they may in fact at times be caused by the influence of A of larger-scale EEG.

Smoking Gun For Top-Down Processes

There is a body of evidence that suggests a specific topdown 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 short-term memory (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.

SMNI CONTEX

Since 1981 about 30 papers on a statistical mechanics of neocortical interactions (SMNI) has been detailed properties of short-term memory, long-term memory, EEG analyses, and other properties of neocortex [11]–[16]. This discussion compares the momentum of a Ca\(^{2+}\) ion with macrocolumnar EEG fields. Columnar EEG firings calculated by SMNI lead to electromagnetic fields which can be described by a vector potential 4-vector [17]. In the standard gauge, the 3-vector components of this vector potential describe magnetic fields, denoted here as A, are of interest. In this context 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 not as detailed [16]. Note that gauge of A is not specified here, and this can lead to important effects especially at quantum scales [18]. Current research is directed to more detailed interactions of SMNI-VP firing states with Ca\(^{2+}\) waves.

This paper concerns a dipole model for collective minicolumnar oscillatory currents, 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 [19], [20].

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 papers with a “centering mechanism” affected by changes in background synaptic activity, multiple columnar collective firing states are developed. It must be stressed that 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 [21], or axonal firings directly affecting astrocyte processes [22]. 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.

Ca²⁺

The roles of Ca²⁺, while not completely understood, are very well appreciated as being quite important. It is likely that Ca²⁺ waves are instrumental in tripartite synaptic interactions of astrocytes and neuronal synapses [23]–[25].

A. Ca²⁺ Momentum

The momentum at issue is calculated to set the stage for comparison to the vector potential.

In neocortex, a Ca²⁺ ion with mass $m_{Ca} = 6.6 \times 10^{-26}$ kg, has speed on the order of 50 µm/s [26] to 100 µm/s [25]. This gives a momentum on the order of $10^{-30}$ kg-m/s. An estimate of molar concentrations [25], gives an estimate of a Ca²⁺ wave as comprised of tens of thousands of such ions.

VECTOR POTENTIAL OF EEG DIPOLES

The effective momentum, $\vec{p}$, affecting the momentum $p$ of a moving particle in an electromagnetic field, is understood from the canonical momentum [19], [27], [28], in SI units,

$$\vec{p} = p + qA$$

where $q = 2e$ for Ca²⁺, $e$ is the magnitude of the charge of an electron $1.6 \times 10^{-19}$ C (Coulomb), and $A$ is the electromagnetic vector potential. (Note that in Gaussian units $\vec{p} = p + qA/c$, where $c$ is the speed of light.

$\vec{p}$ can be used in quantum as well as in classical calculations. Eventually, quantum mechanical calculations including these effects will be performed, as it is clear that in time scales much shorter than neuronal firings Ca²⁺ wave packets spread over distances the size of typical synapses [29]. Note that gauge of $A$ is not specified here, and this can lead to important effects especially at quantum scales [18].

For a wire/neuron carrying a current $I$, measured in $A = $ Amperes = $C/s$,

$$A = \mu / 4\pi (dr / r)$$

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

$$A = \mu / 4\pi \log (z + (Z^2 + s^2)^{1/2}) / s$$

Other formulae for other geometries are in texts [17]. The point here is the insensitive log dependence on distance. The estimates below assume this log factor to be of order 1. The magnetic field $B$ derived from $A$,

$$B = \mu / 4\pi \ast A$$

is still attenuated in the glial areas where Ca²⁺ 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

$$E = iC / ? \ast B = iC / ? \ast A$$

$\mu_0$, the magnetic permeability in vacuum $= 4\pi \times 10^{-7}$ (Henry/meter), where Henry has units of kg-m–C², is
the conversion factor from electrical to mechanical variables. Near neurons,
\[ \mu = 10^6 \mu \text{g}[30], \text{giving}[30], \mu = 10^6 \]
\[ qA \text{ can be calculated at several scales:} \]
In studies of small ensembles of neurons [31], an
electric dipole moment \( Q \) is defined as \( z^\mu r \), where \( z^\mu \) is
the direction unit-vector, leading to estimates of \( |Q| \) for
a pyramidal neuron on the order of \( 1 \, \text{pA-m} = 10^{-12} \, \text{A-m} \).
Multiplying by \( 10^4 \) synchronous firings in a
macrocolum gives an effective dipole moment \( |Q| = 10^9 \, \text{A-m} \)
Taking \( z \) to be \( 10^4 \mu \text{m} = 10^4 \mu \text{m} \) (a couple of
neocortical layers) to get \( I \), this gives an estimate
\[ |qA| = 2 \times 10^{-7} \times 10^9 = 2 \times 10^{-7} \mu\text{A} \cdot \mu\text{m} \]
Estimates at larger scales [32] give a dipole density \( P = 0.1 \, \mu\text{A/mm}^2 \).
Multiplying this density by a volume of
\( \text{mm}^2 \times 10^4 \mu\text{m} \) (using the same estimate above for \( z \)),
gives a \( |Q| = 10^9 \, \text{A-m} \) This is smaller than that above,
due to this estimate including cancellations giving rise
to scalp EEG, while the estimate above is within a
macrocolum (the focus of this study), leading to
\[ |qA| = 10^{-7} \, \mu\text{A} \cdot \mu\text{m} \, \text{s} \]

**SMNI CALCULATIONS**

**A. \( \text{Ca}^{2+} \) Momenta**
The time dependence of \( \text{Ca}^{2+} \) wave momenta is
typically calculated with simulations using code such as
**NEURON** [33], within multivariate differential equations
describing interactions among quite a few
neuronal elements and parameters. In this study, the
resulting flow of \( \text{Ca}^{2+} \) wave momenta will be
further determined by its interactions in ?, the
canonical momenta which includes \( A \).

**B. SMNI-VP**
The outline of coupling the **SMNI-VP** with \( \text{Ca}^{2+} \) waves
follows. Similar to the scaling of mesoscopic columnar
firings to an electric potential \( \Omega \) describe regional **EEG**
that was fitted to large data sets [15], here columnar
firings are scaled to describe the effective current \( I \)
giving rise to the vector potential \( A \),
\[ A = a \mu E + b \, M^E \, r \]  -----(6)
where \( a \) and \( b \) are scaled to something on the order of
\( 10^6 \, \text{pA} \), as discussed above. \( M^E \) is the excitatory
columnar firing of pyramidal neurons, and \( M^I \) is the
inhibitory columnar firing of pyramidal neurons.
The influence of time-dependent \( \text{Ca}^{2+} \) waves is
introduced in the post-synaptic and pre-synaptic SMNI
parameters, which here also are time-dependent as
functions of changing \( \text{Ca}^{2+} \) ions.

Such parameters are present at neuronal scales and
are included in microscopic **NEURON** ordinary
differential equation calculations. However, as in
the original development of **SMNI**, these parameters are
developed to mesocolumnal scales.

For example, SMNI mesoscopic firings are described
by coupled stochastic differential equations, nonlinear
in the drifts and covariance in terms of \( M^E \) and \( M^I \)
variables, and mesoscopic synaptic and neuronal
parameters. It has been most productive to cast these
coupled equations into mathematically equivalent
conditional probability distributions, which are better
served to handle algebraic intricacies of their rather
general nonlinear time-dependent structure, and which
afford
the use of powerful derivations based on the
associated variational principle, e.g., Canonical
Momenta Indicators and Euler-Lagrange equations.
This is all rigorously discussed and calculated in many
preceding **SMNI** papers. This also required developing
powerful numerical algorithms to fit these algebraic
models to data [34], [35] and to develop numerical
details of the propagating probability distributions
using **PATHINT** [36] and **PATHTREE** [37].

**C. Coupled SMNI-VP \( \text{Ca}^{2+} \) System**
For several decades the stated Holy Grail of chemical,
biological and biophysical research into neocortical
information processing has been to reduce such
neocortical phenomena into specific bottom-up
molecular and smaller-scale processes [39]. Over
the past three decades, with regard to short-term memory
(STM) and long-term memory (LTM) phenomena,
which themselves are likely components of other
phenomena like attention and consciousness, the
**SMNI** approach has
yielded specific details of STM capacity, duration and
stability not present in molecular approaches, but it is
clear that most molecular approaches consider it
indefinitely that their approaches at molecular and
possibly even quantum scales will yet prove to be
causal explanations of such phenomena.

The **SMNI** approach is a bottom-up aggregation from
synaptic scales to columnar and regional scales of
neocortex, and has been merged with larger
non-invasive **EEG** scales with other colleagues – all at
scales much coarser than molecular scales. As with
many Crusades for some truths, other truths can be
trampled. It is proposed that an **SMNI vector potential** (**SMNIVP**)
constructed from magnetic fields induced by
neuronal electrical firings, at thresholds of collective
minicolumnar activity with laminar specification, can

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give rise to causal top-down mechanisms that effect molecular excitatory and inhibitory processes in STM and LTM. Such a smoking gun for top-down effects 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.

While many studies have examined the influences of changes in Ca\(^{2+}\) distributions on large-scale EEG [40], there have not been studies examining the complimentary effects on Ca\(^{2+}\) ions at a given neuron site from EEG-induced magnetic fields arising from other neuron sites. Thus, a single 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 atomic-scale bottom-up processes.

This suggests that, instead of the common assumption that Ca\(^{2+}\) waves contribute to neuronal activity, they may in fact at times be caused by the influence of A of larger-scale EEG. Such a “smoking gun” for top-down effects 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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