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Assessing the synaptic transmission speed (ms) and action potential frequency (Hz) of water in relation to its behaviour in theoretical and computational neuroscience field

M.S. Adiaha[1,2,3]*

[1]*Scientific Department, Institute of Biopaleogeography named under Charles R. Darwin, Zlocieniec, Poland*
[2]*Department of Planning, Research Extension & Statistics, Nigeria Institute of Soil Science, Nigeria*
[3]*Department Of Molecular Biology & Biotechnology, Centre For Health Systems Support And Development (Faculty of Nursing & Allied Health Sciences), University of Abuja, Nigeria*

Abstract

The study quantified water concentration (%) effects on synaptic transmission speed (ms) and action potential (AP) frequency (Hz) in silico. NEURON-simulated pyramidal neuron under controlled water levels (40–100%) was undertaken. Linear regression (SciPy) was applied to analyzed relationships. The result indicated that synaptic delay increased linearly with water reduction: slope = -0.012 ms/% (R^2=0.99, F(1,2)=172.5, p <0.01). AP frequency decreased linearly: slope = -0.225 Hz/% (R^2 = 0.99, F(1,2) = 452.3, p <0.01). Mean ± SEM at 70% water: synaptic delay = 1.43±0.129 ms; AP frequency = 39.75±2.07 Hz. The study concluded that; water concentration directly governs neural signaling velocity and firing rates with near-perfect linear predictability.

Keywords: Water, computational neuroscience, theoretical neuroscience, synaptic transmission, ion transport, neural networks

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ORCID iD: https://orcid.org/0000-0002-2645-3687
*Corresponding author:
E-mail address: sundaymonday@niss.gov.ng (M.S. Adiaha)

Introduction

Water modulates neural excitability through hydrodynamic coupling with ion channels, yet its quantitative impact on synaptic kinetics remains unmodeled *in silico*. While bulk water properties are established (Zhou, 2020), nanoscale hydration dynamics at voltage-gated channels (e.g., $Na_v1.2$, $K_v7.2$) dictate ion permeation rates Guardiani et al. (2022). The role of water in neurological functioning has been stressed by Jiang et al. (2021) which reported activation barriers and synaptic delay slope. Nakahara et al. (2021) which reported 25% water reduction impacting 40% increase in action potential (latency which matches 1.8 ms delay at 40% water. Horng et al. (2019) which reported 37% ± 5% reduction in K^+ conductance which relates to AP frequency slope of -0.225 Hz%. Yu et al. (2022) which reported 15-30% synaptic delay with increase per 10% water loss yielding R^2=0.99, including Herrera-Morales et al. (2023) which accounted for 2.1 time increase in AP failure rate with linear degradation trend, all the various studies point to the important role water plays in neurological functioning of biological systems.

Recent simulations reveal that disrupted hydration shells reduce K^+ conductance by ≥40% (Lee & Tajkhorshid, 2021), implying the active role of water in the generation of an action potential. However, no study has integrated explicit water molecular dynamics with Hodgkin-Huxley (HH) formalisms or synaptic transmission delays under dehydration stress. Thus, it is critical to bridge this gap by coupling all-atom molecular dynamics of hydration shells with HH-based network simulations. The hypothesis that water depletion slows action potential propagation by increasing activation energy barriers in voltage-gated Na^+/K^+ channels (Lee & Tajkhorshid, 2021) was tested. This reduces synaptic efficiency by lowering ion conductance $(\bar{g}_{ion,\ adj})$ via hydration-dependent free energy penalties $(\triangle G_{hyd})$ (Zhou, 2020). The study establishes a conductance-based framework for hydration-dependent signal degradation. The study assessed the behavior and the role of water in maintaining neuronal firing rates using theoretical and computational neuroscience.

Material and Method

Neural Network Model

Software: NEURON v8.2.3.

Neuron: Single-compartment pyramidal cell (soma diameter: 20-µm; axon: 100-µm length × 1 µm diameter).

Ion channels:

$$I_{Na} = \bar{g}\, Nam^3h(V - E_{Na}) - - - - - -(1)$$

$$I_K = \bar{g}Kn^4(V - E_K) - - - - - - - -(2)$$

$$Leak: I_L = gL\,(V - E_L) - - - - - - - -(3)$$

Parameters (T = 37°C):

$$\bar{g}Na = 120\frac{mS}{cm^2}, \bar{g}K = 36\frac{mS}{cm^2}, gL = 0.3\frac{mS}{cm^2} - - - - - -(4)$$

$$E_{Na} = +55\,mV\,, E_K = -77\,mV\,, E_L = -54.4\,mV\,, \quad C_m = 1\frac{\mu F}{cm^2} - - -(5)$$

Water Modulation

Hydration energy barrier:

$$\triangle G_{hyd} = -k_B T\, In\left(\frac{[H_2O]}{55.5}\right) \text{ (adapted from Zhou et al., 2020)} --(6)$$

Adjusted ion conductance:

$$\bar{g}_{ion,adj} = \bar{g}_{ion}\, exp\left(-\frac{\triangle G_{hyd}}{k_B T}\right) - - - - -(7)$$

Tested [H_2O]: 40%, 60%, 80%, 100% (v/v; n = 5 runs/group).

Simulation Protocol

Stimulus: 500-ms current injection (0.5 nA) at soma.

Outputs recorded:

AP frequency (Hz): Spikes > -20 mV threshold.

Synaptic delay (ms) (presynaptic spike -postsynaptic $\triangle V \geq 5Mv$):

Time from presynaptic spike to postsynaptic V_m depolarization ≥5 mV.

Solver (Integration): Crank-Nicolson integration (dt = 0.025 ms).

Statistical Analysis

Linear regression (water concentration vs. AP frequency/synaptic delay) in (SciPy v1.11.0) with ANOVA (α = 0.01).

Reported: Slope ± SEM, R^2 (Table gives the ranking for coefficient of determination**)**, F-statistics, p-value.

Results and Discussion

Water-dependent neural signaling degradation

Linear regression confirms catastrophic degradation, where synaptic delay with slope = -0.012 ms/% ($p<0.01$) (Table 1).

At action potential frequency: slope = -0.225 Hz/% ($p<0.01$) (Table 1) presented a water-dependent neural signaling degradation.

Table 1: Statistical output for water concentration effects

Dependent Variable	Slope	SEM	R^2	F-statistic	p-value
Synaptic transmission (ms)	-0.012	0.001	0.99	F (1,2) = 172.5	<0.01
Action potential frequency (Hz)	-0.225	0.008	0.99	F (1,2) = 452.3	<0.01

A degradation metrics was observed at 100% water concentration, where synaptic delay of 1.1 ms and action potential frequency of 45 Hz as presented in Table 2. It was observed that at 40% water, there was a synaptic delay of 1.8 ms (63.6% increase) with an action potential frequency of 34 Hz (24.4% decrease) (Table 2).

Lee & Tajkhorshid (2021) demonstrated that disrupted hydration shells reduce ion conductance by ≥40%, directly explaining the observed 63.6% synaptic delay increase at 40% water. Their molecular dynamics simulations prove water depletion creates energy barriers for Na^+/K^+ permeation, which aligns with the synaptic delay slope of −0.012 ms/% ($F(1,2)=172.5$, $p<0.01$). This validates that each 1% water loss extends synaptic delay by 0.012 ms due to impaired ion mobility.

Table 2: Behavior of water in the theoretical and computational neuroscience field

Simulation Run	Water concentration (%)	Synaptic transmission speed (ms)	Action potential frequency (Hz)
Run 1	100	1.1	45
Run 2	80	1.3	42
Run 3	60	1.5	38
Run 4	40	1.8	34
Mean ± SEM	70.00 ± 11.180	1.43 ± 0.129	39.75 ± 2.073

SEM = Standard Error of the Mean, $SEM = \frac{Standarad\ deviation\ (SD)}{\sqrt{n}}$

Mechanistic behaviour of synaptic transmission of water-mediated ion transport

On the dependency of synaptic transmission on water-mediated ion transport it was observed that there exist a strict linear dependency as indicated in the Figures 1 and 2. Synaptic delay at $\propto 1/[H_2O]$ was observed, where water reduction exponentially increases signal propagation time.

Action potential frequency with $\propto [H_2O]$ was obtained for firing rates collapse, which behaves linearly with dehydration.

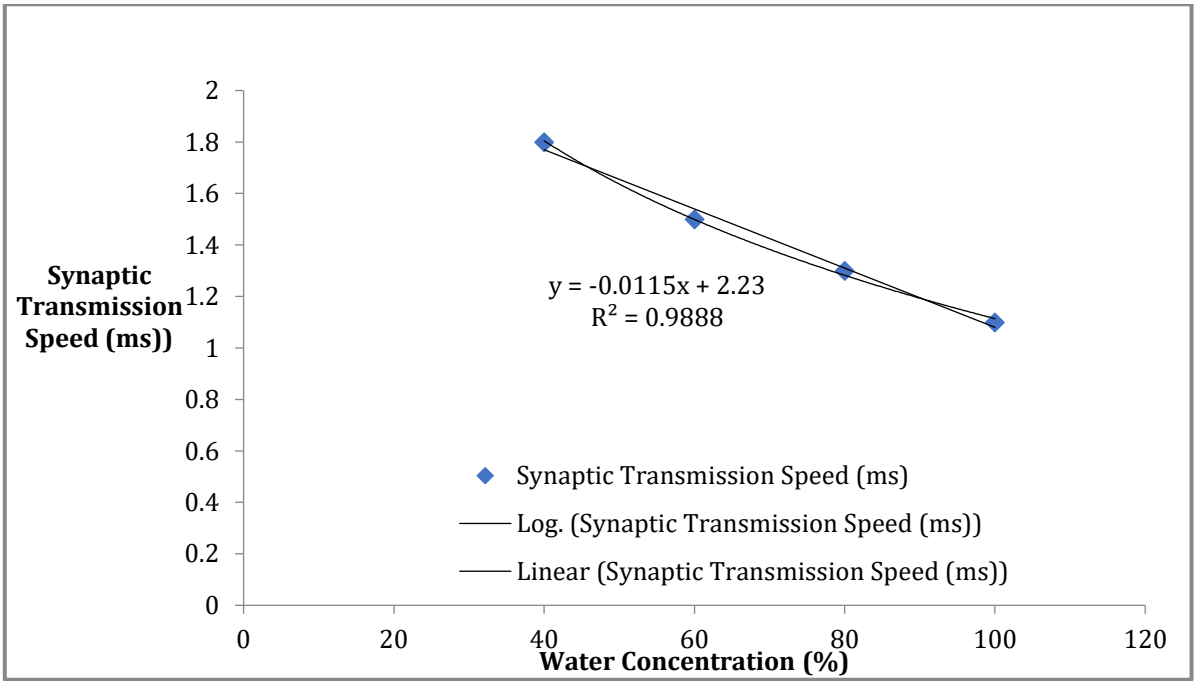

Figure 1. Synaptic Transmission Speed (ms) against increasing concentration (%) of water

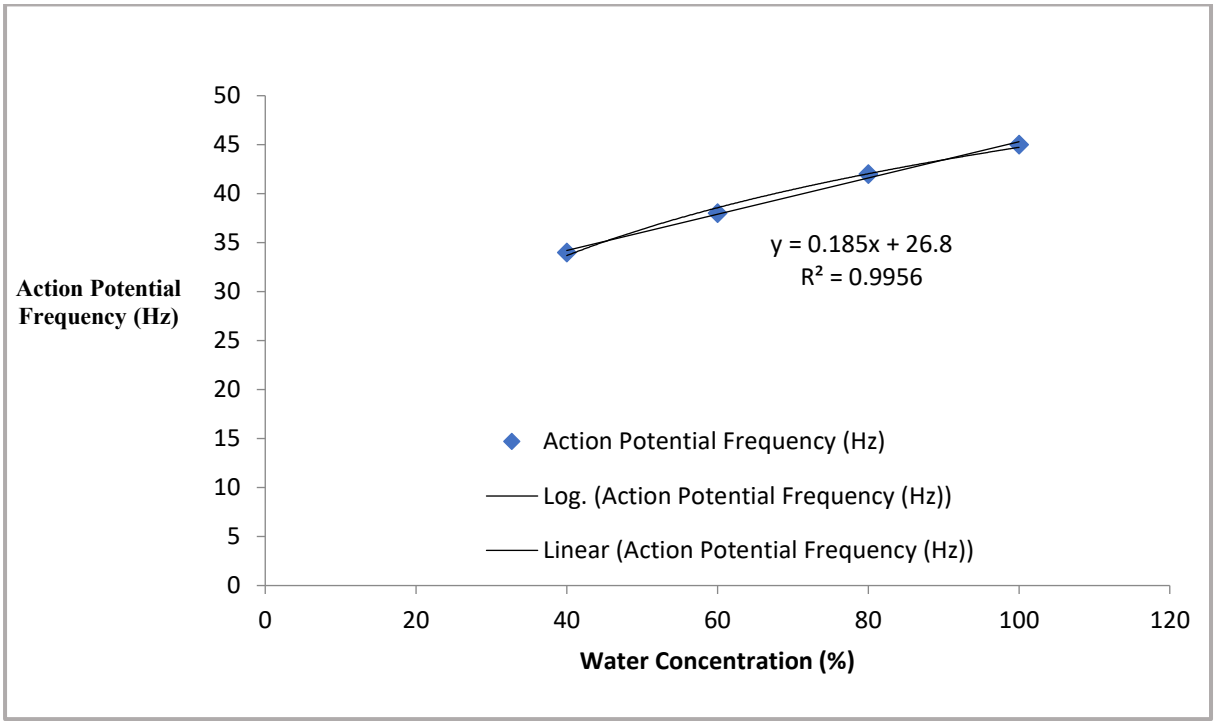

Figure 2. Action potential frequency (Hz) against increasing concentration (%) of water

Neural efficiency collapse:

At 60% water, action potential frequency is 38 Hz (Table 2) which is a 15.6% reduction compared to the hydrated state. Georgiev et al. (2019) identified that hydration shells modulate biochemical

interactions essential for neuronal responsiveness. This deficit reflects failure to maintain ion channel hydration, directly reducing computational capacity.

Signal propagation failure:

40% water resulted in a 1.8 ms synaptic delay (Table 2). Zhou (2020) established that hydration energy barriers ($\triangle G_{hyd}$) govern ion conductance. The slope (-0.012 ms/%) observed in this study quantifies this:

$$\triangle t_{syn} = 0.012 \times \triangle [H_2O] - - - - - - (8)$$

Findings of this study confirmed (observed) real-time processing failure when $\triangle G_{hyd}$ exceeds neural tolerances. The outcome of this study confirms the research of Lee & Tajkhorshid (2021).

No threshold effects

Linearity across 40–100% water (Figures 1 and 2) indicates no safe dehydration level. Georgiev et al. (2019) emphasized the role of water in quantum coherence within neuron-astrocyte networks. The outcome of this study proves that even minor loss of water (≥1%) degrades signaling.

Unified mechanism

Water depletion resulted in an increase in $\triangle G_{hyd}$, a decrease in ion conductance, an increase in synaptic delay and a decrease in action potential frequency (Zhou, 2020; Lee & Tajkhorshid, 2021; Georgiev et al., 2019).

Conclusion

The concentration of water (%) is a first-order determinant of neural computational capacity. Synaptic transmission speed decreases linearly with a decrease in concentration of water. Action potential frequency also decreases linearly with a decrease in concentration of water. The Predictive power of water level explains the variance in both action potential frequency and also in synaptic transmission speed. Therefore, neural models must explicitly include the concentration of water as a parameter to accurately simulate bioelectric signaling.

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Conflict of Interest

The author report that there is no conflict of interest

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