A Quantum Statistical Model of Decision Making in a Single-Cell Eukaryote

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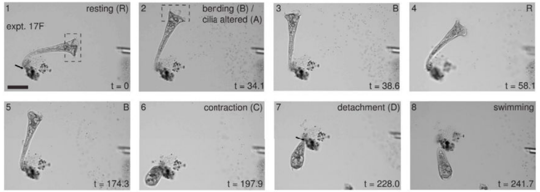
Background

Stentor Roeselii is a free-living, trumpet shaped single-celled ciliate found in freshwater ponds. In 1906, the biologist Herbert Spencer Jennings reported that Stentor Roeselii exhibited signs of complex behavior, potentially indicating a form of decision-making (Jennings, 1931). In 2019, Jenning's results were verified by Dexter et al. (Dexter 2019). Specifically the protist follows an escalatory sequence of the following actions to avoid toxins in their environment.



Analyzing Dexter et al. data we can observe that the protist will follow the action sequence **R-A/B-C-D**, and will stop when the toxin is no longer a threat to the protist's survival. Note that each action in the sequence is more energy intensive then the last.The protist can skip actions or repeat actions in this sequence but the order is preserved. A possible action sequence where **p** represents the re-introduction of a toxin may look like

Interaction

RABABp AACp ABABCCDp CCCD

Sequence

From the 44 sequence experimental dataset developed by Dexter et. al, one can observe that following interaction/sequence level trend assuming that **P(AB) = λ**

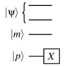
		Interaction	Sequence
P(AB| Last Action was AB & Failed)	**=**	**λ - ρ**	**30%**
P(AB| Last Action was AB & Succeeded)	**=**	**λ + ρ**	**70%**

This would seem to indicate that the protist is an *operant learner* who is trying to maximize the probability of eliminating the toxin while also minimizing it's energy costs.

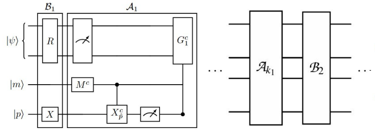
Model

Recent finding indicate that quantum processes may play an important role in intracellular information process in various contexts including light harvesting (*Fleming 2011*) and responding to environmental cues (Babcock 2024). Motivated by these finding we attempt to model stentor roseli's behavior using only quantum permissible processes. To that end we first introduce a 4 qubit quantum state that represents the protists internal biases towards each action (R,AB,C,D) along with a memory and toxin detection qubit.

$$|\psi\rangle = \begin{pmatrix} r \\ d \\ c \\ ab \end{pmatrix}$$



Next we instantiate a quantum process that effectively simulates the introduction of a toxin and forces the protist to select AB as its first recourse. Over the course of an interaction the protist adjusts it's internal biases, tracks the presence of toxins in its environment and keeps a record of it's last action through the following quantum gates.



$$G_{AB,C}(\theta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\theta & \sin\theta \\ 0 & 0 & -\sin\theta & \cos\theta \end{pmatrix}$$

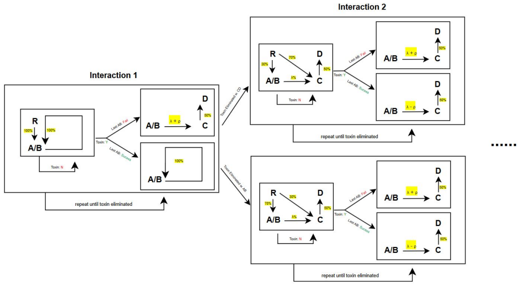
$$G(|m\rangle, |p\rangle) = \begin{cases} G_{AB,C}(\theta), & \text{if } |m\rangle = |0\rangle \text{ and } |p\rangle = |1\rangle \\ U_{|t\rangle}(|\psi\rangle), & \text{if } |m\rangle = |1\rangle \text{ and } |p\rangle = |1\rangle \\ U_{|00\rangle}(|\psi\rangle), & \text{if } |p\rangle = |0\rangle \end{cases}$$

$$M = \begin{cases} U_{|+\rangle}(|m\rangle), & \text{if } |\psi\rangle = |00\rangle \\ U_{|0\rangle}(|m\rangle), & \text{if } |\psi\rangle = |11\rangle \\ U_{|1\rangle}(|m\rangle), & \text{if } |\psi\rangle = |10\rangle \\ U_{|-\rangle}(|m\rangle), & \text{if } |\psi\rangle = |01\rangle \end{cases} \quad X_{\hat{p}} = \begin{cases} X_0, & \text{if } |m\rangle = |+\rangle \\ X_{\frac{1}{10}}, & \text{if } |m\rangle = |0\rangle \\ X_{\frac{1}{2}}, & \text{if } |m\rangle = |1\rangle \\ X_1, & \text{if } |m\rangle = |-\rangle \end{cases}$$

$$R(|m\rangle) = \begin{cases} U_{|c\rangle}|\psi\rangle, & \text{if } |m\rangle = |1/-\rangle \\ U_{|ab\rangle}|\psi\rangle, & \text{if } |m\rangle = |0\rangle \\ X \otimes X, & \text{if} |m\rangle = |+\rangle \end{cases}$$

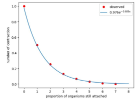
$$|c\rangle = \begin{pmatrix} 0 & 0 & \sqrt{0.7} & \sqrt{.3} \end{pmatrix}$$
$$|ab\rangle = \begin{pmatrix} 0 & 0 & \sqrt{0.3} & \sqrt{.7} \end{pmatrix}$$
$$|t\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 1 & 0 \end{pmatrix}$$

ρ= 1-cos(Θ), and can be inferred by choosing Θ such that the average experimental interaction length is preserved. We find that the average interaction level "learning rate" is 0.1725. The quantum process described may be difficult to decipher but luckily it can be roughly translated into the following decision tree, where λ is initialized as 0.

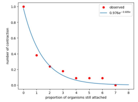


Results

Using our computational model we generated 957,489 sequences contained in 100,000 multi sequence patterns. The average depth of each sequence generated has an expected depth of 2.52 compared to Dexter's average sequence lengths of 2.44. Additionally the probability that a protist stays attached after k contractions is roughly 1 2k which is similar to Dexter's experimentally determined probability.

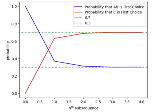


(a) Proportion of protists attached after n contractions across 957,489 generated sequences

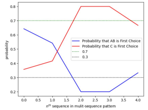


(b) Proportion of protists attached after n contractions across 109 experimental sequences

We observe that in a multi-sequence pattern, the probability that AB is chosen first converges to 0.30 while the probability that C is chosen first converges to 0.70. While Dexter's dataset only has 56 multi-sequence patterns, we still observe a similar trend. In short, our quantum model is capable of reproducing the statistical trends observed in Dexter's data. Additionally across the 957,489 generated sequences 87 of Dexter's 109 experi mentally determined sequences were exactly reproduced.



(a) C or AB chosen first in 100,000 generated multi-sequence patterns



(b) C or AB chosen first in 56 experimental multi-sequence patterns (Dexter et al., 2019)

We note that, to date, there are not experimental studies confirming the use of quantum processes within stentor-roseli's decision-making, however we hope that the simple quantum circuit proposed lends credence to the idea that such a quantum process is possible.

Citations

1. Jennings, H. S. (1931). 11. introduction and behavior of cœlenterata. In Behavior of the lower organisms (pp. 188–232). New York Chichester, West Sus sex: Columbia University Press. Retrieved 2024-09-15, from https://doi.org/10.7312/jenn90464-011 doi: doi:10.7312/jenn90464-011
2.Dexter, J. P., Prabakaran, S., & Gunawardena, J. (2019). A complex hierarchy of avoidance behaviors in a single-cell eukaryote. Current biology, 29(24), 4323–4329.
3. Fleming, G. R., Scholes, G. D., & Cheng, Y.-C. (2011). Quantum effects in biology. Procedia Chemistry, 3(1), 38-57. (22nd Solvay Conference on Chemistry) doi: https://doi.org/10.1016/j.proche.2011.08.011
4. Babcock NS, Montes-Cabrera G, Oberhofer KE, Chergui M, Celardo GL, Kurian P. Ultraviolet Superradiance from Mega-Networks of Tryptophan in Biological Architectures. J Phys Chem B. 2024 May 2;128(17):4035-4046. doi: 10.1021/acs.jpcb.3c07936. Epub 2024 Apr 19. PMID: 38641327; PMCID: PMC11075083.