COST Action CA 21169

2025 DYNALIFE Conference on QUANTUM INFORMATION AND DECISION MAKING IN LIFE SCIENCES

PROGRAMME and ABSTRACTS

Faculty of Economics and Management,
Czech University of Life Sciences Prague,
Kamýcká 129, 165 00 Prague
April 28-29, 2025

Jointly organised by
Institute of Information Theory and Automation
The Czech Academy of Sciences
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Faculty of Economics and Management
Czech University of Life Sciences Prague
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Dear participant,

Welcome to Prague for the 2025 DYNALIFE Conference!

We are delighted to have you join us in our beautiful city, renowned for its stunning historical monuments, classical architecture, and rich cultural heritage. Prague has a proud tradition in the natural sciences, having been home to many esteemed scientists, including Bernard Bolzano, Tycho Brahe, Johannes Kepler, Christian Doppler, Albert Einstein, and Jaroslav Heyrovsky.

We are excited about the intensive scientific program, which we hope will inspire lively discussions and foster meaningful collaborations that extend well beyond our time together.

Enjoy this event, and we wish you a wonderful stay in Prague. Thank you for your valuable contribution to the success of this gathering!

With kind regards,

Local Organising Committee

PROGRAMME

MONDAY APRIL 28	
8:50--9:20	Registration
SESSION I	**Chair:** I. Richter and B. Dragovich
9:20—9:30	Welcome and Opening
9:30—10:20	**Invited Talk:** Igor Jex (CZ) *Quantum Buridan's Ass*
10:20—10:40	**Contributed Talk**: Martin Štefaňák (CZ) *Survival probability and quantum transport in Grover Walk on finite graphs*
10:40—11:10 Coffee Break	
SESSION II	**Chair:** I. Jex
11:10—11:30	**Contributed Talk:** Alessandro Chiolerio (ITA) *Room Temperature Multi-particle Entanglement in Ferrofluids*
11:30—11:50	**Contributed Talk:** David Ellerman (SLO) *A Fundamental Duality: From Logic to Biology*
11:50—12:10	**Contributed Talk:** Michel Planat (FR) *Topological quantum computing: from baryonic matter to the building blocks of life*
12:20—14:00 Lunch Break	
SESSION III	**Chair:** Ch.Fuchs
14:00—14:50	**Invited Talk:** Emmanuel Pothos (UK) *The Quantum Sequential Sampler*
14:50—15:10	**Contributed Talk:** Stoyan Kurtev (BG) *Quantum or quantum-like scattering of waves in cognitive parameter space*
15:10—15:50	Poster Spotlights. **Chair:** T.V. Guy
15:50—17:00 Coffee Break and **Poster Session**	
17:00—18:00	**Roundtable Discussion:** Modeling Life's Decisions: New Mathematical Tools for Biological Complexity **Moderator:** B. Dragovich
19:00—22:00	**SOCIAL EVENT** Restaurant “Na Rozhrani”, Srbská 7, Praha 6 (100 m from metro Hradcanska)

PROGRAMME

TUESDAY, APRIL 29		
8:30--9:00		Registration
SESSION IV		**Chair:** T.V. Guy
9:00—9:50		**Invited Talk:** David Rios Insua (SP) *Explorations in dynamic artificial life: Decision making in social emotional robots.*
9:50—10:10		**Contributed Talk:** Miroslav Kárný (CZ) *On the role of prescriptive decision-making theory in natural sciences*
10:10—10:40	**Coffee Break**	
SESSION V		**Chair:** M. Kárný
10:40—11:30		**Invited Talk:** Christopher Fuchs (USA) *QBist Descending a Staircase, No. 2*
11:30—12:20		**Roundtable Discussion:** *Is 'Quantum Agent' Real? Subjectivity, Information, and Decision in Physics vs. Life Sciences* **Moderator: Christopher Fuchs**
12:20—12:30	**Event Photo**	All participants
12:30—14:00	**Lunch Break**	
SESSION VI		**Chair**: E. Pothos
14:00—14:50		**Invited Talk:** Felix Benninger (IL) From Quantum Foundations to Clinical EEG: Rethinking the quest for Objective biomarkers
14:50—15:10		**Contributed Talk:** Oded Shor (IL) *From Questions to Reality: Emergent Subjectivity-Driven Dynamics of Relational Information*
15:10—16:30	**Coffee Break**	
SESSION VII		**Chair:** M. Planat
16:30—17:20		**Contributed Talk:** Nataša Ž.Mišić (RS) *The emergence of complex biological organization at the interface of quantum and gravity*
17:20—17:40		**Contributed Talk:** Branko Dragovich (RS) *Photons and Biophotons*
		Closing remarks

INVITED TALKS

Igor Jex, Czech Technical University, CZ

Title: Quantum Buridan's Ass

joint work with G. Chadzitaskos, J. Novotný, S. M. Barnett, T. Kiss

Abstract:

The interplay between symmetry and dynamics is central to physics, as well as to other branches of science. An interesting situation arises in decision making when you are offered several equally viable solutions and you are forced to select one. The ensuing delay is generally known as the Buridan's paradox. We investigate a sketch of this situation in the context of optical multiports and comment on the role of symmetry and how physics deals with the dilemma of many options.

It is noteworthy that in its simplest form the evolution away from its initial state is speeded up by quantum interference. However, more fully connected networks can display the frustration familiar from the classical paradox. The role of symmetry breaking is analyzed for several cases and implications for the paradox discussed. Our results have implications for quantum communications networks and other distributed quantum systems.

Emmanuel Pothos, City University of London, UK

Title: The Quantum Sequential Sampler

Abstract:

Paradoxical findings in decision making have been a driving force in the development of quantum cognitive models since the inception of such models. However, some of these paradoxical findings were first discovered several decades ago. Current quantum models and corresponding Bayesian models are generally considered to offer a good explanation for many of decision findings, from the research tradition of especially Kahneman, Tversky, and their colleagues. Therefore, there is a question of how to advance decision empirical research, in a way to discover new, exciting findings and challenge existing probability models. I will present a large empirical investigation in decision making related to the US Presidential elections (for Biden vs Trump). Amongst other interesting findings, these results revealed systematic violations of binary complementarity, which could not be accounted for either by the original quantum model or the Bayesian ones. I then discuss an extension to the original quantum model, involving sequential sampling mechanisms, whose effect is to introduce a particular kind of noise into predictions. This model, the Quantum Sequential Sampler, performs very well and allows several new insights into the underlying cognitive principles.

Christopher Fuchs, University of Massachusetts Boston, USA
Title: QBist Descending a Staircase, No. 2

Abstract:
QBism (pronounced cubism) is a foundational program for quantum mechanics premised on the idea that quantum probabilities should be understood as personalist Bayesian probabilities—that is, quantified degrees of belief or gambling attitudes for specific agents and not objective properties of nature. Philosophers hate the idea. "Wah, wah, wah, your quantum states aren't real; they have to be real because *my philosophy* says so!" What the philosophers have never appreciated (or perhaps cared about) is that this turn in thinking has motivated a significant number of theorems in quantum information science that might not have been discovered otherwise. In this talk, I will sketch QBism's most ambitious project yet—rewriting the quantum formalism so that it wears its Bayesian character on its sleeve. One of our key moves will be to replace the notion of Hilbert space with the notion of a reference measurement. But which reference measurement is the most revealing of quantum theory's essence? In trying to answer this question, we will see that it leads to a deep mathematical question related to Hilbert's (still unsolved) 12th problem and suggests a novel measurement with a growing number of applications in quantum information science, including generating states of maximal "magic" for Clifford-gate quantum computation.

Felix Benninger, Tel Aviv University, Israel
Title: From Quantum Foundations to Clinical EEG: Rethinking the quest for Objective biomarkers
joint work with Oded Shor, Andrei Khrennikov

Abstract:
The history of quantum theory foundations can be seen as a long-standing tension between objectivity and subjectivity. Objective interpretations have sought to resolve Niels Bohr's assertion: the outcomes of measurements are not objective properties of systems, but rather describe the interrelation between a system (S) and an observer (O). However, despite attempts to recover an objective reality—through Many-Worlds Interpretation (MWI), Bohmian Mechanics, or others—probability remains central to all these interpretations, and so does the role of subjective knowledge.

- In MWI, one must interpret probability as uncertainty about which branch one finds oneself in.
- In Bohmian Mechanics, predictions still rely on the agent's knowledge of hidden variables.
- Even in Relational Quantum Mechanics (RQM), system properties only exist relative to other systems, making the observer's perspective indispensable.

Thus, subjectivity is never truly eliminated; in fact, it may be fundamental. From this angle, quantum mechanics becomes a personalized decision-making guide (as in Qbism), helping agents structure beliefs and make consistent choices based on how the world responds to their actions.

This agent-centered view has striking parallels in clinical medicine, especially in diagnosis and treatment. A medical doctor begins forming beliefs from the first day of training—first through textbooks and lectures, later through practical experience with real patients. Over time, their

subjective beliefs evolve, shaped by each new encounter. Clinical actions—whether diagnostic tests or treatments—are guided by these beliefs, constantly updated in light of outcomes.

Medical tests (like EEG, imaging, blood work) are often treated as additive sources of "objective" data. But in practice, each test is more like a projective lens through which the hidden clinical state is refracted—analogous to RQM's postulate that new information can always be obtained from a system, updating our subjective beliefs. However, since we lack the full reverse function to map these projections back to the underlying "objective" state, the pursuit of a perfectly objective biomarker is likely a mirage. What we can achieve, instead, are "good enough," coherent, subjective-choice-making biomarkers.

In this talk, we present a relational information framework for extracting such "informational physical analogs" biomarkers from EEG signals. Each EEG-derived relational information "physical" feature is viewed as a projection of the underlying clinical state. We demonstrate how this approach supports diagnosis of neuropsychiatric conditions and shows promising potential for guiding personalized treatment decisions. This perspective honors the complexity of clinical reasoning, embracing subjectivity not as a flaw, but as a principled foundation which emerges by the combined dynamic of subjective and hidden objective information which enables rational action.

David Rios Insua, ICMAT-CSIC, Spain

Title: Explorations in dynamic artificial life: Decision making in social emotional robots

Abstract:

Social emotional robots are designed to interact with groups of persons in pursue of certain objectives in which affective elements are crucial, including accompanying old persons, supporting children with autism or providing educational services. The talk will describe key decision-making strategies when designing social emotional robots covering elements from multi objective decision making under risk, adversarial risk analysis, the evolution from cooperation to competition (and vice versa), the role and impact of affective elements, reinforcement learning and a management by exception principle. It will also describe how are we implementing them within the EMOROBCARE project.

LIST OF POSTER PRESENTATIONS AND ABSTRACTS

The posters will be on boards from 15:30 till 18:00, Monday.
Presenting authors are requested to be ready to present their posters during the poster spotlights session (15:30-15:50) and the poster session (15:50-18:00) on Monday.

Poster spotlights are meant to be strictly brief (3 minutes) presentations of posters.

No.	Authors	Title
P-01	Iana Bashmakova, Emmanuel Pothos, Liane Gabora	Is Creativity Truly Quantum?
P-02	Jakub Tesař, Michael Drašar, Gor Vartazaryan	Understanding Question Order, Disjunction, and Conjunction Effects in Political Surveys: Insights from Quantum Models of Cognition and Decision-Making
P-03	N. Resul Tanyildizi, Fatih Ozkaynak	Limitations of True Randomness in Quantum Integrable Systems: A Theoretical Investigation for Cryptographic Applications
P-04	Vesselin Baev, Mariyana Gozmanova, Galina Yahubyan	NGS Strategies and Decision Making in Bacterial Genomics and Metagenomics.
P-05	Tomáš Procházka	Efficient Algorithm for Structure Estimation in Linear Regression
P-06	Adam Jedlička	Fault Detection Using Reinforcement Learning
P-07	Jurij Ružejnikov, Tatiana Valentine Guy	MDP-Based Analysis of Agent Interactions: From Collaborative to Adversarial Dynamics
P-08	Aleksej Gaj, Miroslav Kárný	Quantum model of a rat in the maze
P-09	Vlastimil Hudeček, Aurél Gábris	Identifying topological properties of quantum walks using quantum classification algorithms
P-10	Siavash Fakhimi Derakhshan	Leveraging Quantum Logic for Data-Driven Decision-Making in Imitation Learning for Intelligent Agents

Room Temperature Multi-particle Entanglement in Ferrofluids

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Submitted to: 2025 DYNALIFE Conference on Quantum Information and Decision Making in Life Sciences

Abstract. Magnetic fluids, commonly called *ferrofluids*, have been employed in several important research fields, including computation, energy harvesting, biomedicine, soft robotics, and exploration. Our study presents the discovery of significant phase correlations between two physically isolated volumes of ferrofluid. We have developed a theoretical model to explain this phenomenon in terms of entanglement among the nano-scale components of the fluid. When a pre-conditioned fluid is divided into two separate containers and an electrical stimulus is applied to one of them, we observe a remarkable signature in the impedance fluctuations of the other vial, demonstrating a neat correlation between the two separate reservoirs. The electromagnetic field influence is excluded by adopting a total shielded environment. Key to this phase correlation is a "twinning" pre-conditioning, where the fluid sample is sealed in a container and subjected to hysteresis cycles. Then, half of the volume is extracted and sealed in a second shielded container for the correlation measures. The novelty of the experimental observation of the phase correlation between macroscopic quantum systems is thus resting on the coherent state property of the quantum condensate. The collective multi-particle effect is independent of electromagnetic fields and holds in the temperature range 10–50°C adopted in the experiments. It was verified in both water-based and hydrocarbon-based ferrofluids.

Keywords: Ferrofluid, Multi-particle entanglement, Microwave impedance spectroscopy, Learning

Topological quantum computing: from baryonic matter to the building blocks of life

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Key words: topological quantum computing, representation theory, molecular biology

Topological quantum computing (TQC), originally conceived in the context of inert matter, may also offer insights into the organization of living systems. TQC is a-fault tolerant model of quantum computation that has two prevailing paradigms (a) the **non-Abelian anyon approach** and (b) the **algebraic-geometric approach**, rooted in SL(2,**C**) character varieties and the low dimensional manifolds.

Ordinary baryonic matter (OBM) is organized in triplets of quarks -up (u), down (d) or strange (s)- as seen in the proton (uud) and the neutron (udd). In parallel, the genetic code is built on **codon triplets** composed of nucleotide bases A, T/U ,G and C. The mass multiplets of OBM are traditionally described by SU(3) representations (Standard model) but they can also be captured via the **irreducible characters of the discrete group** GL(2,3) [1] just as the degeneracies of essential amino acids [2]. This suggests that **both inert and living matter share a common core of discrete symmetries.**

Furthermore, the full spectrum of baryons, involving u, d, s, c and b quarks can be modelled within TQC of type (a), specifically using $SU(2)_2$ **Ising anyons** whose braiding statistics are governed by a finite group of order 192 [1].

On the biological side, the **multiplets of proteinogenic amino acids** correspond to the symmetry group $Z_5 \rtimes$ GL(2,3) [2]. In living systems, TQC of type (b) becomes relevant not for the genetic code itself, but for the **topological and dynamical pattern**s underlying gene expression, such as those found in **transcription factors and microRNAs** [3].

In conclusion, matter in the universe may have followed **two distinct topological routes**: one governing the structure of baryonic particles via anyonic braiding, and another shaping the molecular mechanisms of life through algebraic and geometric symmetries. These two paths are explored in detail in our paper.

[1] Baryonic matter, Ising anyons and strong quantum gravity.
Int. J. Topol. **2025**, *2*(2), 4; https://doi.org/10.3390/ijt2020004

[2] Complete quantum information in the DNA genetic code.
Symmetry **2020**, *12*(12), 1993; https://doi.org/10.3390/sym12121993

[3] Topology and dynamics of transcriptome (dys)regulation.
Int. J. Mol. Sci. **2024**, *25*(9), 4971; https://doi.org/10.3390/ijms25094971

The emergence of complex biological organization at the interface of quantum and gravity

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Key words: quantum biology, gravity, microtubules, genetic code, decoherence, scale-free dynamics, information processing

The existence of living organisms in the mesoscopic realm may be quite nontrivial and actually may emerge from the interplay between quantum mechanics and gravity. On one side, quantum biology investigates how quantum mechanical phenomena, such as superposition, entanglement, and tunnelling, contribute to biological processes. These quantum effects, once thought to be irrelevant in the "warm, wet, and noisy" environment of living organisms due to decoherence, have been found to play significant roles in various biological systems, from photosynthesis to enzyme catalysis. On the other side, gravitational forces have been implicated in the organization of microtubules, which are essential for maintaining cellular structure and function. Recent studies have demonstrated that gravitational forces can induce three-dimensional chromosomal conformational changes, which are associated with rapid transcriptional responses in human T cells. Some theories propose that gravity might play a role in decoherence, such as in the Penrose-Hameroff model, which proposes that quantum coherence in microtubules could be the basis for conscious awareness and quantum computing-like information processing, with gravity playing a role in the collapse of the quantum wave function. The model predictions that microtubules can support long-range coherent phenomena have been confirmed by experimental observations of superradiance from mega-networks of tryptophan UV-excited transition dipoles, particularly in microtubule architectures. Another experimental research highlights that microtubule network exhibits a hierarchy of three-fold resonant frequency patterns across biological scales – from tubulin proteins to microtubules and neurons. This suggests a quantum-to-classical transition governed by scale-free dynamics, potentially underlying information processing in the brain. A very intriguing fact is that at the most fundamental level of the origin of life, the standard genetic code, we can observe the scale-free computing that arises from arithmetic regularities of the nucleon numbers related to the code's numerous symmetries. Given that some of these symmetries probably originate from different evolutionary epochs, such scale-free computing may be a latent background mechanism of the organization of the genetic code and therefore relevant to natural computing.

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Identifying topological properties of quantum walks using quantum classification algorithms

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Key words: Discrete-time quantum walks, Topological properties of quantum walks, Quantum computing, Quantum machine learning, Quantum neural networks,

Discrete-time quantum walks have emerged as a powerful tool quantum computing. It has been recognized that DTQWs can exhibit a plethora of topological phases, which may be exploited in designing applications that are particularly robust against various types of noise and disorder. The ability to determine the topological phase in which the DTQW is in, is one of the essential tasks for any application. The presented project focuses on exploring the possibility of using quantum classification methods to determine the topological phases of DTQWs. The presented materials will cover the development of a method that uses quantum computer implementations for the training. The emphasis of the talk will be on the techniques used in the programming of quantum algorithms in latest Qiskit SDK, their execution of IBM QPUs and hardware aware optimization.

Quantum model of a rat in the maze

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Key words: quantum mechanics, quantum model, expressing non-physical properties via quantum model, models of living matter

Quantum mechanics (QM) provides a formal framework for modelling uncertainty and dynamic evolution in physical systems. While its mathematical structure is well established, its application beyond microscopic phenomena remains an area of active discussion. This work attempts to illustrate the axioms of QM in an intuitive and accessible way on a textbook example. The example is constructed to make an easy parallel with decision-making tasks.

The model considers a rat moving in a finite number of rooms within a box, where some rooms are directly connected, while others are not. The rat's state is represented as a vector in a finite-dimensional Hilbert space, evolving unitarily over time. Measurement corresponds to observing the rat's presence in a given room, collapsing the state with a probability dictated by the Born rule. Additionally, the rat's preferences influence the system's dynamics, introducing a simple analogy to decoherence or external perturbations.

Such seemingly trivial example opens a variety of questions concerning interpretation of the whole task and understanding the model behind. This model does not offer new contributions to QM theory but serves as a conceptual bridge, demonstrating its fundamental principles in a setting that includes a living organism. The approach may be useful in educational contexts or as a stepping stone for exploring quantum-inspired models in decision-making and behaviour modelling of living matter. A Jupyter notebook implementation accompanies the theoretical formulation, providing an interactive tool for visualization and exploration.
The work also discusses links to contemporary interpretations of QM.

The authors would like to acknowledge the contribution of the COST Action CA21169, supported by COST (European Cooperation in Science and Technology).

MDP-Based Analysis of Agent Interactions: From Collaborative to Adversarial Dynamics

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Abstract

In multiagent systems (MAS), agents often share policy information to influence one another's decisions. Agent interactions can be categorized as either adversarial or cooperative, and these behaviors can be intentional or unintentional. In the intentional case, agents may share misleading policies to either hinder or support other agents' decision-making, whereas in the unintentional case, the interaction is merely incidental. From a single-agent perspective, the agent must be able to adapt to various interaction types. This work models MAS using the Multiagent Markov Decision Process (MMDP) and introduces a necessary condition for both intentional cooperative and adversarial interactions. We classify possible policy communications by their truthfulness and intent, and we lay the groundwork for a dynamic, trust-based framework that allows an agent to evaluate and incorporate shared policy information. The proposed approach enables robust and adaptive behaviour in both cooperative and adversarial environments.

Keywords

Markov decision process (MDP), multiagent systems, trust modelling, policy inference, agent interaction dynamics, information fusion

1 Introduction

Multiagent systems (MAS) consist of multiple autonomous entities, known as agents, that interact within a shared environment. Each agent follows a policy that determines its behaviour in the environment. These policies can be communicated to other agents to influence their decision-making process. Agents operating in a shared environment are able to interact in various ways, as seen in many real-world scenarios (examples are provided in Section 2.1). Such interactions can be categorised as cooperative, where agents work together towards common goals, or adversarial, where agents have conflicting objectives. Furthermore, interactions can be intentional or non-intentional. In the case of intentional interactions, agents may share a policy different from the one they actually follow in order to influence the behaviour of others. From the perspective of a single agent, the ability to distinguish and model these interaction dynamics is crucial for designing effective decision-making strategies in MAS applications, such as robotics [1], economics [2], or distributed computing [3]. In this work, we adopt the Multiagent Markov Decision Process (MMDP) within a setting where agents exchange policy information. We present a necessary condition for intentional interaction types and lay the groundwork for how a single agent can dynamically integrate the shared policy with its own estimate of another agent's policy, while accounting for the possibility that the shared policy may be misleading.

2 Main contribution

Popular approach to modelling decision-making in MAS is the Multiagent Markov Decision Process (MMDP). An MMDP provides a mathematical framework for modelling decision-making in situations where outcomes are partly random and partly under the control of the decision-makers. In this work, we formally define the MMDP as a discrete-time stochastic process represented by the following sequence:

$$(\mathcal{S}, \mathcal{A}, \mathcal{T}, \{\mathcal{R}_i\}_{i=1}^{n}, \{\pi_{i,t}\}_{i=1}^{n})_{t=0}^{\infty}, \tag{1}$$

where:

- $\mathcal{S}$ is a discrete set of states s, representing all possible configurations of the environment, shared by all of the agents;
- $\mathcal{A}$ is the discrete set of actions a available to all agents;
- $\mathcal{T} : \mathcal{S} \times \prod_{i=1}^{n} \mathcal{A}_i \to \mathcal{P}(\mathcal{S})$ is the system transition model defining the probability distribution over next states s' given the current state s and the joint actions of all agents $\mathbf{a} = \{a_1, a_2, \ldots a_n\}$.
- $r_i : \mathcal{S} \times \mathcal{A} \times \mathcal{S} \to \mathbb{R}$ is the reward function of agent i, which remains unchanged over time, and represents the reward that the decision maker receives in given state s when action a is implemented and the environment transitions to state s';
- $\pi_{i,t} : \mathcal{S} \to \mathcal{A}_i$ is the policy of agent i at time step t, mapping each state $s \in \mathcal{S}$ to an action $a_i \in \mathcal{A}_i$. The policy $\pi_{i,t}$ defines the agent's behaviour in the environment, determining the action to be taken in each state and may change over time.

For simplicity let us consider a two agent setup, the following diagram illustrates the interaction between agents and the environment at time step t.

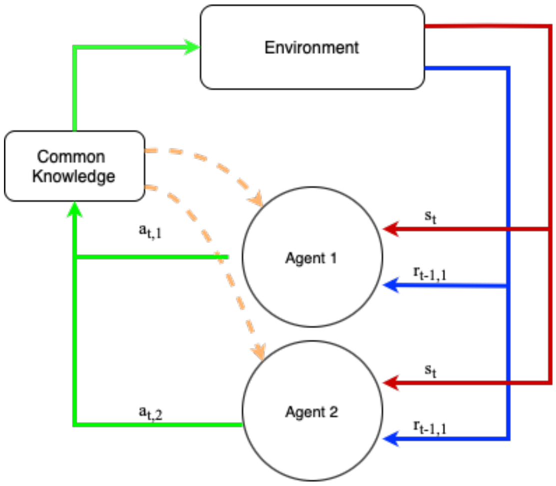

Figure 1: Diagram illustrating the interaction dynamics in a two-agent MMDP.

Additionally, no agent has knowledge of the other's reward function, nor can it observe the rewards received by other agents. Agents are only aware of the current state of the environment and can observe other agents' actions only after they have been executed.

2.1 Agent interaction categorisation

We distinguish all possible combinations of policy communication between agents based on the truthfulness of the communicated policy and its actual intent.

- **Intentional**
  - **Cooperative**
    - *Truthful communication of a cooperative policy (cooperative intent).*
      Example: Two autonomous vehicles approach an intersection. One truthfully communicates its intention to yield, allowing the other to proceed safely.
    - *Deceptive communication of a cooperative policy (adversarial intent).*
      Example: In a multi-robot exploration task, Robot A falsely claims it will cover a high-value region of the environment. Robot B, trusting this information, reallocates its path to a lower-value region to avoid redundancy. As a result, the high-value region remains unexplored, reducing Robot B's ability to maximise its reward.
  - **Adversarial**
    - *Truthful communication of an adversarial policy (adversarial intent).*
      Example: In a competitive trading scenario, a bot announces its intention to undercut prices, which it then follows through on to reduce competitors' profits.

* *Deceptive communication of an adversarial policy (cooperative intent).*
  Example: In a multi-faction strategy game, Agent A publicly declares an aggressive policy toward Faction B, prompting B to reinforce its defenses. However, A is secretly collaborating with B to mislead a third faction, C, into believing that A and B are at odds. By diverting C's attention and resources away from a real threat, this deception ultimately supports A and B's shared objective of undermining C, illustrating a fundamentally cooperative (though deceptive) intent.

- **Non-intentional**: Agents' actions may result in non-intentional cooperative or adversarial interactions. In such cases, no deliberate misdirection occurs.
  Example: Two warehouse robots independently optimise for efficiency and unintentionally block each other's paths, causing delays. The resulting conflict is not deliberate.

2.2 Necessary condition for intentional interaction

We define a *goal-based state space* $\mathcal{S}_g \subset \mathcal{S}$ as the subset of states in which the reward function $r(s, a, s')$ is non-constant with respect to its arguments. Formally, for some state $s \in \mathcal{S}_g$, there exists at least one combination $(a, s', b, x') \in \mathcal{A} \times \mathcal{S} \times \mathcal{A} \times \mathcal{S}$ such that $r(s, a, s') \neq r(s, b, x')$. A necessary condition for intentional cooperative or adversarial interaction is that the goal-based state spaces of the agents must overlap. If these sets are disjoint, i.e., $S_{g,1} \cap S_{g,2} = \emptyset$, then no intentional cooperative or adversarial interaction can occur. In plain terms, if two agents have completely separate goals, neither has an incentive to cooperate nor to sabotage the other. Consequently, if the goal-based state spaces are disjoint, any information about an agent's policy $\pi_{i,t}$ cannot improve the other agent's decision-making task. This condition is useful for detecting situations when no adversarial or cooperation interaction occurs, particularly if and agent is equipped with reward structure estimation such as inverse reinforcement learning [4, 5].

2.3 Dynamic Trust-Based Policy Incorporation

In practical settings, agents may switch from non-intentional to intentional interaction (and vice versa), and thus must adapt to changing interaction types. From a single-agent perspective in described MMDP setting, the agent (for purposes of this section referred to as *the supported agent*) observes other agents actions after execution. Consequently, the supported agent can dynamically model the other agent's policy as the sequential decision-making process unfolds, enabling adaptive responses to changing interaction types. In this setting, agents also share their policies $\pi_{i,t}$. Incorporating a received policy into the supported agent's own decision-making can enhance its ability to achieve its goals. However, as noted, the other agent may share a policy different from the one it actually implements. To address this, we propose that the supported agent merge its internally estimated model of the other agent's policy with the communicated policy using dynamic probability-fusion methods [6, 7]. Moreover, to assess the truthfulness of the shared policy, we propose extending these fusion methods to include a similarity–dissimilarity measure, comparing the supported agent's estimate of the other agent's policy with the policy that is actually provided. A solution for dynamic merging probabilities while accounting for the changing reliability of the information source can be found in [8].

3 Conclusions

In this work, we categorized agent interactions in dynamic multiagent systems (MAS) using the MMDP framework, examining their truthfulness and intent. We then derived a necessary condition for intentional adversarial or cooperative interaction. Next, we proposed a method for incorporating shared policy information into the supported agent's estimate of another agent's policy, along with a trust-based extension that enables the supported agent to adapt to different interaction types. In the future, we plan to formalize these concepts in a unified framework and extend our approach to partially observable settings.

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Fault Detection Using Reinforcement Learning

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Keywords: Reinforcement Learning, Fault Detection, Markov Decision Processes

A wide variety of tasks including modeling biological problems can be modeled by Markov Decision Process (MDP). Reinforcement learning (RL) is an approach to solving MDP. In RL the agent learns to make the optimal actions by using feedback (reinforcement) signal. Due to its ability to handle dynamic environments with high uncertainty, RL has been successfully applied to various biological problems: generating novel molecular structures in drug discovery [1], predicting protein folding [2], etc.

A very basic application of MDP terms in the example of the task of discovering new drugs mentioned earlier is as follows. A generative model (agent) learns a series of actions to create new molecules (states) for maximizing a score given by a predefined score function. RL is applied similarly in an example of genome assembly and other tasks in biology.

Apart from these tasks, RL can also be used for so-called fault detection. Fault detection (FD) refers to a problem, where there are two or more processes that follow a different mathematical model (for example change of parameter) and the task is to determine which process is followed at the given time (which process generated the data).

An example of the utility of FD in biology is highlighted in [3], where a fault is monitored in the "Cad System in E-coli" (CSEC) model. CSEC models localization and dynamics of the pH sensor and transcriptional regulator CadC in cells. Another example is mentioned in [4], where a water treatment process is monitored for faults in order to ensure its stability.

It is important to mention, that neither of the above-mentioned articles relating to the usage of FD in biology does not use RL to find faults as it is not a widely used approach. However, while not widely used, it might perform better in certain cases with large datasets.

The proposed poster will i) introduce some basic FD methods ii) briefly introduce mechanisms of RL and outline its use for CSEC model [5].

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[2] John Jumper et al. Highly accurate protein structure prediction with AlphaFold" John Jumper et al. "Highly accurate protein structure prediction with AlphaFold

[3] Majdi Mansouri et al. Fault Detection of Biological Phenomena Modeled by S-systems

[4] Meng Zhou et al. Fault Detection of Wastewater Treatment Plants Based on an Improved Kernel Extreme Learning Machine Method

[5] Radhia Fezai et. Al. Fault diagnosis of biological systems using improved machine learning technique

NGS Strategies and Decision Making in Bacterial Genomics and Metagenomics.

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Key words: NGS, bacterial genomics, Illumina, ONT, metagenomics

Bioinformatics plays an important part in bacterial genomics and metagenomics research, which helps exploring the microbial communities and their functions. The rapid achievements of DNA-seq methods have resulted in an explosion of genomic data, needing a sophisticated computational tool for analysis. Furthermore, computational tools enable the efficient processing and interpretation of these large-scale genomic datasets, improving identification of gene functions, metabolic pathways, and regulatory networks in bacteria.

In the field of next-generation-sequencing (NGS), the Nanopore ONT technology have created a revolution in bacterial genomics by providing whole genome assemblies through its capability of long-reads and resolving complex structural elements. Nanopore sequencing is characterized by very long reads that can sequence across repetitive regions, circumventing the short-read limitations of sequencing platforms such as Illumina. Further refinements in ONT chemistry, for instance, the more recent R10.4.1 flow cells, have contributed to a read accuracy and long-read assemblies are now feasible enough to displace hybrid approaches. Moreover, the portable nature of ONT sequencing technology allows for extremely time-effective bacterial identification in clinical scenarios or in the field environments.

In metagenomics, bioinformatics tools are essential for annotating sequence data from complex microbial communities. Whether using traditional 16S rRNA amplicon sequencing or shotgun sequencing approaches, these tools allow researchers to explore microbial diversity and investigate microbe-environment interactions. And each method has their advantages and limitations.

Ultimately, decision-making in NGS methods and bioinformatics is critical for bacterial genomics and metagenomics. Choosing the right sequencing technologies—such as Illumina for high accuracy or Nanopore for long reads—and employing tailored bioinformatics pipelines ensures efficient data analysis.

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Limitations of True Randomness in Quantum Integrable Systems: A Theoretical Investigation for Cryptographic Applications

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Key words: Quantum integrability, cryptographic randomness, quantum random number generators, conserved quantities, quantum chaos, deterministic predictability.

This study examines the fundamental limitations in true random number generation capabilities of quantum integrable systems. Despite quantum mechanics being generally considered a perfect source of randomness, we demonstrate how the deterministic solvability of integrable systems restricts the generation of random numbers used in cryptographic applications. Our work mathematically characterizes observable patterns and correlations in number sequences generated from these systems by analyzing a range of commonly used quantum integrable models. In particular, we show how the presence of conserved quantities in exactly solvable systems such as the XXZ Heisenberg spin chain and the Lieb-Liniger model constrains random number generation. Our findings suggest that quantum chaotic systems should be preferred over integrable systems when designing quantum random number generators for high-security cryptographic applications. This study emphasizes the importance of the concept of integrability in the field of quantum cryptography and random number generation, aiming to contribute to the development of more secure post-quantum cryptographic protocols.

Photons and Biophotons

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Key words: biophotons, biological information, quantum information

According to modern physics, all matter is composed of elementary particles governed by four fundamental interactions (strong, weak, electromagnetic and gravitational). From a simplified point of view, a living organism is a special dynamic state of a set of atoms and molecules connected by electromagnetic interaction.

The description of electromagnetic phenomena at the deepest level is done within the framework of the formalism of quantum electrodynamics (QED). In fact, QED describes the interaction between Dirac field quanta (electrons and positrons) and electromagnetic field quanta (photons). These quanta can be virtual and real (free). Virtual photons are carriers of electromagnetic interaction. Electrons and positrons can emit and absorb virtual photons according to quantum uncertainty relations. In the case of scattering of two electrons, the interaction is realized in such a way that virtual photons emitted by one electron are absorbed by the other.

Free photons are emitted, propagated and absorbed as electromagnetic field quanta with the usual expressions for momentum p and energy E. The source of photons in living organisms can be atoms and molecules in cells or some other organic structures. A discrete spectrum of radiation is especially important. Having specific energy, i.e. frequency, such photons are suitable transmitters of information about the state of the emitter.

Photons in the ultraviolet and some visible range of light, which are low intensity and have origin in a biological system, are usually called biophotons. Biophotons were predicted by the Russian and Soviet scientist Alexander Gurvich (1874-1954) and discovered in 1923. Biophotons have not yet been sufficiently investigated experimentally and described theoretically. In a broader sense, biophotons should mean all photons that are emitted, absorbed or scattered by living organisms.

In this talk, we will mainly consider the possibility in which biophotons are transmitters of a special quantum biological information.

Understanding Question Order, Disjunction, and Conjunction Effects in Political Surveys: Insights from Quantum Models of Cognition and Decision-Making

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Key words: question order effect, disjunction effect, conjunction effect, quantum model, QQ-equality, public opinion

Question order, disjunction, and conjunction effects are among the most studied phenomena of social sciences, providing strong support for quantum models of cognition and decision-making. Quantum modeling literature convincingly shows that while the classical (commutative) probability theory cannot easily account for those effects, they are a natural fit for the (non-commutative) algebra of vector spaces over complex numbers. While the quantum cognition literature is vast in modeling those survey effects, it lacks two crucial aspects. First, the three effects are rarely discussed together, limiting the insights they provide to practitioners of public opinion research. Second, the literature vastly relies on a limited number of empirical studies to lean support for quantum modeling. In this paper, we address both of these gaps. First, we extend the canonical Moore's typology of question order effects to encompass all theoretically possible combinations of effects between two questions. Second, we reinterpret disjunction and conjunction effects as specific cases of question order effects, thereby integrating them into an established framework. Third, we consider the key prediction of the quantum models, the QQ-equality, to see what constraints it imposes on any of the effects. Finally, we explore the relevance of our typology using new survey data on domestic and international political attitudes in Czechia. This approach enriches our theoretical understanding of named effects and demonstrates practical applications for survey design and analysis.

Is Creativity Truly Quantum?

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Key words: creativity, order effect, metaphor, quantum cognition

Creative cognition relies heavily on uncertainty, ambiguity, and contextuality (Estes & Ward 2002). Theoretical models propose a quantum basis for creativity (Gabora, 2017, 2023; Gabora & Carbert, 2015), and empirical findings suggest quantum effects in humor (Gabora & Kitto, 2017), which is a type of creativity. If creativity is indeed quantum-like, individuals exhibiting stronger quantum order effects (QOE) should perform better in creative tasks. We tested this hypothesis in two experimental studies. In Study 1, we examined whether unfamiliar information would elicit stronger QOE, which would, in turn, enhance creativity in a metaphor production task (based on: Silvia & Beaty, 2012; Silvia & Benedek, 2023). Participants ($N = 111$, $M_{age} = 20.71 \pm 5.7$), all English speakers, were randomly assigned to four groups: groups 1 and 3 were presented a relatively familiar English word, while groups 2 and 4 – an unfamiliar word in Russian (both defined). Groups 1 and 2 then answered 6 dichotomous questions about the word, while groups 3 and 4 were presented the same questions in reverse to assess QOE. Contrary to expectations, QOE was stronger in the familiar condition (BF = 17.2), and ordinal logistic regression showed no significant relationship between creativity and QOE ($b = –0.15$, $p = .67$). We note that the higher OE group (familiar) was coded 1, thus there is a negative trend in the creativity-QOE relationship. Study 2 ($N = 55$, $M_{age} = 22.69 \pm 7.05$) employed within-subject design with only the familiar condition that produced high QOE in Study 1. To avoid recency effects, we used distractor tasks. Again, creativity and QOE were not significantly correlated (Spearman's $r = –.21$, $p = .12$), replicating the negative trend. These findings challenge the assumption that quantum-like thought benefits creativity. Instead, they suggest that creativity may not rely on QOE, or that current experimental approaches fail to capture this relationship effectively. Future research should explore alternative methods to quantify both creativity and quantum-like cognition.

On the role of prescriptive decision-making theory in natural sciences

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Key words: decision making, knowledge acquisition, modelling tools

Decision making (DM) is the choice of an action applied to a world part in order to reach some aim. The prescriptive theory recommends the optimal way how to do it. The natural sciences aim to acquire knowledge about the natural world: they describe the world. Seemingly, the prescriptive DM offers nothing to them. This contribution challenges this widely adopted opinion. The corner stones of this challenge are:

- the knowledge acquisition is the DM action that has no direct influence on the world but affects those who acquire it (briefly agents), who aim to model the world in the best way;
- prescriptive DM theories models the agent-world pair as a closed loop [1,2] affected by both and develops tools for tuning the closed loop optimally: its outcome include, for instance,
  - tools explaining outcomes of dynamic interactions in closed loops [3]: such loops are present everywhere, and it is desirable to predict their damped, stationary or explosive behaviors,
  - learning techniques complementing missing parts of the used models [4], and also exploration strategies, which include sequential stopping rules guiding experimentation with the world,
  - analysis of acting in hostile environments [5],
  - the choice of appropriate mathematical tools for describing uncertainty of any origin in knowledge-acquiring loop: the quantum modelling of macro-world [6,7] addressed at this conference is a hot and fruitful example of contemporary research in this respect.

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A Fundamental Duality: From Logic to Biology

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There is a basic duality that runs throughout the mathematical and natural sciences, from logic to biology. [1] Mathematically, it is the reverse-the-arrows duality of category theory that runs throughout mathematics. [2] That category-theoretic duality gives the duality between subsets and partitions (or equivalence relations or quotient sets) which gives the dual logics of the Boolean logic of subsets and the logic of partitions. [3] At the most basic level, it is the duality between elements or "Its" of subset and distinctions or "Dits" of a partition (pairs of elements in different blocks or equivalence classes). The quantitative versions of that duality give the duality between probability theory (logical probability = normalized number of Its in a subset) and logical information theory (logical entropy = normalized number of Dits in a partition). [4] The Its side of the duality applies to the classical physical notion of reality as being definite "all the way down" as expressed in Leibniz's Principle of Identity of Indistinguishables. Partitions or equivalence relations are the natural math to express indefiniteness (e.g., elements in an equivalence class) which in physics is the objective indefiniteness of superposition states in quantum mechanics. [5] In the life sciences, the Its side of the duality is associated with the selectionist mechanism fundamental to biology. The partition/equivalence-relation or Dits side of the duality is associated with the notion of a generative mechanism, essentially a mechanism that moves from indefiniteness (e.g., stem cells) to definiteness by implementing a code, e.g., to break symmetries. [6] Examples of generative mechanisms include Chomsky's Principles & Parameters version of a generative grammar, the RNA/DNA mechanism to produce proteins, and embryonic stem cell development.

Fundamental Duality	Its side	Dits side
Math: Category Theory	Subobjects, Limits	Quotient objects, Colimits
Logic	Boolean logic of subsets	Logic of partitions
Quantitative logic	Logical probability	Logical entropy
Physics view of reality	Classical full definite	Quantum obj. indefiniteness
Biological mechanisms	Selectionist mechanism	Generative mechanisms

The point is to fit all these aspects of the mathematical and natural sciences into one mathematically defined framework of duality.

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Quantum or quantum-like scattering of waves in cognitive parameter space

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Abstract

It is possible to construe conscious mental states analogously to the way a physical particle is imagined in quantum mechanics. Based on this analogy, some phenomena related to the occurrence of wave-like patterns in data from cognitive psychology experiments are interpreted as evidence for the quantum nature of consciousness. More specifically, the wave-like patterns arise in perceptual parameter space when measures of performance, such as the standard deviations of the response times, are sampled at multiple data points of the parameter. The properties of those patterns seem to be influenced by properties of the cognitive state. Increased effort and attention, indicating higher "energy" of the mental state, seem to be associated with higher frequency of the waves, and logical opposites, such as "higher" and "lower," seem to be associated with waves with opposite phases (mirror images of each other). Together, those two phenomena are analogous to the conceptual picture of the interaction of the wavefunction with a potential barrier, which is labeled as "scattering" in quantum mechanics.

Keywords

quantum consciousness, quantum cognition, response times

1 Introduction

Nearly 100 years ago, in 1929, Niels Bohr noted that "...the apparent contrast between the continuous onward flow of associative thinking and the preservation of the unity of the personality exhibits a suggestive analogy with the relation between the wave description of the motions of material particles, governed by the superposition principle, and their indestructible individuality." [1] (originally published in German in 1929, first publication in English in 1934)

The suggested analogy is between how a quantum physicist imagines the behavior of a particle and how a psychologist or a philosopher imagines the workings of the mind. Thus, it is an analogy between the phenomenology of matter and mind in more general terms, implying that they are, in fact, the same kind of substance. Therefore, the structure and the dynamics of the "mental state" should have some similarities with the analogous properties of the "quantum state" of a particle. Broadly speaking, the "train of thought," which represents the successive instantiations of concepts in one's mind, is analogous to the picture of unitary evolution of the quantum state punctuated by collapses due to acts of measurement/observation of the state. Although there are alternative interpretations of quantum mechanics that do not involve a collapse of the wavefunction, they still posit a choice of one alternative out of many, which is analogous to the act of shifting attention to a specific concept out of many.

In terms of the structure of the state, some of the most basic properties of the quantum state of a particle are its position and energy/momentum. According to the analogy, the mental state would have a position in "mental space," which would be the abstract state space of the instantiations of all possible concepts, and an "energy," which would indicate how much it affects other mental states. The "mental space" needs to be high-dimensional, since most of the concepts are different from each other, meaning that they cannot be ordered naturally in a sequence to form a dimension. There are some exceptions to this postulate, e.g., the numbers, especially in the range from one to twelve, where they have individual labels in the English language. Other examples are perceptual properties that form a continuous spectrum, such as loudness, pitch, orientation in space, length, weight, color, etc. When sampling from the physical parameters producing the corresponding perceptual mental states, one can determine from which location in the spectrum they come from, resulting in a one-dimensional "mental space" with some extension that the mental state can occupy. In contrast, there is no natural ordering of the different concepts belonging to categories like "furniture" or "countries," and they need to be imagined as high-dimensional subspaces without much extension in each dimension (only the unit length). This is, indeed, how they are modeled within the framework of quantum cognition (see [2] for an example).

The "mental energy" parameter is more difficult to define, since it is not clear how to determine the impact of one mental state on another. However, it is possible to compare different instantiations of the same mental state in different contexts, analogously to measuring the energy of the same type of quantum system prepared in different ways. It would be natural to assume that, for example, a mental state instantiated with a higher degree of "cognitive effort" ([3]) would be analogous to a quantum system in an excited state with higher energy. The same applies to a mental state instantiated in the context of "increased attention" ([4]), which may or may not be voluntarily instantiated. Finally, greater "clarity of perception" would also indicate higher "mental energy," since it would allow the state to affect other states to a greater degree.

Thus, according to the analogy, when probing a property, like "mental energy," for multiple values within a range of a perceptual parameter, like the numerosity of scattered dots on the screen, one should expect to obtain a wave pattern, rather than a random one or a regular monotonically increasing or decreasing one. This has been demonstrated in [5], where multiple experimental results are reported from various numerosity estimation tasks, all resulting in a seemingly regular wave-like pattern, which is symmetric across the midpoint separating the negative and the positive arms of the plot. This finding can be explained by positing a mechanism converting oscillations in neural activity unfolding in time to oscillations in the space of cognitive parameters with extended range, such as numerosity (or orientation, size, pitch, etc.), however, the question why such mechanism exists would still remain. A more parsimonious, and natural, from that point of view, explanation can be provided under the assumption of a quantum nature of consciousness. From this perspective, the conscious mental state is physically realized in the brain by quantum entangled ensembles of particles, somewhat like those performing the computations in a quantum computer. In that case, oscillations would occur both in time and in parameter space, such as the position and momentum representations of the quantum state of the ensemble. In addition, the energy of the system will be related to the frequency of the oscillations – higher "energy" will be associated with higher frequency of the waves. In cases where the "mental energy" of two cognitive states is comparable, the wave patterns would be expected to have the same frequency, but may differ in phase. The hypothesized frequency and phase modulation effects together are analogous to transmission and reflection in models of interaction of the wavefunction with a step potential, respectively, where the wavefunction either changes its frequency or (possibly) its phase..

2 Method

The "mental energy" parameter is defined in terms of cognitive effort, focused attention or clarity of perception, which are more familiar cognitive constructs. For the case of different "mental energies", an opportunistic sample of seven freely available datasets from cognitive psychology experiments is presented, that employs a paradigm containing a parameter representing magnitude, and where the dataset can be split in two equal halves that differ only in the "mental energy " parameter. The two halves are processed in the same way, and the resulting patterns are plotted along the magnitude parameter. In addition, the power spectral density of the two wave-like patterns is calculated using Welch's method, which is more robust towards noise. For the case of same "mental energies", an opportunistic sample of four freely available datasets is presented, where the dataset is split in two halves within a condition with the same "mental energy". For example, this could be the two choices in a two-alternative forced choice (2AFC) experimental paradigm, such as choosing left versus right, or higher versus lower. The two halves are again processed in the same way and the standard deviations of the response times are plotted along the cognitive parameter representing magnitude.

3 Results

In the different "mental energies" case, the two resulting wave-like patterns in the standard deviations of the response times plotted along the "magnitude" dimension differ in the frequency of the waves, according to the mean wavelength (computed as the mean peak-to-peak distance) and the power spectral density analysis, where higher power is observed for the high "mental energy" condition at higher frequencies, and at lower frequencies for the low "mental energy" condition. In all seven cases, the higher "mental energy" condition, in terms of higher cognitive effort, more focused attention or more clarity of perception, is associated with the wave pattern with higher frequency (see Figure 1 below). In addition, the mean response time is slightly (but statistically significantly) shorter in the higher "mental energy" condition, which is in line with the analogy with quantum physics, where

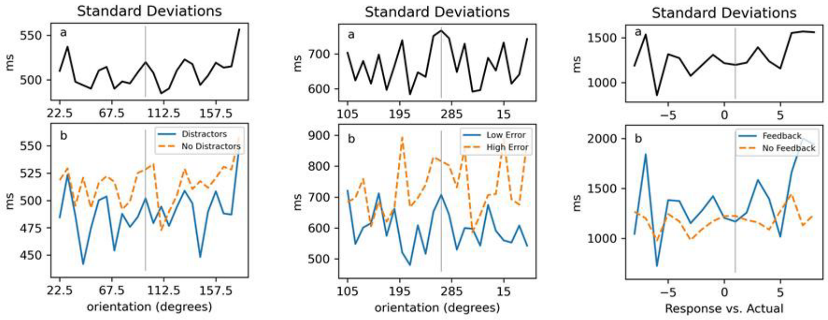

Figure 1: Three examples of wavelength/frequency modulation in the standard deviations of the response times (y axes) when plotted for multiple values of a perceptual parameter (x axes). Panels "a" show the plot from the whole dataset (after removing outliers), and panels "b" show two separate plots after dividing the dataset into two roughly equal halves based on an indicator of effort or attention (i.e., "mental energy") present in the individual trials. The dashed yellow line indicates the plot from trials with lower "mental energy," while the solid blue line indicates higher "mental energy." The number of peaks, and therefore the frequency of the wave pattern, is higher for the higher "mental energy" plot. The vertical gray line indicates an arbitrarily chosen axis of symmetry of the wave pattern, which is typically near the natural middle of the range of values for the x axis.

higher energy would be associated with faster transition from one state to another (in this analogy from the perceptual state to the decision state). In the equal "mental energies" case, the two wave-like patterns are with opposite phases when the responses are subsequently rated with high confidence as being correct (see Figure 2 below), and with the same phases when the responses are rated with low confidence.

4 Discussion

The observed effects have an explanation both within the traditional classical physics and neural oscillations framework and within the suggested analogy with quantum physics. Other research has found that the periodicity of attention is modulated by the difficulty of the task, with faster oscillation in time when the task demands higher attentional effort [6]. Thus, if there is a neural mechanism for converting oscillations in time to oscillations in cognitive parameter space, that mechanism would be expected to produce also the frequency and phase effects presented here. However, as stated in [5],

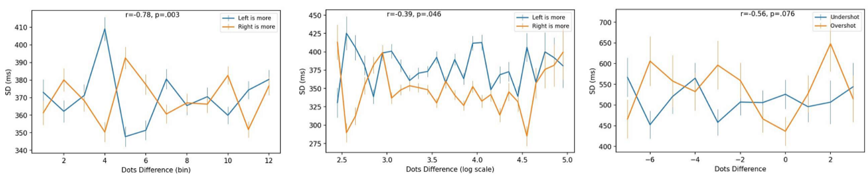

Figure 2: Three examples of inversion of the wave pattern in the standard deviations of the response times (y axes) when plotted for multiple values of a perceptual parameter formed by the difference between the actual number of dots on the screen and the provided estimate (x axes). The two lines in the plot (blue and yellow) indicate two opposite choices (Left vs. Right, or Undershot vs. Overshot the target). The data has been cleaned from outliers and the linear trends have been subtracted from each line individually in order to calculate correlations between the two lines in an unbiased way. The Pearson's r values for the correlations are shown near the top, together with the significance p-values. The vertical lines at the data points indicate the standard error of the standard deviation (which depends only on N).

the quantum analogy seems to be a more parsimonious (conceptually simpler) explanation, and in addition, the two alternative explanations are not mutually exclusive – they refer to phenomena at different spatial scales (macroscopic and microscopic), and may well be coexistent in the brain. The finding that opposite concepts, such as left and right, or higher and lower, are associated with wave patterns with opposite phases offers some insight into how conscious mental states are physically realized in the brain and may inform the implementation of artificial intelligence systems based on quantum computing.

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