Towards Brain-like Information Processing based on Quantum Cognitive Computing

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Abstract

As the next stage of Artificial Intelligence, Brain-like Intelligent Computing will play a fundamental role in the forthcoming China Brain Project. Researchers have attempted to leverage the brain' s framework structure and functions to develop a new generation of information theory and computational methods (such as new-generation artificial intelligence systems). Unlike traditional information processing based on classical physics and logic, the human brain should rely on deeper-level physics (such as quantum mechanics) to process information and generate consciousness and awareness. The project will seek to exploit quantum information theory in models of information interaction and processing related to human cognition. The overall research goal is: in typical information interaction scenarios (such as exploratory information access and natural language understanding), to model non-classical (quantum or quantum-like) experimental phenomena, develop quantum models of cognitive behavior, and establish a new framework for brain-like information interaction models, with applications to typical tasks in information interaction scenarios.

Full Text

Preamble

Towards Brain-like Information Processing based on Quantum Cognitive Computing

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Abstract

As the next stage of Artificial Intelligence, Brain-like Intelligent Computing will play a fundamental role in the forthcoming China Brain Project. Researchers have attempted to leverage the brain' s structural framework and functional mechanisms to develop a new generation of information theory and computational methods (such as next-generation artificial intelligence systems). Unlike traditional information processing based on classical physics and logic, the human brain likely relies on deeper-level physics (such as quantum mechanics) to process information and generate awareness and consciousness. This project seeks to exploit quantum information theory in modeling human cognition-related information interaction and processing. The overall research goal is to model non-classical (quantum or quantum-like) experimental phenomena in typical information interaction scenarios (such as exploratory information access and natural language understanding), develop quantum models of cognitive behavior, and establish a new framework for brain-like information interaction models, with applications to typical tasks in information interaction scenarios.

Keywords: information interaction; natural language understanding; quantum cognition; brain-like intelligence; deep learning

1. Research Trends

Currently, artificial intelligence, machine learning, and other intelligent information processing technologies have brought tremendous changes to economy and society. However, the significant gap between machine intelligence and brain intelligence is increasingly becoming a bottleneck for the development of intelligent information processing technology. Physicist Pan points out that there exists a close correlation between quantum entanglement, quantum superposition, and the mechanisms of mind. In quantum mechanics, the uncertainty principle implies that everyone is immeasurable, and this "uncertainty" supports the essential difference between humans and robots. Today, using quantum information theory to model the brain has opened the field of quantum-like artificial intelligence, in which machine learning can operate based on quantum algorithms. NASA and Google have announced the initiation of a quantum artificial intelligence lab, an event that may demonstrate that quantum-like artificial intelligence has strong prospects and positive practical significance. Our project plans to further develop quantum cognition, investigating the feasibility of applying quantum cognition to information interaction and neural networks. By combining experimental investigation with quantum logic and quantum information processing, we can develop quantum cognition computing and advance research in brain-like information processing.

2. The Main Objectives of This Project

1. To judge and identify non-classical user cognition phenomena in information interaction scenarios (e.g., exploratory information access and natural language understanding) based on the core concepts of quantum interference and quantum entanglement in quantum theory.
2. To design experimental paradigms for phenomena such as quantum interference and quantum entanglement in the process of information access

and interaction, abiding by the criteria of cognitive science research, and to explore the cognitive processing mechanisms and brain functional networks underlying specific quantum cognition phenomena.

3. To model quantum entanglements among concepts in natural language using deep neural networks, leading to a natural language understanding model under the quantum cognition framework.
4. To replace the conventional IAR paradigm with a geometry of IAR. As this geometry will be based on the quantum mechanical framework, probability, quantum logic, and vector space can be combined into one unified formalism.
5. To model quantum contextuality, order effects, quantum interference, and quantum entanglement in user interaction behaviors for exploratory information access tasks using the information geometry paradigm.

3. Background, Merits and Importance

Quantum cognition refers to the application of quantum theory to model cognitive phenomena. Cognition encompasses the brain' s information processing, memory, human judgment, decision-making, and even intuition and other logical processes. The brain can be viewed as a computer, whether classical or quantum. Brain cognition and decision-making behavior exhibit a quantum nature, meaning that a complex brain system can generally be described by quantum information theory and probability. We hope that quantum theory can supersede classical probability theory to further explain these quantum cognition phenomena. Current research includes quantum cognitive brain information processing, decision-making behavior, concept representation and reasoning, human memory and perception, information retrieval, etc. Although quantum theories of cognition have made great progress, they have not fundamentally solved the important problem of cognitive brain function: researchers have not uncovered specific cognitive mechanisms, and much work merely explains some quantum phenomena while ignoring the nature behind these phenomena. This project will focus primarily on natural language understanding and exploratory information access tasks, conducting user cognitive behavioral studies of non-classical phenomena to explain the brain' s cognitive processing modes and mechanisms underlying these phenomena, and developing natural language understanding and information interaction models based on the quantum cognition system.

4. Scientific Issues Targeted

1. How to judge and identify non-classical cognition phenomena (quantum or quantum-like) in user information interaction scenarios (e.g., natural language understanding and exploratory information access tasks).
2. How to analyze non-classical cognition phenomena from the perspective of brain cognition? We will design event-related experimental paradigms and utilize brain imaging techniques to research phenomena such as quantum interference and quantum entanglement in information access and interac-

tion scenarios, explain the mechanisms of brain cognition, and construct the brain functional network underlying non-classical phenomena.

3. How to integrate quantum cognitive phenomena of information interaction into natural language understanding models? The project will use deep neural network models to integrate quantum entanglement among concepts, leading to a quantum recognition-based natural language understanding system.
4. How to integrate the quantum/quantum-like phenomena of brain cognition and decision-making into exploratory information access models? In this proposal, we will investigate the process of brain cognition and decision-making in exploratory information access tasks from three viewpoints: quantum contextuality, quantum interference effects, and quantum entanglement phenomena.

5. Proposed Methodologies

Our proposed methodology is divided into six work packages (WP), detailed below.

WP1: Judging and Modeling the Quantum Interference of User Relevance Judgment in Exploratory Information Access Tasks

In the exploratory information access process, users need to continuously interact with information systems and other users to gradually satisfy their information needs and search tasks. An important behavior in this decision process is conducting relevance judgments for candidate information objects (e.g., webpages, images, videos, and merchandise) with respect to users' information needs. Users' interaction behaviors influence their relevance judgments in certain ways that cannot be explained by classical theory. For example, the total probability equation is violated in some relevance judgment scenarios when judging the relevance of an information object after viewing an interfering information object prior to the judgment. This phenomenon exhibits the property of quantum interference. In this project, we will propose experimental paradigms to judge and identify quantum interference phenomena in relevance judgment during exploratory information access.

To study quantum interference in relevance judgment for exploratory information access, we present the following hypotheses: (i) Quantum interference between users will influence users' relevance judgment, analogous to the double-slit interference experiment. In this analogy, information objects are analogous to photons from a light source, the current user and other users are analogous to the double slits, and relevance judgment is analogous to the collapse of photons on the screen. Double-slit interference changes the distribution of photons on the screen; similarly, users' relevance judgments for information objects will change after quantum interference between users. (ii) Quantum interference between information objects will influence users' relevance judgment according to the quantum order effect. A user' s relevance judgment for one information object is considered a quantum measurement. The relevance judgment for one object when a user measures it directly differs from the relevance judgment when the user measures it after observing some other related information objects. The total probability equation is violated in these experiments, demonstrating that quantum interference phenomena exist between information objects. (iii) Quantum interference between different modalities (e.g., text, image, video, voice) or dimensions (e.g., topicality, novelty, understandability, scope, and reliability) of the same information object can influence relevance judgment in different ways. One is like the double-slit interference experiment: two information modalities (dimensions) can simultaneously influence users' relevance judgment like the double-slit experiment and can also sequentially influence relevance judgment according to the quantum order effect.

In this project, we will design experiments from different angles to verify these hypotheses. For example: (i) We will ask users to conduct two rounds of relevance judgment experiments to judge the relevance degree for a series of information objects (e.g., documents, images, videos, and voices) with respect to a given information need in two different experimental settings. The first round requires users to judge information objects directly. The second round requires users to judge information objects after reading/observing some other related information objects or discussing the same topics with other users. We will analyze the experimental results using different statistical methods to verify if quantum interference effects exist among users. (ii) We will ask two groups of users to judge the same information objects. One group judges the relevance of information objects directly, while the other group judges the relevance of each information object after reading/viewing/observing another related information object. We will analyze the final relevance judgment results to determine if they violate the total probability equation. If the total probability equation is violated, the results show that quantum interference exists between information objects according to the order effect. (iii) We will design experiments similar to (i) and (ii) to investigate whether quantum interference exists between different information modalities and information dimensions for the same information object.

The experimental results will motivate the design of future exploratory information access models, enabling the capture of users' dynamic and complex information needs through modeling different types of quantum interferences.

WP2: Exploration of Quantum Entanglement in Semantic Concept Space of User' s Natural Language Understanding Scenarios

To establish feasible algorithms for discovering quantum entanglement in semantic concept space, it is essential to distinguish classical modeling from quantum cognition modeling. In quantum cognition, each concept can be represented by a superposed state, which is fundamentally different from a classical state. After a user understands the meaning of a word or text, the state collapses into a concrete state. Therefore, semantic concepts can be represented by quantum superposition states. In natural language understanding scenarios, the user' s cognitive state of a word' s sense can be superposed, and this superposed state becomes concrete in a specific context.

Semantic concepts can also be represented by quantum composite systems. In a system where quantum entanglement exists, the system cannot be factorized into several subsystems using the tensor product. In natural language understanding, the concept of a semantic component model can be expressed not only as a compositional model but also as a non-compositional model. In natural language, a concept is the basic unit of human understanding, but different concepts have different combinations of properties. For some concepts, word frequency distributions indicate that the concept may not be factorizable into a number of distributions, and these concepts can be used to model non-component models.

This project will study the concept of non-component models in depth via quantum entanglement. The main idea is as follows: First, we plan to design experiments to determine whether quantum entanglement exists by establishing Bell' s inequality and subsequent inequalities [such as CHSH inequality]. Second, for any text fragments in the post-measurement setup, we can determine the existence of entangled states by testing whether the probability distribution cannot be factorized unconditionally. If so, it corresponds to an entangled state before measurement. Third, for user dialogue or real-time query expansion, we will try to determine whether nonlocal action at a distance occurs between the association process words. In addition, considering that the system will evolve over time and show dynamic properties, we can investigate the quantum Zeno effect and Temporal Bell Inequality to study the dynamic cognitive state in user interaction scenarios.

WP3: Paradigm Design for Quantum Cognition Phenomena Abiding by the Criteria of Brain Cognition Research

Taking the electroencephalograph (EEG) based approach as an example, current brain electrical data acquisition equipment with ultrahigh temporal resolution can noninvasively collect EEG data from the scalp that meets scientific analysis precision requirements. Event-related potentials (ERPs), which are processed EEG products, are related to mental activities and can reflect potential variations in different brain regions during information and cognition processing when information stimuli are received through various perceptual systems. ERP-based research typically conducts analysis through four aspects: latency period, electric polarity, wave amplitude, and distribution topology. Various ERP components related to cognitive resource allocation have been widely adopted as study objects in cognition processing research, such as N280/Lexical Processing Negativity (LPN), N400, N170, P600, P300, Early Left Anterior Negativity (ELAN), Mismatch Negativity (MMN), etc. The practicability and feasibility of source analysis using EEG has been elucidated by Gevins (1995).

Generally speaking, experimental paradigm design should consider critical aspects including the choice of stimulus material, selection of subjects, and form of stimuli. Next, we will illustrate our ideas for ERP-based experimental paradigm design for two specific cases of quantum cognition phenomena.

The first is quantum interference phenomenon-oriented experimental paradigm design. We select the order effect influencing text relevance judgment as the case study. In the order effect phenomenon, a user' s relevance judgment of a specific document may change after checking a prior document, representing interference between documents. The case paradigm we design for the order effect is briefly illustrated as follows: In each trial, the system selects one term T from many elaborately selected terms, each of which correlates with two short interference texts A and B. For example, the term T "North Korea' s nuclear test"correlates with short text A "The missile defense system may be deployed in South Korea after the North Korea' s nuclear test" and B "South Korea reaches an agreement with U.S. on the deployment of Thad missile defense system," where the relevance judgment for B may be influenced by reading A in advance. Two groups of subjects are required to conduct T→A→B and T→B "read and judge" sequences respectively; in each trial, the subject must judge and report the relevance of B to T. In the data analysis period, we will try to identify differences in brain activities between the two groups of subjects who have different relevance judgments for B, and explain the interference phenomenon from a neurocognitive science perspective.

The second is quantum entanglement phenomenon-oriented experimental paradigm design. Here we take Concept Combination as an example to illustrate our paradigm design ideas. Concept Combination is a phenomenon in natural language where a new combined concept is constructed by combining two or more concepts, and the meaning of the combined concept cannot be expressed by either isolated concept alone. For example, the combination "pet human" is related to "slave" —a case of emergent association—and the combination "mountain story" is a case of abduction, which can be understood as "a story happened in a mountain" or "a story about a mountain." These combined concepts can be seen as entangled quantum particles. In Mednick' s "theory of associative creativity," it is a form of creativity to associate and reconstruct different things, concepts, and elements that are far apart. In the semantic network of concepts, different concepts correlate with each other through semantic strength. As mentioned above, our paradigm design in this case focuses on investigating the brain' s cognitive processing during the association of concepts with different semantic distances. We select concepts with different semantic distances, such as "mountain-magazine," "Sun Wukong-monkey," etc. In each trial, the system begins by showing the first isolated concept, followed by the second one. After the presentation is complete, subjects must report whether they have successfully associated these two isolated concepts to construct a new one. In the data analysis period, we will group subjects according to success or failure of the association process, compare the two groups, and explain the neurocognitive process during the Concept Combination period.

WP4: A Natural Language Understanding Model Based on Quantum Cognition

In information interaction, the fundamental task of a natural language understanding model is to obtain text representation in semantic space. Based on WP1, the human brain exhibits complex quantum or quantum-like phenomena such as concept composition, semantic abstraction, and word association during natural language understanding. Given the success of deep learning in modeling natural language, we will combine the study of quantum cognitive phenomena with existing deep neural network models and propose a novel quantum cognition-based natural language understanding model to reveal quantum properties among concepts in natural language.

To achieve this goal, we must first investigate existing neural network models for natural language understanding. Overall, for natural language understanding tasks, traditional machine learning methods rely on manually designed input features and obtain optimal prediction results by adjusting model parameters. However, manual feature design is often time-consuming, and the features are usually incomplete or task-dependent. Deep learning methods integrate feature learning and prediction models, which can automatically learn features from original text to obtain abstracted semantic representations and use these new representations in various tasks (such as text classification, grammatical structure analysis, sentiment analysis, etc.).

Quantum cognitive phenomena in natural language understanding mainly involve entangled states between concepts—that is, semantic units that cannot be decomposed into independent sub-components. Meanwhile, entanglement between concepts (concept combination) can serve as abstract concepts in combination with other concepts, leading to higher levels of concept abstraction. From this viewpoint, we will utilize recursive neural networks to learn the hierarchical structure of entanglement between concepts. First, based on preliminary studies by the applicant teams, we can quickly identify the presence of quantum entanglement (equivalent to pure unconditional dependency) of concepts with various orders in post-measurement setup (where order refers to the number of concepts included in the entanglement). Second, in recursive neural networks, the concept is represented as a semantic vector, and entanglement can be defined as the tensor operator among concept vectors. Finally, we will train the network using large-scale data to optimize predictions of the concept entanglement structure.

The obtained concept vectors can be further used to model the word association process. With a set of historical words, we can use neural networks to obtain hierarchies of concepts with various levels of abstraction. We can then extract the words that best match the historical concept from a set of candidate words and recommend that word to represent what the brain associates after seeing the historical words. The semantic vector representation of concepts can also be applied to various information interaction tasks. This project will focus on its application in exploratory information access.

WP5: Subspace Representation and Query Logic in Information Interaction

To model contextual features, information needs, and logic, we aim to replace the conventional IAR paradigm with a geometry of IAR based on the quantum mechanical framework. This project will focus on three aspects: (a) defining abstract vector subspaces to build contextual features; (b) defining a query logic theory based on subspace representation; and (c) defining a ranking function based on subspace representation and query logic.

First, defining abstract vector spaces to build multimodal complex features. Consider the feature spaces defined by WP2. From this representation, complex features will be defined within abstract vector spaces and represented by multi-dimensional subspaces spanned by one or more complex feature vectors; complex features can be planes when defined by two vectors, cubes when defined by three vectors, and in general they are hyperplanes. For example, a word in natural language is an example of a textual feature, the gray level of a pixel or a codeword of an image is another example, and chroma-based descriptors for content-based music representation are yet another example. A finite vector space contains k distinct features, which is also the dimensionality of the vector space. Given k real coefficients a , i = 1,···,k and the k feature vectors w , i=1, ···,k, a complex feature vector is defined as t=a w + • • • +a w for a . Given m complex feature vectors t , . . . , t , m k, an even more complex feature is represented by the subspace of all vectors expressed as b t + • • • + b t ; for example, a complex feature can be represented by a plane in 2-dimensional space as {b t +b t }.

Second, defining logic in abstract vector spaces. A general subspace-based query language will be defined. It may be utilized by the end user and will also formalize how the document collection will be searched. Specifically, two basic operators "meet" and "join" will be defined to combine subspaces that represent "themes" and information needs expressed in multimodal ways. The meet is the smallest subspace containing both subspaces. For example, the meet of two one-dimensional themes = t and = t can be defined by = and can be represented by the subspace of vectors = b + b . The join is the largest subspace contained by both subspaces. For example, the join of two bi-dimensional themes and can be defined by = and can be represented by the subspace of vectors in the intersection between the subspace spanned by the basis of and the subspace spanned by the basis of . Note that for meet and join, the traditional distributive law is violated. If an expression like (A B) (A C) would be equivalent to A (B C) using traditional Boolean logic, an expression like ( ) ( ) is not equivalent to ( ) using our subspace-based logic. There is evidence that human cognition and decision-making exhibit non-classical and quantum-like nature; our subspace-based query language provides new opportunities for a user interacting with a retrieval system to experiment with many more non-classical expressions of their information need. In addition to meet and join, more operators will be investigated, such as entailment, orthogonality, and other relatedness between subspaces.

Lastly, defining a ranking function in abstract vector space. The ranking rule utilized to measure the degree to which a document is about an information need (as a complex feature subspace determined by the user-formulated query and current retrieval context) relies on the theory of abstract vector spaces. To measure this degree, a representation of a document in a vector space and a representation of a complex feature in the same space are necessary. A document is represented by a vector = (c ,···,c)' such that c is the measure of the degree to which the document represented by the vector is about complex feature i. Let {v ,···,v } be an orthogonal basis representing complex features. The measure of the degree to which a document is about a complex feature represented by the subspace spanned by this basis is the size of the projection of the document vector onto the complex feature subspace, that is tr[(v v * + ··· v v *)] where tr is the trace operator according to the mathematical theory of quantum mechanics.

WP6: Novel Exploratory Information Access Models Inspired by Quantum Cognition

In the process of exploratory information access, users interact with information through a series of interaction behaviors (e.g., query requests, browsing webpages, clicking and reading). Each interaction behavior involves brain cognition and decision-making processes. For example, users tend to change queries to represent dynamic information needs, decide which webpages to click and read, and decide whether to continue information interaction behaviors. In this project, we will develop novel exploratory information access models based on previous research results. Specifically, we will propose novel exploratory access modes and methods inspired by quantum interference phenomena and quantum entanglement phenomena in brain cognition revealed in WP1, WP2, and WP3. Moreover, we will implement effective exploratory information access models using the natural language understanding and subspace logic techniques proposed in WP4 and WP5. We introduce the quantum cognition-inspired exploratory information access models as follows:

First, novel exploratory information access models based on quantum interference. We have investigated three types of quantum interference in users' relevance judgment during exploratory information access: between-users quantum interference, between-information-objects quantum interference, and between-modalities/dimensions quantum interference. We will model these three quantum interferences in exploratory information access scenarios such as personalized web search, session search, dynamic search, and dialogue systems. We will model between-users quantum interference in personalized web search, where the representation of information need changes under the influence of other users' information interactions. In session search, previously observed documents will influence the representation of information need for the current query. In dynamic search, we will use quantum probabilistic automata to model user cognition state transition after quantum interference.

Second, novel exploratory information access models based on quantum entanglement. We have developed effective natural language understanding methods using quantum entanglement. In this project, we will use these natural language understanding methods to understand users' dynamic information needs represented in natural language, such as spoken text, dialogue text, and query language.

Third, novel exploratory information access models based on quantum contextuality. In this work package, we will use quantum contextuality to model users' information needs and use subspace logics to develop novel exploratory information access models. A subspace is composed of a series of basis vectors, where each basis vector can represent one contextual dimension (e.g., topicality, novelty, readability, reliability, information scope, interest, and habit) of information need. One important difficulty is how to capture the dynamics of users' brain cognition during exploratory information access tasks, since the brain cognition state is uncertain. The uncertainty principle in quantum mechanics is similar to brain cognition. In this project, we will borrow the strong representational capability of quantum theory to represent users' dynamic information. Furthermore, we have formalized unified subspace logics and operators. In exploratory information access tasks, we will use subspace logics to compute the relevance between dynamic information needs and information objects represented by subspaces, inspired by quantum contextuality.

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Note: Figure translations are in progress. See original paper for figures.