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Information processing by networks of quantum decision makers

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HIGHLIGHTS

- A new model is advanced for a society of agents interacting by exchanging information.
- Decisions are made by agents taking into account utility and attractiveness of prospects.
- The dual nature of information processing is described by means of quantum rules.
- The model is a quantum intelligence network that can be used for creating artificial intelligence.
- Dynamic disjunction effect is treated demonstrating very good agreement with empirical data.

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ABSTRACT

We suggest a model of a multi-agent society of decision makers taking decisions being based on two criteria, one is the utility of the prospects and the other is the attractiveness of the considered prospects. The model is the generalization of quantum decision theory, developed earlier for single decision makers realizing one-step decisions, in two principal aspects. First, several decision makers are considered simultaneously, who interact with each other through information exchange. Second, a multistep procedure is treated, when the agents exchange information many times. Several decision makers exchanging information and forming their judgment, using quantum rules, form a kind of a quantum information network, where collective decisions develop in time as a result of information exchange. In addition to characterizing collective decisions that arise in human societies, such networks can describe dynamical processes occurring in artificial quantum intelligence composed of several parts or in a cluster of quantum computers. The practical usage of the theory is illustrated on the dynamic disjunction effect for which three quantitative predictions are made: (i) the probabilistic behavior of decision makers at the initial stage of the process is described; (ii) the decrease of the difference between the initial prospect probabilities and the related utility factors is proved; (iii) the existence of a common consensus after multiple exchange of information is predicted. The predicted numerical values are in very good agreement with empirical data.

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1. Introduction and related literature

Modeling the behavior of multi-agent social systems and social networks has recently attracted a substantial amount of activities of researchers, as can be inferred from the review articles [1–3] and numerous original papers, of which we can cite just a few recent [4–8]. High interest to such a modeling is due to two reasons. First, being able of describing the behavior of societies is of great importance by itself. Second, modeling the collective interactions of autonomous multientity systems has already been widely envisioned to be a powerful paradigm for multi-agent computing.

Nowadays, there exists an extensive literature on decision making in multi-agent systems, which can be categorized into three main directions: (i) Studies of how the agents, inhabiting a shared environment, can decide their actions through mutual negotiations. There can be two types of agents, cooperative and self-interested. Cooperative agents cooperate with each other to reach a common goal [9]. Self-interested agents try to maximize their own payoff without concern to the global good, choosing the best negotiation strategy for themselves [10,11]. (ii) Studies of how a network of agents with initially different opinions can reach a collective decision and take action in a distributed manner [12]. (iii) Studies of how the dependence among multi-agents can lead to emerging social structures, such as groups and agent clusters [13].

The main goal of a decision process in a multi-agent system is to find the optimal policy that maximizes expected utility or expected reward for either a single agent or for the society as a whole. Various models of multi-agent systems can be found in the books [14–19].

The maximization of expected utility, expected reward, or other functionals is based on the assumption that agents are perfectly rational and no restrictions on computational power and available resources are imposed. However, since Simon [20], it is well known that only *bounded rationality* can exist, so that any real decision maker, in addition to having limited computational power and finite time for deliberations, is subject to such behavioral effects as irrational emotions, subconscious feelings, and subjective biases [20–23].

The behavioral effects become especially important when decisions are made under uncertainty. There are two sides of uncertainty that can be caused either by objective lack of complete knowledge or by subjective preferences and biases. Even when the agents in the society are assumed to possess complete knowledge, they cannot become absolutely rational decision makers due to the inherent dual property of human behavior that combines conscious evaluation of utility with subconscious feelings and emotions [24].

Thus, real decision making is a complex procedure of dual nature, simultaneously integrating the rational, conscious, objective evaluation of utility with behavioral effects, such as irrational emotions, subconscious feelings, and subjective biases. This feature of realistic decision making can be called *rational–irrational duality*, or *conscious–subconscious duality*, or *objective–subjective duality*. Keeping in mind these points, we can call this feature the *behavioral duality of decision making.*

As a result of this behavioral duality, a correct description of decision making in a real multi-agent system has to deal with two sides — maximization of expected reward, and taking account of behavioral effects [25–27]. To take the latter into account, several modifications of utility theory have been suggested, such as prospect theory, weighted-utility theory, regret theory, optimism–pessimism theory, dual-utility theory, ordinal-independence theory, and quadratic-probability theory, whose description can be found in the review articles [28–31]. However, such so-called nonexpected utility models listed in reviews [29–31] have been refuted as being merely descriptive and having no predictive power [32–36]. A more detailed discussion can be found in Refs. [37–39].

As has been shown by Safra and Segal [34], none of non-expected utility theories can resolve all problems and paradoxes typical of decision making of humans. The best that could be achieved is a kind of fitting for interpreting just one or, in the best case, a few problems, while the other remained unexplained. In addition, spoiling the structure of expected utility theory results in the appearance of several complications and inconsistencies. As has been concluded in the detailed analysis of Al-Najjar and Weinstein [35,36], any variation of the classical expected utility theory “ends up creating more paradoxes and inconsistencies than it resolves”.

Stochastic decision theories are usually based on deterministic decision theories complemented by random variables with given distributions [40,41]. Therefore, such stochastic theories inherit the same problems as deterministic theories embedded into them. Moreover, stochastic theories are descriptive, containing fitting parameters that need to be defined from empirical data. In addition, different stochastic specifications of the same deterministic core theory may generate very different, and sometimes contradictory, conclusions [42].

One more difficulty in modeling decision making of real humans is that they often vary their decisions, under the same invariant expected utility, after information exchange between decision makers, as has been observed in many empirical studies [43–50]. This implies that agent interactions through information exchange can influence decision makers emotions, without touching their evaluation of utility.

In all previous works, behavioral effects, when being considered, have been treated as stationary. The principal difference of the present paper from all previous publications is that we develop a model that takes into account the dual nature of decision making, and allows for the description of dynamical behavioral effects caused by agent interactions through information exchange.

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