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博士論文の要旨

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論文題目　Self-organization of reference structure and its effect on decision accuracy
参照構造の自己組織化と意思決定の正確さ

It has been revealed by empirical and theoretical works that humans incorporate others' opinions (social information) when they make their decision in many circumstances. Such use of social information can yield an advantage of *collective intelligence*. For example, the majority-rule voting based on independent opinions for a binary choice can result in higher accuracy than when decided by a single individual or expert. However, it has also been shown that the correlation between opinions can undermine collective intelligence. In addition, sequential decision-making, in which each individual makes decision using earlier opinions by other individuals, is known to sometimes lead to situations in which most individuals fail to give correct answers (*incorrect information cascade*). These facts suggest that, although the use of social information would be advantageous to individuals' decision making, once some individuals start using it and their correlated opinions become a part of social information, social information could progressively lose its independency and quality so that no one eventually dares to use it. To my knowledge, the reference structure among people has been given artificially in most of existing experimental and theoretical works for collective intelligence and decision accuracy of humans. However, some studies showed that whom to follow in the reference structure affects the decision accuracy of individuals. Therefore I ask how the reference structure self-organizes, when each individual tries to use social information to secure the accuracy of his/her decision-making. I also evaluate the decision accuracy in the self-organized reference structure.

I try to answer these questions theoretically. To model the reference structure between individuals, I consider a directed network in which each node represents an individual and each directed link represents reference. Individuals are assumed to make a decision sequentially on a given problem with the majority-rule voting among its own and his or her neighbors' opinions. Since each agent makes decision with majority vote, his or her probability to find a correct answer by oneself, which I call his/her "ability", is different from his or her actual probability of finding a correct answer by referring to others, which I call "performance". I also assume that individuals vary in their ability. It should be natural to assume that each individual assesses the credibility of the referents and decides to either keep or stop following them accordingly. Thus, I assumed the rewiring rule as follows; each individual

monitors his or her neighbors' performance and breaks the link if the neighbor's performance becomes worse than a preset threshold. I therefore consider the mutually affecting changes of reference link structure and each agent's opinion accuracy. Through this interaction the network structure is self-organized. This idea is related to *adaptive network models*, in which feedback loops between node dynamics and network topology are considered. I conducted extensive computer simulations on this adaptive network model. I also developed an analytical theory to explain the results obtained in the simulations.

My analysis shows the following results. (A) The distribution of the number of followers in the self-organized network significantly differed from the initial Poisson distribution for the random network. In fact, the distribution of the number of followers in the self-organized network was close to exponential distribution. This suggested that there were a few nodes that had much larger number of followers than the mean. (B) The mean number of followers increased approximately exponentially, i.e., more than linearly, with agents' ability. Therefore small difference in ability can lead to large difference in the number of followers in the self-organized network. (C) The mean performance of an agent increased linearly with his/her own ability. I defined group performance as the proportion of agents who stated correct answers in the population. The mean performance of each agent and the mean group performance was the lowest when the agent made decisions independently of others, which is improved by collective intelligence when agents can refer to randomly assigned referents in the initial random network and further improved by adaptive rewiring in the self-organized network. The group performance temporally fluctuates by stochasticity in the self-organized network. The temporal standard deviation (SD) of group performance also increased in the same order as the mean group performance, i.e., the group performance temporally fluctuated more when the mean group performance became higher. (D) The threshold for rewiring affected the strength of heterogeneity in the number of followers in the self-organized network. When I set the threshold lower, the heterogeneity in the number of followers became larger. At the same time, the dependence of an agent's mean number of followers on his/her ability was more exaggerated, i.e., agents refer more to higher ability agents in the self-organized network. This leads to a higher mean performance of each agent compared with when the threshold was larger. However, the SD of the group performance, i.e., the fluctuation of the group performance, was also higher for a lower threshold.

To understand the source of centralization of reference links, I decomposed the causal relationship between mean number of followers of each agent and his/her ability into three components: the relationship between the ability and the mean performance, the relationship between the mean performance and the mean duration of keeping a follower, and the relationship between the mean duration of

keeping a follower and the mean number of followers. I explained analytically the simulation result of each relationship of these three, by using a theory of stochastic process and some approximation methods related to the network structure. Among these three relationships, only the relationship between the mean performance and the mean duration of keeping a follower is nonlinear and the other relationships are linear. Therefore, I conclude that the nonlinear dependence of the number of followers on agent's ability originates from the non-linear dependence of the mean duration of keeping a follower on the mean performance of that agent. This relationship between the mean performance and the mean duration corresponds to the performance-monitoring process assumed in my model.

To sum up, in the self-organized reference structure, I observed the strong centralization of reference in which the number of one's followers increases more than linearly with his/her ability. The mean performance of each agent was higher compared with a random network or the case of independent decision-making. However, the group performance fluctuated more in the self-organized network. There was a counter-intuitive relationship between the degree of generosity to referents in a society and the mean performance of the society. When I set the rewiring threshold lower (i.e. when individuals are more generous to their referents), individuals refer to higher ability agents in the self-organized reference structure than when I set it higher, leading to the higher mean performance of the society. To my knowledge, there is no study on the decision accuracy in groups showing such a counter-intuitive phenomenon. This result would be testable by empirical studies. In my study, I also found a trade-off between accuracy and stability in the self-organized network. The higher mean performance and more stability (suppression of fluctuation) of performance are incompatible. This trade-off was observed when I compare the performance in the case of independent decision, random references and the high-ability-agent-oriented self-organized networks. It was also observed when I compare the performance in a high-threshold case with that in a low-threshold one.

As future perspectives, I suggest that the following two points are important to be considered in the study of the self-organization of humans' reference structure. Firstly, it may be possible to consider the situation in which humans choose not only reference partners but also the extent to which they depend on social information. As I showed in my study, there is a trade-off between accuracy and stability. If individuals depend more on social information, they may be able to improve their performance on average, but they may be involved in information cascades more frequently. Secondly, it may also be possible to consider that humans conform to others not only to make their decision more accurately but also to correspond to others' expectation (*normative social influence*). Reflecting these features of humans' decision-making in the model of self-organization of

reference structure should lead to further understanding of humans' collective decision making and its accuracy.

（備考）

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博士論文審査結果

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Title
論文題目　Self-organization of reference structure and its effect on decision accuracy

出願者は、人が意思決定をする際の意見参照ネットワークの自己組織化のプロセスと、その結果生成される参照構造のもとでの集団の意思決定の正確さについて理論的な研究を行った。

出願者は、本博士論文の研究テーマの背景を以下のようにまとめている。人は意思決定をする際に、しばしば他者の意見（社会的情報）の影響を受けることが知られている。このような社会情報を利用することによって、意見を集約した人は、集合知(collective intelligence)の効果を享受することができる。例えば、参照先から収集した独立な意見の多数決によって意思決定を行えば、個人が自分だけで判断するよりも正確な意思決定が行える。しかし一方で、集められた個々の判断が相互参照の影響を受けて独立性が低い場合には、集合知の効果は大きく損ねられてしまう。さらに、多数の個体の間で、順に意思決定が行われる場合には、先行する個体の誤った判断が、後続の個体の判断に影響する誤情報カスケード (incorrect information cascade)がしばしば起こる。これらが示唆するのは、より正確な意思決定を行うために、個人が社会情報に依存するようになればなるほど、個々の情報の独立性が低下し、社会情報を利用するメリットが減少するというジレンマである。誤情報カスケードに関する過去の実験的および理論的な研究では、あらかじめデザインされて固定された参照ネットワークが用いられていたが、これでは上記のジレンマが如何に解消されるかという問いに答えることができない。

そこで、出願者は以下のような動的なネットワークモデルを構築し、その挙動を調べることで上記の問題に答えることを試みた。何度も異なる二択問題が与えられるような状況で、それぞれが意思決定を行う個体の集団を考え、個人を頂点で、各個人の参照相手を有向枝で表したネットワークで集団の状態を表現する。各個人が二択問題に対して単独で意志決定するとき正しい判断をする確率（能力）は一定の分布に従ってばらつくとする。各個人は意見を参照できる相手を一定数持つ。参照先は最初ランダムに与えられるが、それぞれの二択問題の正解が分かった後、各個体は参照先のその回を含む過去の判断の正確さの評価を行い、評価値がある閾値を下回れば、その参照リンクを解消し、新たな参照相手を集団からランダムに選ぶ。これを多数回繰り返すシミュレーションの結果生成される参照ネットワーク構造の特性と、意思決定の正確さの集団平均について解析した。また、定常状態のネットワーク特性に関する解析的な理論解析も行った。

出願者は、このモデルの網羅的なシミュレーションと理論解析により以下の結果を得た。（１）定常状態においてフォロワー（その個体を参照している個体）数の分布は、初期状態に見られる一山のポアソン分布から指数分布に近づく。これは、各個人がより正確な意思決定を求めて参照リンクを適応的につけ変えることにより、多数のフォロワーを得る少数の個体（オピニオンリーダー）が出現することを表す。（２）参照リンク解消の閾値が低いほど（参照相手の評価基準が緩い集団であるほど）、フォロワー数の定常分布の裾はより長く伸び、フォロワー数の不均一性が大きくなる。逆に参照相手を厳しく評価して参照リンクを頻繁に付け替える集団では、顕著なオピニオンリーダーは出現しにく

い。（３）単独で正しい判断のできる能力の高い個体がより多くのフォロワーを得る傾向があるが、能力の増加に対して平均フォロワー数は非線型的に急速に増加する。また、その加速度的増加の傾向は、リンク解消の閾値が低い集団ほど強い。（４）定常状態のネットワークにおいては、問題に対する集団の平均正答率が初期状態に比べ上昇する。しかし同時に平均正答率の時間変動の程度も大きくなる。これは、少数のオピニオンリーダーに参照先が集中するネットワークで、オピニオンリーダーの誤判断が集団の平均正答率を大きく下げる情報カスケードを引き起こしやすいことを意味する。また、出願者はシミュレーションだけではなく、個体が単独で正しく判断する能力と、その個体がフォロアーを維持する平均時間との関係、および、フォロワー維持の平均時間と平均フォロワー数との関係を解析的に導いており、それらの対応関係がシミュレーション結果をよく説明することを示した。

出願者のこれらの研究は、適応ネットワーク上の集合知の特性と情報カスケードとの関係を詳細に明らかにした独創的な研究であり、集団内におけるヒトの意思決定の正確さを改善するための集合知の有向な利用方法についての示唆を与える重要な貢献であると考えられる。以上の理由により、審査委員会は、本論文が学位の授与に値すると判断した。