# Improved Cooperation by Balance Exploration and Exploitation in Intertemporal Social Dilemma Tasks

Abstract: When individual behavior has rational characteristics, it may lead to irrational total benefits for the group. Humans and animals with many social traits tend to evolve a social trait of cooperation to meet this challenge. Therefore, cooperation between individuals is of great significance for social organisms to adapt to the changes of their natural environment. Based on multi-agent reinforcement learning, we propose a learning rate defined by the difference between the cumulative benefits of individual stages and the target benefits. This learning rate can adjust the strategies of agents by switching between exploration and exploitation according to the environmental benefits, so as to form an individual strategy with relatively better overall benefits for the group. The results show that this strategy has a relatively better overall strategy in the intertemporal social dilemma problem, and its strategy does not need to directly acquire the information of other individuals in the group. In particular, the heterogeneity of individual internal needs can help individuals better balance exploration and exploitation, so as to promote group cooperation.

## 1 介绍

The results of group behavior of animals or humans are not only affected by the environment, but also affected by individual behavior strategies within the group. For example, the migration of animals or humans will be affected by the environmental resources they are in, and animals or humans will tend to migrate to places with abundant environmental resources. At the same time, the benefits obtained by individuals in the group from the environment are also affected by the strategies of other individuals in the group. When the strategy of all individuals in a group is to move to an area where resources are abundant, the gains of the individuals in that area will gradually decrease. The problem that individual rationality leads to group irrationality is the so-called intertemporal social dilemma problem [1]. In order to obtain the optimal total return in the situation of intertemporal social distress, the individual in the group needs to be able to make a trade-off between individual short-term gain and group long-term gain. However, it is not clear how individuals' strategies balance their short-term gains against the group's long-term gains.

Multi-agent reinforcement learning can simulate the behavior strategies of multiple agents in dynamic and variable environments. At present, many studies have found that multi-agent reinforcement learning can simulate how groups form cooperation, so as to obtain the optimal solution in various social dilemmas. These models often use internal rewards to make intelligent bodies rational strategies for the group. Intrinsic rewards include aversion to inequality [2], prosociality [3], and reputation [4]. These internal rewards discourage agents from adopting strategies that are detrimental to the group's overall benefits. For example, an agent abhors inequality, and when it finds that its own benefits are far greater than those of other agents, it discourages itself from pursuing a strategy that maximizes its individual benefits. In order to form internal rewards, these models all assume that an individual in a group can directly obtain information from other peers, thus forming an individual's prosocial attributes. However, it is difficult to provide a reasonable explanation for the formation of cooperation mechanisms in groups that can only indirectly obtain information from a small number of partners, such as fish and ants.

Based on Ericcharnov's marginal value theory, this study proposes that agents can simply adjust the learning rate to balance exploration and exploitation, so as to form cooperation in intertemporary social hardship tasks, thus obtaining higher total group benefits. In the reinforcement learning model, exploration is represented by agents choosing the actions that currently fail to obtain the optimal reward in order to avoid the local optimal solution, while exploitation refers to agents selecting the actions that currently receive the optimal reward. In order to make a trade-off between exploration and exploitation, we proposed a learning rate defined by the difference between an individual's cumulative return and the target return based on deep Q learning. This learning rate can adjust the strategies of agents by switching between exploration and exploitation according to the environmental benefits, so as to form an individual strategy with relatively better overall benefits for the group.

## 2 Related research

In the face of social dilemmas, how agents gradually form cooperative behavior has always been an important research problem in social science, economics and psychology. By constructing a strategy game in which two participants interact, Komorita and Parks [5] et al. (1995) found that by setting the benefits of two strategies of "worry" and "greed", the cooperative behavior of two participants can be formed. Evolutionary dynamics models have found that cooperation is promoted by a tit-for - tat strategy (Axelrod 1984 [6]), by cooperating with those who directly help one (Nowak 2006 [7]), or by punishing others in order to obtain sufficient rewards (Fehr and Gachter 2002 [8]). Although the above studies have given the possible factors of forming group cooperation, they have not given the specific strategies of individuals.

With the remarkable achievements of reinforcement learning in solving games such as Go [9] and multi-agent cooperative games [10, 11], many researchers have begun to use the multi-agent reinforcement learning model to study the mechanism of how groups form cooperation [12, 13]. By setting the decision task of the agent and the strategy parameters needed by the agent to form cooperation, the model is used to explain the possible strategy parameters of the animal or human when forming cooperation behavior. Sequeira et al. [14] proposed that agents form social attributes by exploring intrinsic motivations. Foerster et al. [15] (2017) made agents form cooperation in the multi-round Prisoner's Dilemma game by modeling the learning results of other individuals. Peysakhovich et al. [16] (2018) found that when agents pay more attention to other individual benefits, they can form prosocial strategies in Stag Hunt Games. Hughes [12] et al. (2018) integrate the aversion to inequality into the internal reward of the agent, so as to adjust the strategy when its own benefit is much larger than that of other individuals in the group or its own benefit is much smaller than that of other individuals in the group, thus forming cooperation. Jaques [17] et al. (2018) converted the influence of individual actions on the group into internal rewards to form cooperation among agents in social dilemma. Wang [18] et al. (2019) proposed evolutionary deep reinforcement learning, which defined past and future rewards of other individuals as internal rewards of agents to evolve cooperative strategies. Khadka et al. [19] (2019) designed a method for learning multiple strategies with shared playback buffers and dynamically selecting the best learner to evolve cooperation between multiple agents. Badjatiya [13] et al. (2020) proposed to design a status-quo loss function to make agents follow the Status Quo as far as possible, so as to evolve cooperative behavior in a social dilemma environment. McKee et al. [20] (2020) sample their rewards from groups with heterogeneous characteristics, allowing agents to acquire prosocial attributes. Danassis [21] et al. (2021) found that agents can improve their cooperative behavior by integrating common signals (such as periodic numbers such as time and date) during learning. A common feature of the above models is that agents need to directly obtain relevant information of all other agents in order to form cooperative behaviors. These models do not provide a reasonable explanation for the formation of cooperation mechanisms in groups that can only indirectly obtain information from a small part of the group, such as fish and ants.

Due to the dynamic changes and uncertainties of the environmental state, the agents either use the existing experience for exploitation or take the risk of not being able to get better returns for exploration in the hope of getting better strategies. Therefore, exploration and exploitation have always been important research topics in reinforcement learning. In the early days of solving the multi-armed gambling machine problem, Epsilon-greedy [22], Upper confidence bounds [23] and Boltzmann exploration [24] can be used in exploration and exploitation to get the best overall benefit. However, in the real environment, due to the sparse nature of reward signals and the abnormal noise in the environment state, the above simple exploration strategy cannot obtain good overall income.

A more general method is to design an internal reward function to form the internal motivation of the agent [25], so as to guide the agent to explore through such as curiosity. Curiosity includes discovering new states, or improving the accuracy of agent's estimation of environmental changes [22], etc. This kind of exploration strategy based on internal reward may have problems such as slow convergence speed and non-stationary exploration return, which makes it difficult to form a fixed exploration strategy. Therefore, the memory-based exploration strategy [26] and the resampling Q-value exploration strategy [26] were developed to avoid the shortcomings of the exploration strategy based on internal rewards. However, the above single agent exploration strategy is not necessarily suitable for multi-agent cooperative exploration.

In the case of multi-agent exploration, it is not only necessary to encourage agents to explore new states and deal with the problem of sparse reward signals, but also to cooperate with the actions of agents to form cooperation to explore the environment. Agogino and Tumer [27] define a method for evaluating the effectiveness of a reward function for multiple agents in a smaller-scale state space. Jaques [17] et al. defined an intrinsic reward function for multi-agent reinforcement learning, which encourages agents to take actions that have the greatest impact on the behaviors of other agents, so as to obtain cooperative exploration strategies. Mahajan et al. [28] introduced a mechanism for implementing 'commitment' exploration, allowing agents to explore common strategies for temporary expansion. Wang et al. [18] defined impact-based rewards that encourage agents to visit areas where their behavior affects the transformation and reward of other agents. Recently, Iqbal and Sha (2021) [29] proposed a kind of exploration method based on internal reward. The main feature of this method is that it can coordinate the exploration strategies among agents and enable agents to better obtain overall benefits. The above multi-agent exploration strategy still requires the agent to obtain the information of other agents by lipolysis. Further research is needed for the exploration strategy under the condition that only a small part of other agents can be obtained, or even the information of other agents is not required.

## 3 Multi-agent reinforcement learning and decision making tasks

### 3.1 Multi-agent reinforcement learning

We define the multi-agent reinforcement learning model as a quad, which includes the state set , the state transfer function , the action set and the reward , i.e. . There are agents in the environment, and the state that each agent can perceive is ，it means that the can observe dimensions of the state. That is, the agent can only partially observe its state. Each agent in the environment interacts with the environment through its actions *An*, and the actions of the agent will cause changes in the state of the environment. The change is described by the state transition function: . That is, the actions of all agents in the environment work together to change the state of the environment from to another state .

Each agent learns the strategy according to its observation . After the agent executes the action , it will get the reward , and evaluate the result of the action through the reward. The goal of the agent is to learn an optimization strategy in order to obtain the greatest long-term benefits. The definition of long-term benefits of an agent as：

Formula 1.

Among them, is a discount factor between 0 and 1. For simplicity, . For agent , in order to obtain the maximum expected return, the function can be updated according to the following function [30].

Formula 2.

### 3.2 Learning rate based on target benefit

We consider to define the learning rate through the staged cumulative benefits and target benefits of the agent. The learning rate reflects the impact of changes in the environment on the agent's strategy. In order to achieve this goal, we define the difference between the stage cumulative return and the target return as the learning rate：

Formula 3.

is a constant, and the size is set to 0.001. The phase cumulative return is the cumulative reward value of the agent in time , which reflects the indirect influence of other agents on the individual's income in a certain period of time. The target return is a fixed value, and each agent has a target return, which reflects the degree of satisfaction of the agent. When the target profit is large, it means that the agent needs to obtain more accumulated profit to be satisfied. If the cumulative benefit of the agent's stage is less than the target benefit, it indicates that the goal of the agent has not been reached, and it shows more exploration. When the accumulated income of the agent's stage is close to the target income, it indicates that the agent's strategy has reached its expectations, and it shows more exploitation.

According to the above definition of learning rate, when the environment is in a stable state, the agent's strategy gradually converges, and its learning rate is at a low level. When there is a sudden change in the environmental state, the agent's strategy must be able to adapt to this change quickly, and the learning rate during this period is at a relatively high level.

### 3.3 Decision task

According to the resource collection task of Hughes [12] et al. (2018), we designed a similar intertemporal social dilemma task. The task environment contains two resource areas with different values, namely the apple area and the garbage area. The size of the environmental map is units, garbage is distributed in the upper half of the environment, and apples are distributed in the lower half of the environment. Garbage appears in its area with probability , and the amount of garbage in the environment is recorded as . Apples appear with probability in the area where they are located, and the number of apples in the environment is recorded as . Apple’s growth rate is negatively correlated with the amount of garbage:

Formula 4.

Where is the maximum growth rate of apples, and is half of the garbage area in the map.

环境中分布若干数量的智能体，智能体通过在环境中的移动，要么收获所在位置的奖励，要么清理所在位置的垃圾。智能体收获苹果的收益记为，而清理垃圾的收益记为。智能体的目的是获取最多的总收益。在该任务中，各个智能体仅能感知其周围有限视野内的信息，智能体的视野范围大小记为。

该决策任务的困境如下，苹果和垃圾的增长相互影响。由于苹果的收益大于垃圾的收益，智能体的个体策略会倾向采苹果而非清理垃圾。然而，苹果数量的减少会导致垃圾数量的增加，从而抑制苹果出现的概率。因此，对智能体群体而言，需要一部分智能体清理垃圾，一部分智能体采集苹果，才能获得对整体而言较多的总收益。

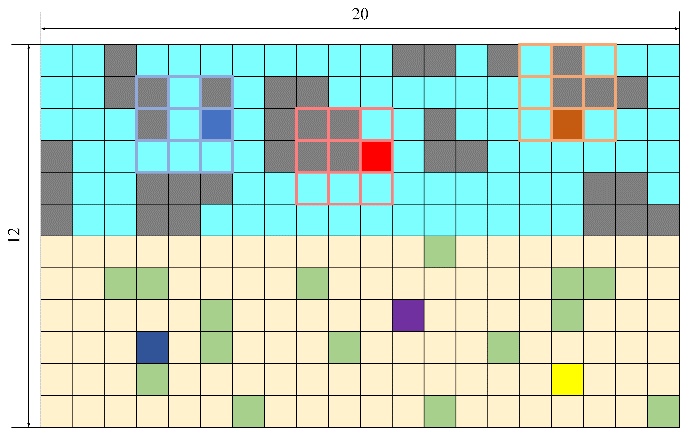


图1. 游戏地图

由于垃圾与苹果的生长并不平衡，多智能体在清理垃圾时清理视野范围内所有的垃圾，而采集苹果时只采集当前位置的苹果。因此，智能体清理垃圾获得的实际奖励为, 采集苹果获得的实际奖励为。决策任务中设定，表示智能体在时间跨度内的总收益。

仿真中，环境中随机放置了6个智能体，它们各自的学习函数见公式1。我们将地图中每个单元格的位置映射到区间内，其中表示垃圾区域内的单元格，表示苹果区域内的单元格。表示每个Agent在环境中的初始位置，且。对每个智能体而言，每个episode包括100 trials，每组实验包括300轮episode。

### 3.4 同质与异质性群体属性

根据取值方法，将智能体群体分为异质性和同质性。异质性表示在给定范围内随机取值，这种异质性反映了智能体个体的多样性。当智能体目标收益满足时，称其为高目标收益者，而当智能体目标收益满足时，称其为低目标收益者，这两种情况下的智能体具有同质性群体属性。仿真中的群体属性相关的参数设置见表1。

表 1 群体属性参数设置

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |
| Heterogeneous |  |  |  | 5 | 10 | 5 |  |
| Homogeneous |  |  |
| 0 |  |

## 4 结果

我们使用阶段累积收益和目标收益定义动态学习率，验证该学习率在跨期社会困境任务中通过平衡 exploration和exploitation以形成群体合作，从而获得相对较优的总体收益。

如图2所示，我们比较了群体在固定学习率和动态学习率下执行跨期社会困境任务的收益。动态学习率下的群体总收益可以收敛达到2200~2500之间，而固定学习率(=0.001)的群体的总收益仅可以收敛到1300~1600之间。智能体仅采用随机策略，总收益收敛在700~1000之间。

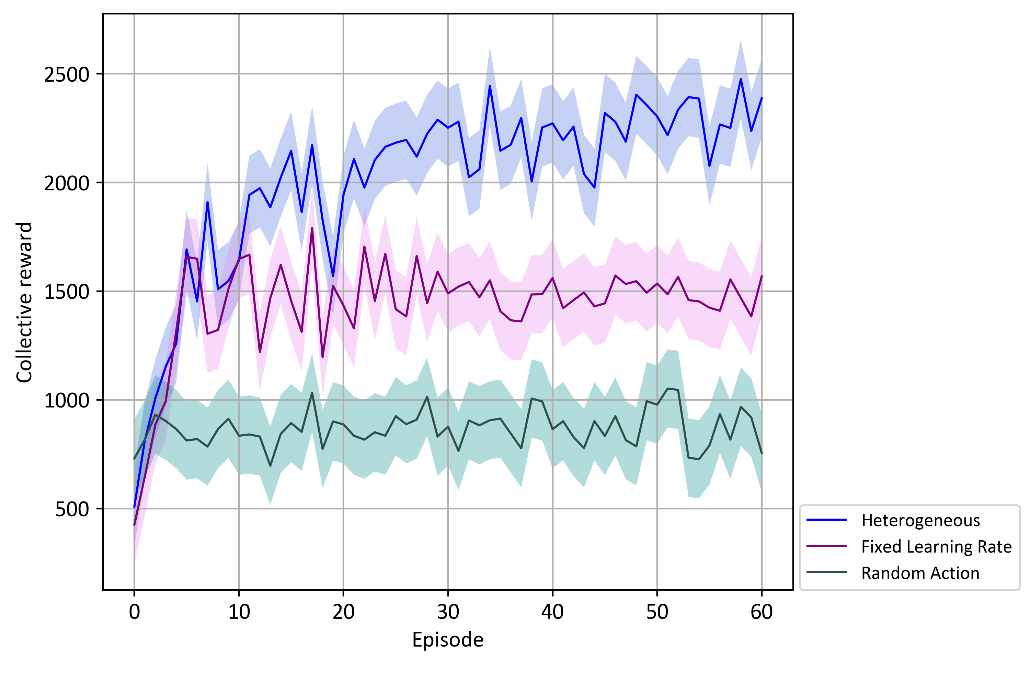


图 2. 动态学习率和固定学习率的收益比较

我们通过设定目标收益不同的分布，来验证目标收益在权衡Exploration和Exploitation时的作用。我们根据目标收益的分布，定义了Heterogeneous、Homogeneous High和Homogeneous Low三种群体属性。如图3所示，这三类群体中Heterogeneous群体的总收益比两种Homogeneous 群体的总收益都高。Homogeneous Low群体的总收益最低，甚至低于随机策略的总收益。

为了更清楚的表示每一个智能体在环境中Exploration和Exploitation的变化，我们在图4中画出每一个智能体在环境中的活动位置。Heterogeneous群体根据自身的目标收益进行Exploitation形成分工（图4 A）。这种分工会让部分智能体（低目标收益的智能体）在垃圾区采集垃圾，而部分智能体（高目标收益的智能体）在苹果生长区采集苹果，正是这种分布导致Heterogeneous群体的总体收益最高。当群体内每个智能体的目标收益都高，导致它们一直在环境中采用Exploration去获取高收益的苹果（图4 B）。而当群体内每个智能体的目标收益都低时，他们在苹果区域获得奖励大于个体本身的期望，模型会抑制低目标收益者贪婪地采集苹果，当智能体Exploration到匹配自身目标收益的区域时(垃圾区域)才会更新策略（图4 C）。完全随机选择动作的群体一直在进行没有目标的Exploration（图4 D）。

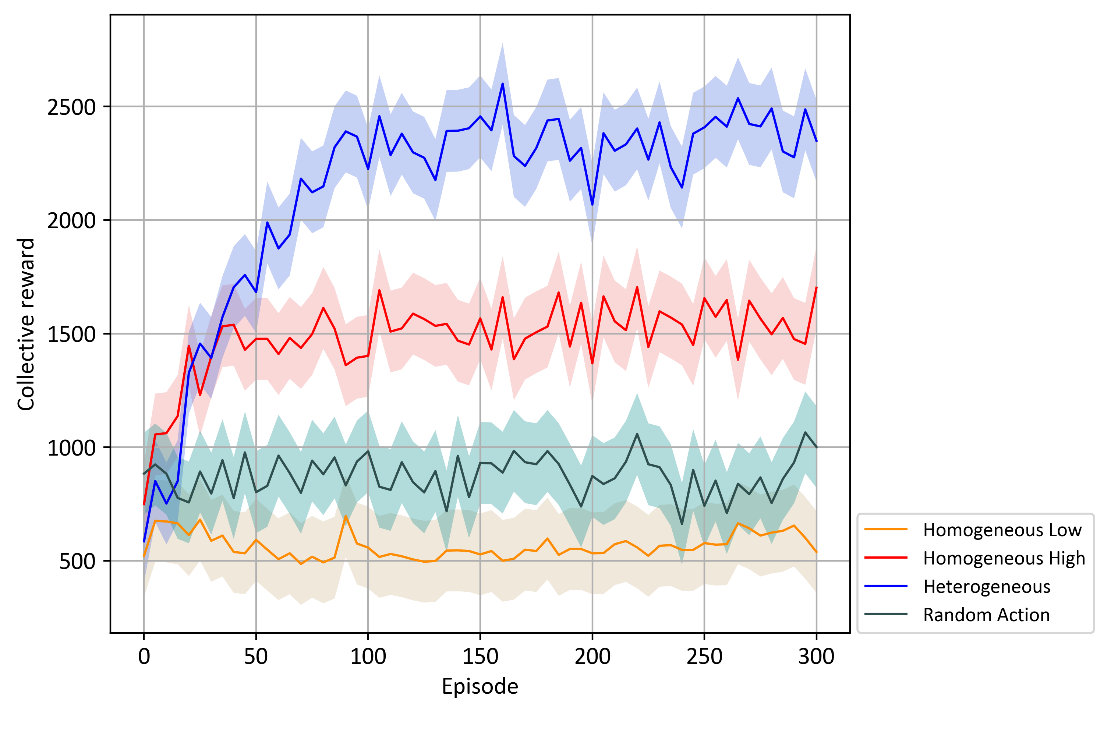


图 3. 个体异质性与个体同质性收益比较

1. Heterogeneous
2. Random Action
3. Homogeneous Low



1. Homogeneous High

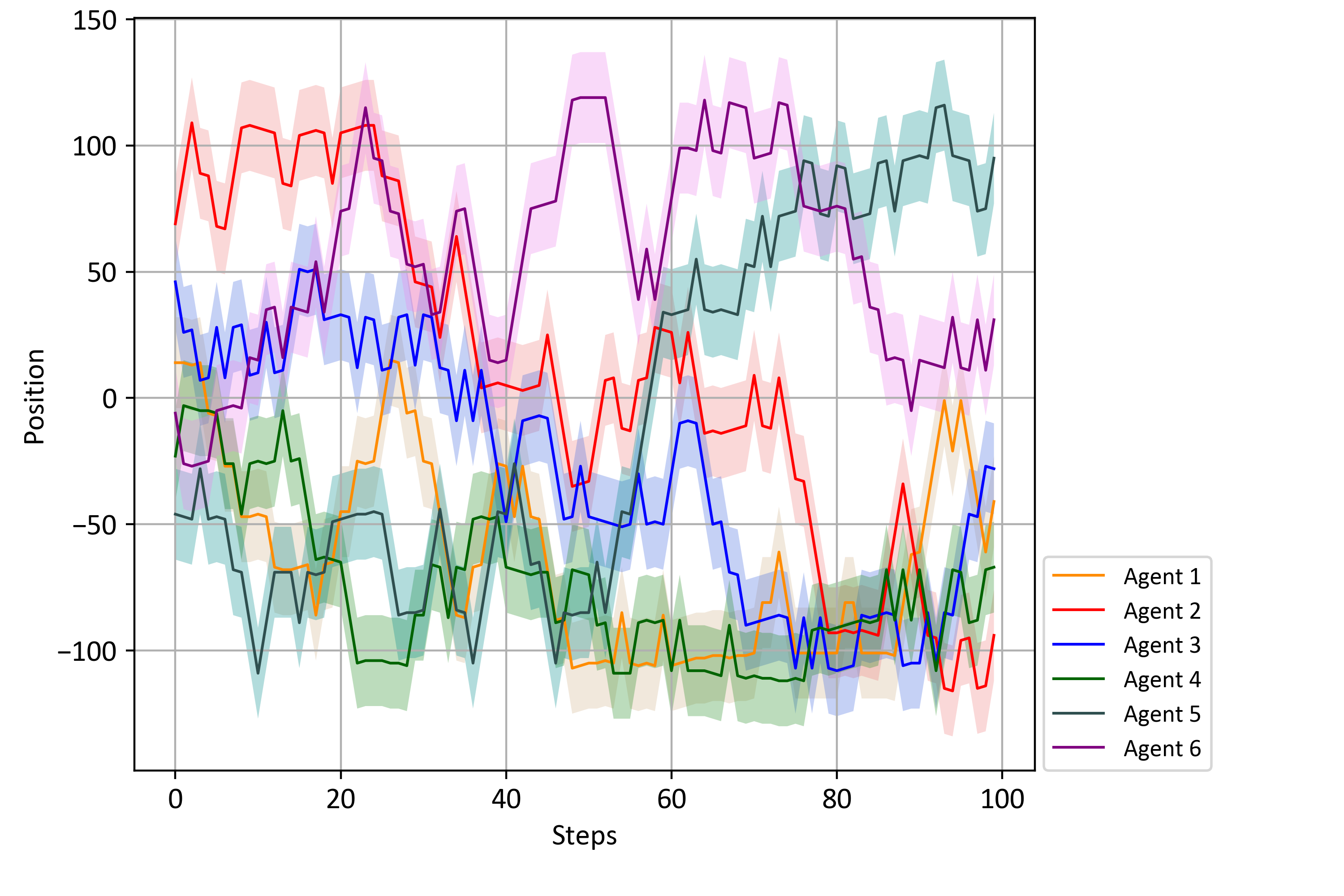
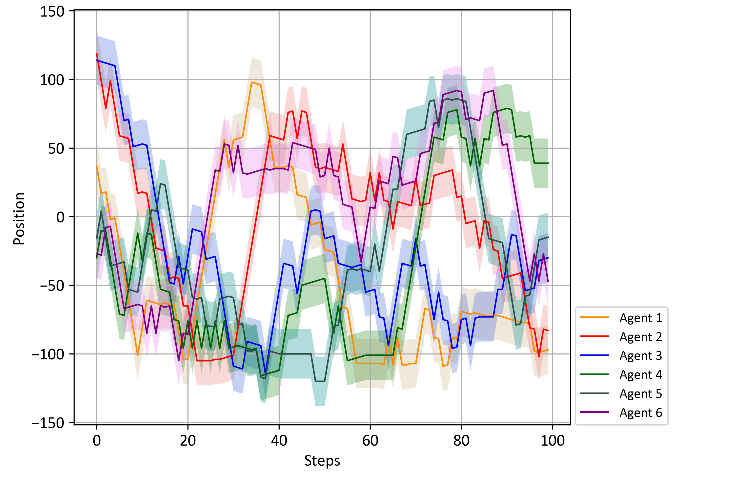


图 4. 异质性群体与同质性群体内智能体的活动位置对比

1. Homogeneous High
2. Random Action
3. Heterogeneous
4. Homogeneous Low

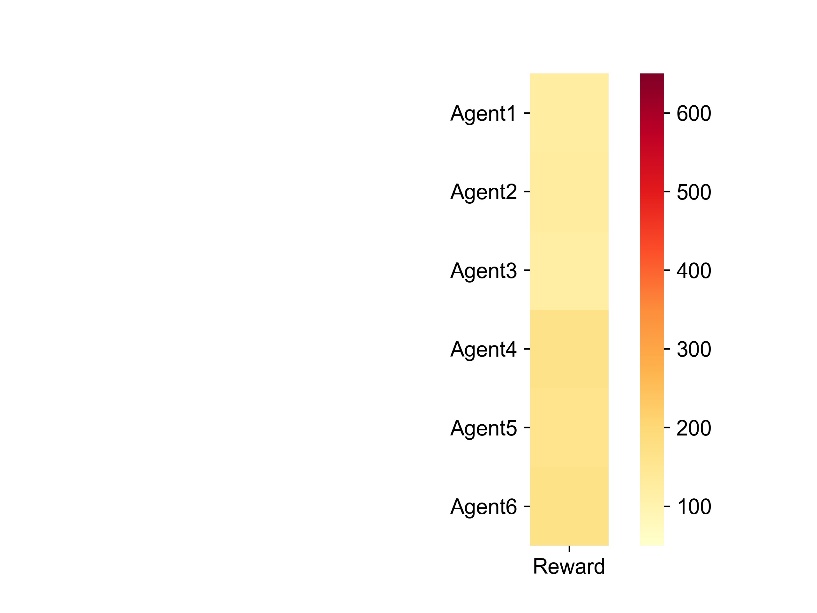
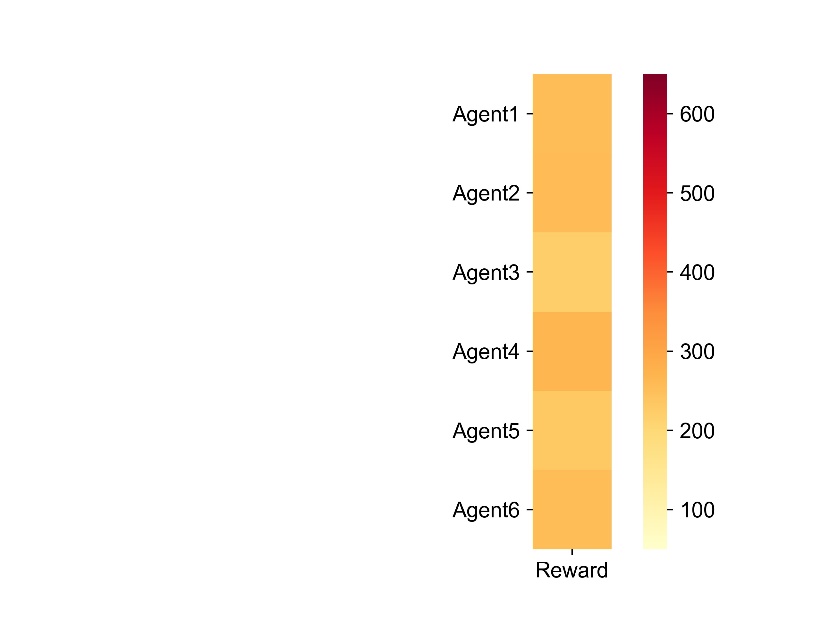
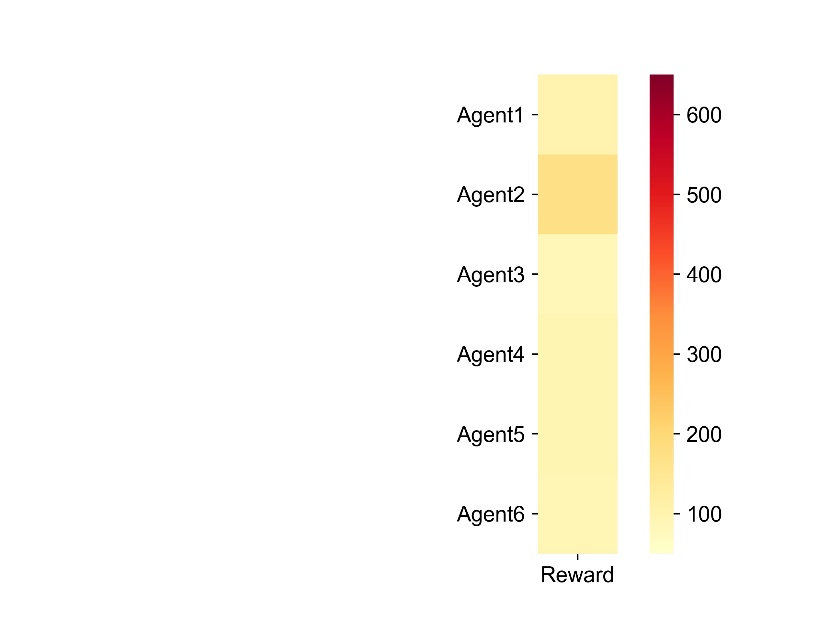
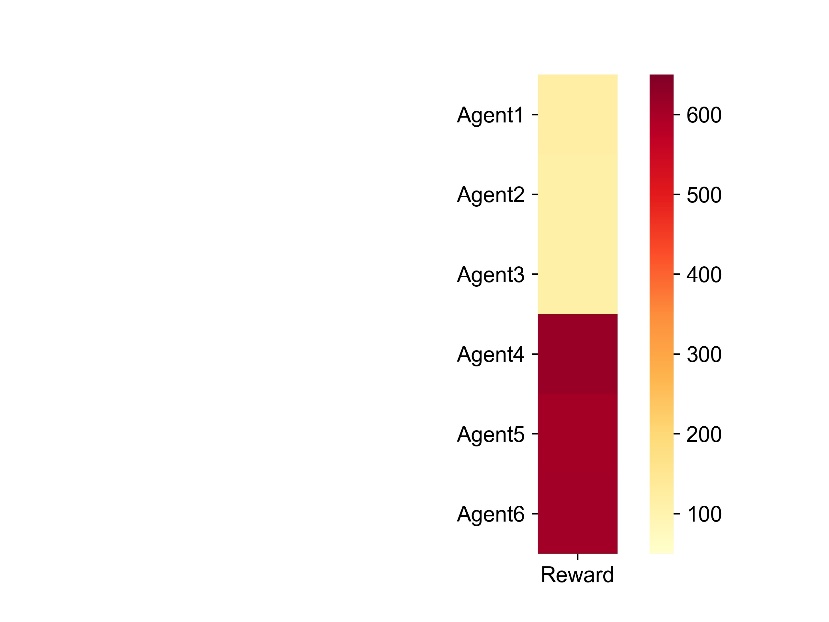


图 5. 不同群体内智能体的收益对比

如图5所示，对比了不同群体中每个智能体之间的收益，以便比较合作行为是否造成智能体间贫富差距。结果表明，相比较于同质性群体内收益差值，异质性群体间收益差值最大。这表明尽管群体的异质性特征促进了智能体间的合作行为，但也会导致群体内个体间贫富差距变大。

我们单独使用Heterogeneous群体作为实验对象，控制每个智能体的目标收益不变，来探究不同的阶段累计长度对群体合作行为的影响。如图6所示，随着的不断增大，群体的总收益不断下降；当的取值过小，智能体总体收益同样较小。当的取值较大时，智能体难以感知环境的变化，从而降低其采用Exploration的可能性。当的取值较小时，智能体仅关注当前收益，同样难以感知环境变化，从而使得智能体频繁采用Exploration。

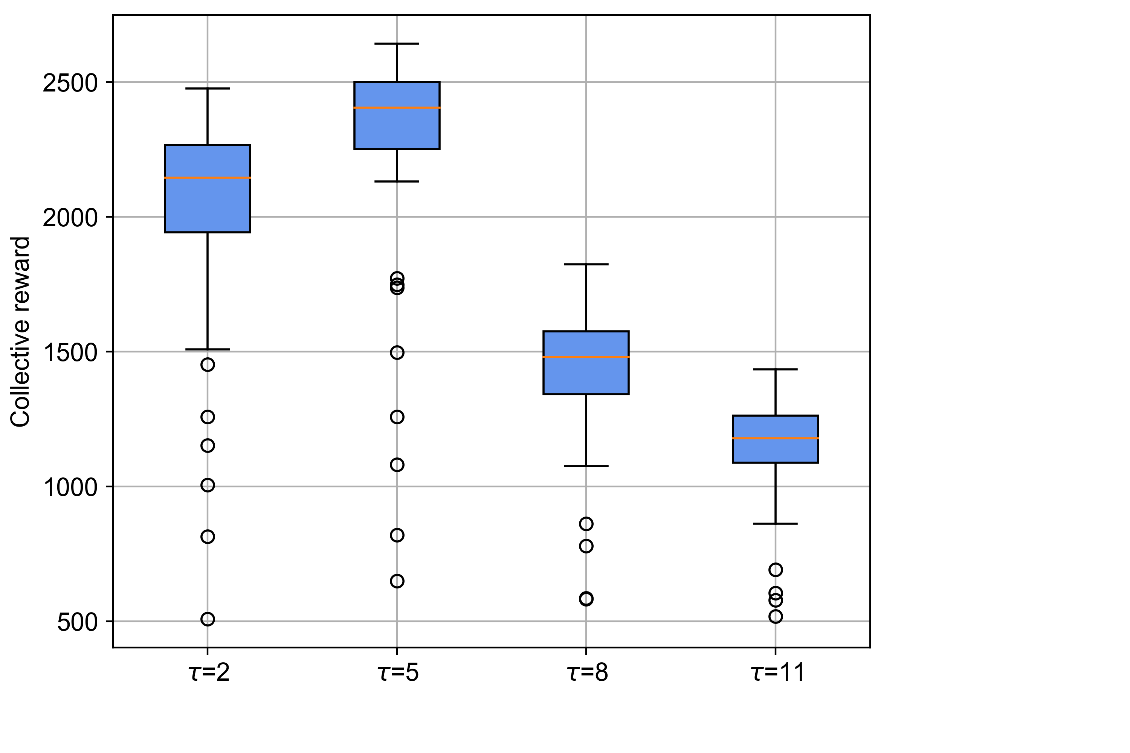


图 6. 不同阶段累计长度的总收益

## 5 结论

边际价值理论提出人对物品的欲望会随其不断被满足而递减。基于边际价值理论我们提出了一个通过平衡利用-探索，从而在跨期社会困境中多智能间形成合作的方法。面对跨期社会困境问题，智能体只需要计算在一段时期内的收益，而不需要从其他智能体获取额外的信息，就可以形成类似合作的行为。我们的结果表明，智能体间的异质性，如各个智能体的目标收益的异质性，是形成合作行为的关键。这个结论与McAvoy等（2020）和McKee等（2020）[31]最近的研究结果类似，他们发现智能体连接数量的异质性和社会偏好的异质性，能促进智能体社会行为的形成。我们的研究结果进一步揭示，其它类型的异质性，如本文设定的各个智能体目标需求的异质性，也能促进智能体间合作行为的形成。在此基础上，我们推断也许还存在其它可以促进智能体形成合作行为的异质性参数，这一点值得后续更为深入的理论与实验研究。

我们研究的一个主要不足之处在于，设计的智能体学习算法并没有考虑智能体间直接的互动和交互。智能体间通过一个时间段内总收益来产生相互的影响。对某个智能体而言，如果群体内的其它智能体行为都是非社会性，那么这个智能体一个时间段内总收益就会变少，这会引起该智能体根据其自身的目标收益来调整利用和探索策略。也就是说，其它智能体的非社会性行为间接引起了该智能体策略的变化。相似地，如果群体内的其它智能体行为都是亲社会性，他们的行为也会间接引起了该智能体利用和探索策略的变化。我们将在后续研究考虑，在算法中增加智能体间交互的参数。

需要特别指出，我们只是在跨期社会困境中验证了智能体通过调整利用与探索策略来形成合作，对于其它类型的社会困境问题能否得到同样的结论还需要进一步的验证。

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