RIIT: Rethinking the Importance of Implementation Tricks in Multi-Agent Reinforcement Learning

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Abstract

In recent years, Multi-Agent Deep Reinforcement Learning (MADRL) has been successfully applied to various complex scenarios such as computer games and robot swarms. We investigate the impact of "implementation tricks" of state-of-the-art (SOTA) QMIX-based algorithms. Firstly, we find that such tricks, described as auxiliary details to the core algorithm, seemingly of secondary importance, have a major impact. Our finding demonstrates that, after minimal tuning, QMIX attains extraordinarily high win rates and achieves SOTA in the StarCraft Multi-Agent Challenge (SMAC). Furthermore, we find QMIX's monotonicity condition improves sample efficiency in some cooperative tasks. We propose a new policy-based algorithm, called RIIT, to verify the importance of the monotonicity condition. RIIT also achieves SOTA in policy-based algorithms. At last, we prove theoretically that the Purely Cooperative Tasks can be represented by the monotonic mixing networks. We open-sourced the code at https://github.com/hijkzzz/pymarl2.

1 INTRODUCTION

MADRL has seen increased interest in recent years due to its capability in allowing neural-network-based agents to learn to act in multi-agent environments through interactions. For discrete cooperative control tasks, value-based algorithms such as QMIX Rashid et al. [2018] which serves as the baseline, Qatten Yang et al. [2020], WQMIX Rashid et al. [2020], and QPLEX Wang et al. [2020a], and policy-based algorithms such as LICA Zhou et al. [2020] and DOP Wang et al. [2020b] have achieved SOTA in SMAC Samvelyan et al. [2019], a standard benchmark for evaluating SOTA MADRL algorithms. These papers claim to significantly improve the performance of the baseline QMIX by weakening monotonicity constraints or extending to policy-based methods. However, they fail to acknowledge that they are using tricks in their implementation to achieve SOTA performance in their experiments. While one may assume that such "choices" are unimportant, there is some evidence that they are, in fact, vital for good performance.

These algorithms are indeed comparable through open-source code; however, due to inconsistent comparison standards and a lack of a reliable baseline, it remains challenging for researchers to judge whether they provide performance improvements because of a genuinely improved architecture or because of implementation tricks. Their experiment results and conclusions may be inaccurate or misleading and stand as a hindrance to future MADRL research. With an understanding of the effects of these tricks, we can then evaluate the correctness of these conclusions.

The main contributions in the paper are: (1) We study how implementation tricks affect the test performance of QMIX; after minimal tuning, QMIX can attain extraordinarily high win rates in SMAC and achieve SOTA. (2) Furthermore, we find QMIX's monotonicity condition improves sample efficiency in some cooperative tasks. Moreover, we propose the new policy-based algorithm called: RIIT (Sec. 5.2) to verify the importance of the monotonicity condition. RIIT also achieves SOTA in policy-based algorithms. (3) At last, we prove theoretically that the monotonicity constraint does not cause performance damage to Purely Cooperative Tasks (Sec. 5.3).

This paper is organized as follows: Sec. 2 discusses the main MADRL algorithms for the discrete cooperative task. Sec. 3 illustrates the benchmark and evaluation metric. Sec. 4 demonstrates how these tricks affect the performance of QMIX. Sec 5 shows our benchmarks and analysis of the monotonicity condition. Sec. 6 and Sec. 7 are related works and conclusion, respectively.

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2 BACKGROUND

Dec-POMDP. A fully cooperative multi-agent task can be described as a decentralized partially observable Markov decision process (Dec-POMDP) Ong et al. [2009] composed of a tuple $G = \langle \mathscr{S}, \mathscr{U}, P, r, \mathscr{Z}, O, N, \gamma \rangle$. $s \in S$ describes the true state of the environment. At each time step, each agent $i \in \mathscr{N} := \{1, \ldots, N\}$ chooses an action $u_i \in \mathscr{U}$, forming a joint action $u \in \mathscr{U}^N$. All state transition dynamics are defined by function $P(s' \mid s, u) : \mathscr{S} \times \mathscr{U}^N \times \mathscr{S} \mapsto [0,1]$. Each agent has independent observation $z \in \mathscr{Z}$, determined by observation function $O(s,i) : \mathscr{S} \times \mathscr{N} \mapsto \mathscr{Z}$. All agents share the same reward function $r(s,u) : \mathscr{S} \times \mathscr{U}^N \to \mathbb{R}$ and $\gamma \in [0,1)$ is the discount factor. Given that π_i is the policy of agent i, the objective of the joint agent is to maximize:

$$J(\pi) = \mathbb{E}_{u_1 \sim \pi^1, \ldots, u^N \sim \pi^N, s \sim T} \left[\sum_{t=0}^{\infty} \gamma_t r_t \left(s_t, u_t^1, \ldots, u_t^N \right) \right] \quad (1)$$

CTDE. The centralized training and decentralized execution paradigm (CTDE) Kraemer and Banerjee [2016] allows the learning process to utilize additional state information. CTDE allows the learning algorithm to access all local action observation histograms and global states and share gradients and parameters. However, in the execution stage, each individual agent can only access its local action observation history τ^i. Next, we introduce the CTDE MADRL algorithms for the discrete cooperative control tasks.

2.1 QMIX

To resolve non-stationarity Hernandez-Leal et al. [2017] in the multi-agent setting, QMIX Rashid et al. [2018] learns a joint action-value function Q_{tot}. It decomposes the joint Q_{tot} value to each agent Q_i through a monotonic Q value mixing network. The relationship between Q_{tot} of the joint agent and Q_i of the invidual agents can be expressed as:

$$\begin{aligned} & Q_{tot}(s, u; \theta, \phi) \\ =& g_\phi \left(s, Q_1 \left(\tau^1, u^1; \theta^1 \right), \ldots, Q_N \left(\tau^N, u^N; \theta^N \right) \right) \end{aligned} \quad (2)$$

$$\frac{\partial Q_{tot}(s, u; \theta, \phi)}{\partial Q_i (\tau^i, u^i; \theta^i)} \geq 0, \quad \forall i \in \mathscr{N} \quad (3)$$

Where ϕ is the trainable parameter of the monotonic mixing network, maximizing joint Q is precisely equivalent to maximizing individual Q_i, and therefore, the optimal individual action maintains consistency with the optimal joint action. Then, QMIX learns by sampling a multitude of transitions from the replay buffer and minimizing the mean squared temporal-difference (TD) error loss:

$$\mathscr{L}(\theta) = \frac{1}{2} \sum_{i=1}^{b} \left[\left(y_i - Q_{tot}(s, u; \theta, \phi) \right)^2 \right] \quad (4)$$

where the TD target value $y = r + \gamma \max_{u'} Q(s', u'; \theta^-, \phi^-)$ and θ^-, ϕ^- are the target network parameters copied periodically from the current network and kept constant for a number of iterations.

2.1.1 Shortage of QMIX.

However, the **monotonicity condition (Eq. 3)** limits the mixing network's expressiveness, which may fail to learn in the non-monotonic case Mahajan et al. [2020], as shown in Table 1 and Table 2.

12	-12	-12
-12	0	0
-12	0	0

(a) Payoff matrix

-12	-12	-12
-12	0	**0**
-12	0	0

(b) QMIX: Q_{tot}

Table 1: A non-monotonic matrix game which violates the monotonicity condition. QMIX may learn an incorrect Q_{tot} which has an incorrect argmax. Bold text indicates the reward of the argmax.

1	0
0	1

(a) Payoff matrix

1	1/3
1/3	1/3

(b) QMIX: Q_{tot}

1/3	1/3
1/3	1

(c) QMIX: Q_{tot}

Table 2: A non-monotonic matrix game (from Rashid et al. [2020]). The convergence of QMIX cannot be guaranteed . QMIX may converge to (b) or (c).

Therefore, the goal of QTRAN++Son et al. [2020], QPLEX, WQMIX, and LICA is to weaken the monotonicity condition of QMIX and claimed to significantly improve performance in SMAC.

2.2 QPLEX

QPLEX Wang et al. [2020a] decomposes Q values into advantages and values based on Qatten, similar to Dueling-DQN Wang et al. [2016]:

$$\begin{aligned} \text{(Joint Dueling) } Q_{tot}(\tau, u) &= V_{tot}(\tau) + A_{tot}(\tau, u) \\ V_{tot}(\tau) &= \max_{u'} Q_{tot}\left(\tau, u'\right) \end{aligned} \quad (5)$$

$$\begin{aligned} \text{(Individual Dueling) } Q_i(\tau_i, u_i) &= V_i(\tau_i) + A_i(\tau_i, u_i) \\ V_i(\tau_i) &= \max_{u'} Q_i\left(\tau_i, u_i'\right) \end{aligned} \quad (6)$$

$$\frac{\partial A_{tot}(s, u; \theta, \phi)}{\partial A_i (\tau^i, u^i; \theta^i)} \geq 0, \quad \forall i \in \mathscr{N} \quad (7)$$

In other words, Eq. 7 (advantage-based monotonicity) transfers the monotonicity condition from Q values to advantage values. QPLEX thereby reduces limitation on the mixing network's expressiveness.

2.3 WQMIX

WQMIX Rashid et al. [2020], just like Optimistically-Weighted QMIX (OW-QMIX), uses different weights for each sample to calculate the squared TD error of QMIX:

$$\mathscr{L}(\theta) = \sum_{i=1}^{b} w(s,\mathbf{u})\left(Q_{tot}(\tau,\mathbf{u},s) - y_i\right)^2 \tag{8}$$

$$w(s,\mathbf{u}) = \begin{cases} 1 & Q_{tot}(\tau,\mathbf{u},s) < y_i \\ \alpha & \text{otherwise.} \end{cases} \tag{9}$$

Where $\alpha \in (0,1]$ is a hyperparameter. WQMIX prefers those optimistic samples (true returns are larger than predicted), thus avoiding ignoring optimal solutions. The authors demonstrate that this approach can resolve the estimation errors of QMIX in the non-monotonic case.

2.4 LICA

Policy-based algorithms allow for convenient modeling of complex action spaces such as AlphaStar Vinyals et al. [2019] and continuous-discrete hybrid control tasks Neunert et al. [2020]. **LICA** Zhou et al. [2020] is an on-policy policy-based algorithm that removes the monotonicity condition through a policy mixing critic (Figure 1):

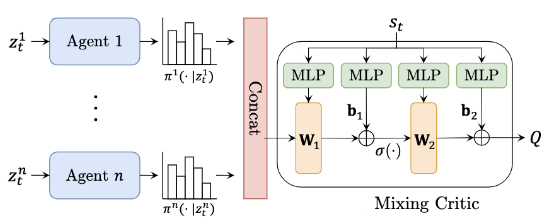

Figure 1: Architecture for LICA (from Zhou et al. [2020]). LICA's mixing critic maps policy distribution to the Q value directly, in effect obviating the monotonicity condition. z denotes local action observation history.

LICA's mixing critic is trained using squared TD error. With a trained critic estimate, the decentralized policy networks can then be optimized end-to-end simultaneously by maximizing $Q^{\pi}_{\theta_c}$ with the stochastic policies $\pi^i_{\theta_i}$ as inputs:

$$\begin{aligned} \max_{\theta} \mathbb{E}_{t,s_t,u_t^1,\ldots,\tau_t^n}\Big[Q^{\pi}_{\theta_c}\left(s_t, \pi^1_{\theta_1}\left(\cdot \mid \tau_t^1\right), \ldots, \pi^n_{\theta_n}\left(\cdot \mid \tau_t^n\right)\right) \\ + \mathbb{E}_i\left[\mathscr{H}\left(\pi^i_{\theta_i}\left(\cdot \mid \tau_t^i\right)\right)\right]\Big] \end{aligned} \tag{10}$$

where the gradient of entropy item $\mathbb{E}_i\left[\mathscr{H}\left(\pi^i_{\theta_i}\left(\cdot \mid z_t^i\right)\right)\right]$ is normalized by taking the quotient of its own modulus length: Adaptive Entropy (Adapt Ent). Adaptive Entropy automatically adjusts the coefficient of entropy loss in different scenarios.

3 STUDY DESIGN

In this paper, we consider the setting of CTDE MADRL for discrete cooperative control. We investigate the tricks of the baseline QMIX and its improved variants: Qatten, QPLEX, WQMIX, LICA, and DOP.

3.1 BENCHMARK ENVIRONMENT

For our benchmark testing environment, we leverage SMAC, a ubiquitously-used multi-agent discrete cooperative control environment for the SOTAs. SMAC consists of a set of StarCraft II micro scenarios used for evaluating how effectively independent agents can coordinate to solve complicated tasks. SMAC classifies micro scenarios into three difficulty levels: Easy, Hard, and Super Hard. The Super Hard scenario *6h_vs_8z* is also hard to explore. Easy scenarios are usually simple to solve using the uncomplicated Value-Decomposition Networks (VDN) Sunehag et al. [2017]. Therefore, we opt to test using Hard and Super Hard scenarios. In past SMAC experiments Samvelyan et al. [2019], QMIX achieves a 0% win rate in three Super Hard scenarios: *corridor*, *3s5z_vs_3s5z*, and *6h_vs_8z*, and so it is meaningful to test on them. In Sec. 5, we also leverage two Purely Cooperative Predator-Prey (Appendix A) games to test the algorithms.

3.2 EVALUATION METRIC

Our primary evaluation metric is the function that maps the steps for the environment observed throughout the training to the median winning percentage (episode return for Predator-Prey) of the evaluation. We repeat each experiment with many independent training runs; results include median performance and percentiles ranging from 25% to 75%. We run the experiment 5 times independently in SMAC.

Our goal is to obtain as many samples from the environments as possible quickly so that we can accurately evaluate the convergence of each algorithm. Therefore, we use **eight rollout processes** for parallel sampling [1].

4 IMPORTANCE OF TRICKS

An implementation trick is an optimization in code that is unaccounted for in the experimental design, but that may significantly affect the result. Our overarching goal is to understand the isolated performance of these MADRL algorithms more deeply. Therefore, we perform analysis on critically important settings and provide some suggestions for tuning.

[1] Our experiments can collect 10 million samples within 9 hours with a Core i7-7820X CPU and a GTX 1080 Ti GPU.

4.1 OPTIMIZATION

Study description. QMIX and most of its variant algorithms use RMSProp to optimize neural networks because it proves stable in SMAC. However, lack of momentum may slow convergence of the network. We try to use Adam to optimize QMIX's neural network:

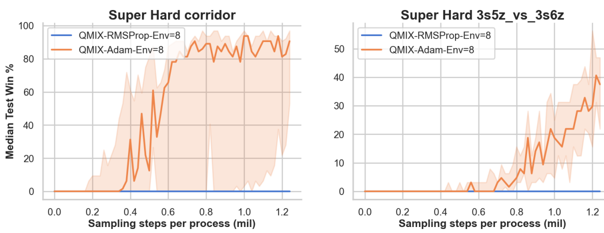

Figure 2: Eight rollout processes are used for sampling; samples are updated quickly. Adam significantly improves performance.

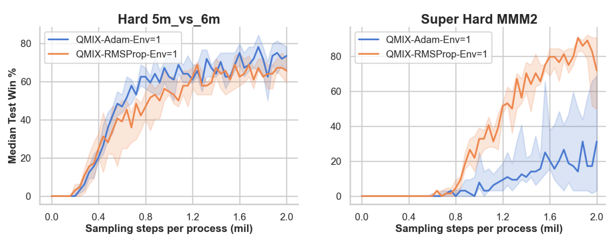

Figure 3: Only one rollout process is used for sampling; samples are updated slowly. The neural network optimized by Adam is prone to overfitting.

Interpretation. Figure 2 shows that Adam Kingma and Ba [2014] increases win rate by 100% on the Super Hard map *corridor*. This is because Adam boosts the network's convergence, allowing for full utilization of the large quantity of samples sampled in parallel. However, Figure 3 shows that when we only use one sampling process, the samples are updated slower than with eight processes (the replay buffer size is fixed), and the neural network becomes prone to overfitting.

Recommendation. Use Adam and quickly update the samples.

4.2 ELIGIBILITY TRACES

Study description. Eligibility traces such as TD(λ) Sutton and Barto [2018], Q(λ) Peng and Williams [1994], and TB(λ) Precup [2000] achieve a balance between return-based algorithms (where return refers to the sum of discounted rewards $\sum_t \gamma^t r_t$) and bootstrap algorithms (where return refers to $r_t + V(s_{t+1})$), speeding up the convergence of reinforcement learning algorithms. Therefore, we study the application of Q(λ) in QMIX:

Q(λ) can be expressed as Eq. 11:

$$\begin{aligned} G_s^\lambda &\doteq (1-\lambda)\sum_{n=1}^{\infty}\lambda^{n-1}G_{s:s+n} \\ G_{s:s+n} &\doteq \sum_{t=s}^{s+n}\gamma^{t-s}r_t + \gamma^{n+1}\max_u Q\left(x_{s+n+1}, u\right) \end{aligned} \tag{11}$$

where λ is the discount factor of the traces and $(\prod_{s=1}^{t}\lambda) = 1$ when $t = 0$. When λ is set to 0, it is equivalent to 1-step bootstrap returns. When λ is set to 1, it is equivalent to Monte Carlo Sutton and Barto [2018] returns.

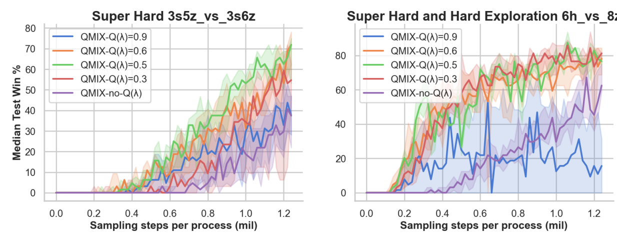

Figure 4: Q(λ) significantly improves performance of QMIX, but large values of λ lead to instability in the algorithm.

Interpretation. The Q networks without sufficient training usually have a large bias that impacts bootstrap returns. This is particularly the case in QMIX because its monotonicity condition limits the model's expressiveness. Figure 4 shows that Q(λ) allows for faster convergence in our experiments by reducing this bias. However, large values of λ may lead to failed convergence due to variance and off-policy bias. Figure 4 shows that when λ is set to 0.9, it has a detrimental impact on the performance of QMIX.

Recommendation. Use Q(λ) with a small value of λ.

4.3 REPLAY BUFFER SIZE

Study description. In Atari games and DQN, the experience replay buffer size is usually set to a large value. However, in multi-agent tasks, as the action space becomes larger than that of single-agent tasks, the distribution of samples changes more quickly. Therefore, we study the impact of the replay buffer size on the performance of QMIX.

Interpretation. Figure 5 shows that a large replay buffer size makes QMIX's learning unstable. The causes of this phenomenon are as follows:

1. In multi-agent tasks, samples become obsolete faster than in single-agent tasks.
2. As we discussed in Sec. 4.1, Adam performs better with samples with fast updates.
3. Q(λ) converges more effectively with new samples than with old samples.

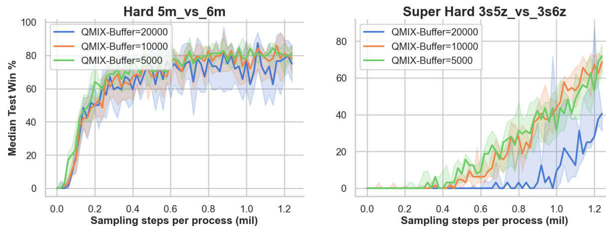

Figure 5: Setting the replay buffer size to 5000 episodes allows for QMIX's learning to be more stable than by setting it to 20000 episodes.

Recommendation. Use a small replay buffer size.

4.4 ROLLOUT PROCESS NUMBER

Study description. When we collect samples in parallel as is done in Advantage Actor-Critic (A2C), Stooke and Abbeel [2018] shows that when there is a defined total number of samples and either an inconsistent or an unspecified number of rollout processes, the median test performance becomes inconsistent. This study aims to understand the impact of the number of processes on the final performance.

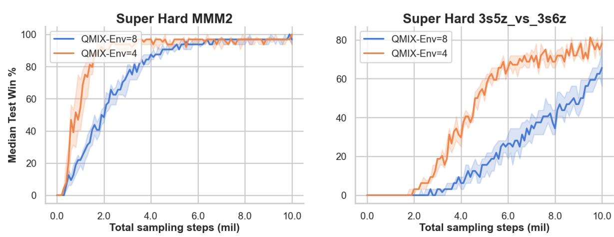

Figure 6: The results show that, given the total number of samples, fewer processes achieve better performance. We set the replay buffer size to be proportional to the number of processes to ensure that the novelty of the samples is consistent.

Interpretation. Under the A2C Mnih et al. [2016] training paradigm, the total number of samples can be calculated as follows:

$$S = E \cdot P \cdot I \tag{12}$$

S is the total number of samples, E is the number of samples in each episode, P is the number of rollout processes, and I is the number of policy iterations. Figure 6 shows that we are given both S and E; the fewer the number of rollout processes, the greater the number of policy iterations Sutton and Barto [2018]; a higher number of policy iterations leads to an increase in performance. However, this also causes both longer training time and decreased stability.

Recommendation. Use fewer rollout processes when samples are difficult to obtain; otherwise, use more rollout processes.

4.5 EXPLORATION STEPS

Study description. In SMAC, some scenarios are hard to explore, such as $6h\_vs\_8z$, so the settings of ε-greedy become critically important. In this study, we analyze the effect of ε anneal period on performance:

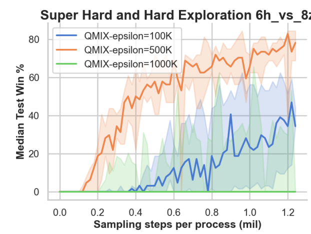

Figure 7: On the hard-to-explore scenario $6h\_vs\_8z$, a proper length of ε anneal period significantly improves performance.

Interpretation. As shown in Figure 7, increasing the length of the ε anneal period from 100K steps to 500K steps allows for a 38% increase in win rate in the Super Hard Exploration scenario $6h\_vs\_8z$. However, increasing it to 1000K will instead cause the model to collapse.

Recommendation. Increase the length of the ε anneal period to an appropriate length on hard-to-explore scenarios.

4.6 BONUS: REWARDS SHAPING

Study description. Table 1 shows the edge case that QMIX cannot solve. However, the reward function in MADRL is set by the users; we investigated whether QMIX could learn a correctly argmax by reshaping the task's reward function without changing its goal.

12.0	-0.5	-0.5
-0.5	0	0
-0.5	0	0

(a) Reshaped Payoff matrix

12.0	-0.3	-0.3
-0.3	-0.3	-0.3
-0.3	-0.3	-0.3

(b) QMIX: Q_{tot}

Table 3: A non-monotonic matrix game which we reshaped the reward (replace the insignificant reward -12 (in Table 1) with reward -0.5). QMIX can learn an Q_{tot} which has an correct argmax. Bold text indicates the reward of the argmax.

Interpretation. Because the reward -12 in Table 1 does not help the agents to get the optimal solution, as shown in Table 3, this non-monotonic matrix can be solved by simply replacing the insignificant reward -12 with -0.5. The reward shaping trick can also help QMIX learn better in other tasks, somewhat non-monotonicity.

Recommendation. Amplify the important rewards of the task and reduce the rewards that may cause disruption.

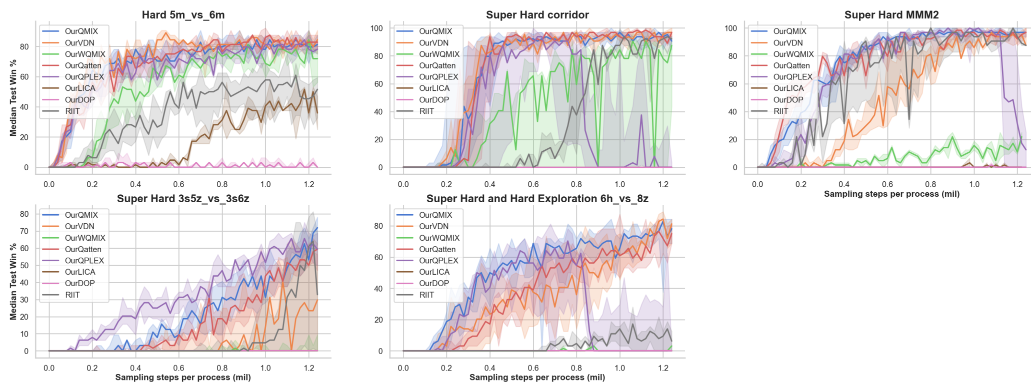

Figure 8: Median test win rate of SOTA MADRL algorithms. After unifying settings to leverage each of these tricks, QMIX achieves the best performance among all algorithms.

4.7 TRICKS OVERALL IMPACT

As Table 4 shows, after adding the tricks we mentioned before, OurQMIX ('Our' as in our customized settings) attains extraordinarily high win rates in all hard and super hard SMAC scenarios, far exceeding the Vanilla-QMIX.

Senarios	Difficulty	Vanilla-QMIX	OurQMIX
5m_vs_6m	Hard	84%	**90%**
3s_vs_5z	Hard	96%	**100%**
bane_vs_bane	Hard	**100%**	**100%**
2c_vs_64zg	Hard	**100%**	**100%**
corridor	Super Hard	0%	**100%**
MMM2	Super Hard	98%	**100%**
3s5z_vs_3s6z	Super Hard	3%	**85%** (env=4)
27m_vs_30m	Super Hard	56%	**100%**
6h_vs_8z	Super Hard	0%	**93%** (λ=0.3)

Table 4: Test results of OurQMIX and Vanilla-QMIX in all hard scenarios. These tricks tremendously improve upon QMIX's performance.

5 RETHINKING AND ANALYSIS

With an understanding of these tricks' effects, we start to rethink their impact on some important conclusions. We organized this section into four parts: (1) Retest these SOTAs based on fair experimental settings, which ensures the same tricks we mentioned before. (2) Rethinking the problem: Does the monotonicity condition limit the performance of cooperative algorithms? Then we propose a simple algorithm: RIIT, to verify the importance of the monotonicity condition. RIIT also achieves the SOTA in policy-based algorithms. (3) We prove theoretically that monotonic mixing networks can represent purely Cooperative Tasks (Def. 5.4).

5.1 OUR BENCHMARKS

Due to these algorithms use different standards and implementation tricks in experiments (as shown in B), making it difficult for researchers to evaluate the algorithms' isolated performance, we firstly define and unify the settings used across the following experiments:

1. We adjust the network size of each algorithm to a reasonable size.
2. We use Adam with a large batch size to optimize the neural networks of each algorithm.
3. To accelerate the convergence of the model, we use eligibility traces to estimate the TD target value for each algorithm.
4. We show all other changes made to the settings of these algorithms in Appendix B (Table 6 and 7).

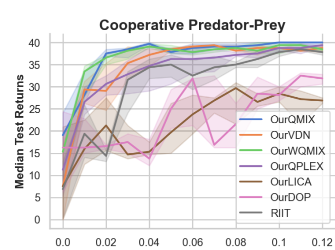

Figure 9: Median episode return of SOTA algorithms on Cooperative Predator-Prey (Appendix A). All these algorithms achieve good performance.

We then retest these SOTAs based on the new settings; to ensure fairness, we did not use the best hyperparameters of QMIX to compare with other algorithms. As shown in Table 5, the test results actually indicate that WQMIX and Qatten in isolated form lead to lower performance than QMIX. Figure 8 shows that QPLEX's policy collapses in the test of Super Hard $6h\_vs\_8z$ and *corridor*. Excitingly, the convergence of QPLEX is faster than QMIX in $3s5z\_vs\_3s6z$,

Algorithms	Mixing Net Size	*5m_vs_6m*	*3s5z_vs_3s6z*	*corridor*	*6h_vs_8z*	*MMM2*	*Cooperative Predator-Prey*
OurQMIX (VB)	41K	**90%**	**75%**	**100%**	84%	**100%**	**40**
OurVDN (VB)	0K	**90%**	43%	98%	**87%**	96%	39
OurQatten (VB)	58K	**90%**	62%	**100%**	68%	**100%**	-
OurQPLEX (VB)	152K	**90%**	68%	96%	78%	**100%**	39
OurWQMIX (VB)	247K	**90%**	6%	96%	78%	23%	39
OurLICA (PG)	208K	53%	0%	0%	3%	0%	30
OurDOP (PG)	122K	9%	0%	0%	0%	0%	32
RIIT (PG)	69K	62%	68%	**100%**	19%	**100%**	38

Table 5: Median test win rate (episode return) of SOTA MADRL algorithms. PG denotes Policy-gradient; VB denotes Value-based. The Mixing(Critic) Net size is calculated under $6h\_vs\_8z$.

which we believe comes from its complex attention mechanism and a large number of parameters. Figure 8 and Table 5 also show that when sample size and network size are reduced, LICA has terrible performance; Figure 9 and and Table 5 shows all these algorithms achieved good performance on Cooperative Predator-Prey. Surprisingly, the baseline QMIX achieves SOTA in these cooperative tasks, and the simplest VDN [2] also works pretty well.

5.2 ALBATION STUDY OF MONOTONICITY

Therefore, based on the following facts:

1. Table 5 shows these new algorithms have weaker monotonicity condition and do not have better performance than QMIX and VDN ($6h\_vs\_8z$).
2. de Witt et al. [2020] shows that the monotonicity condition attains performance boosts in continuous cooperative tasks (the Continuous Predator-Prey and Multi-agent Mujoco de Witt et al. [2020]).

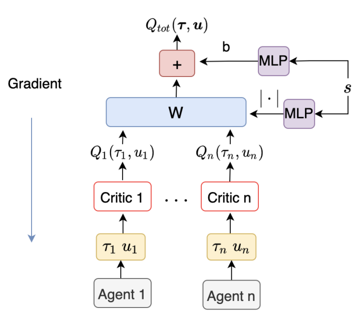

Figure 10: Architecture for RIIT. $|\cdot|$ **denotes absolute value operation**, implementing the monotonicity condition of QMIX. W denotes the nonnegative mixing weights.

We speculate that the monotonicity condition is significant for some cooperative tasks. To further verify the importance of monotonicity and improve the performance of policy-based algorithms. We propose a new end-to-end off-policy policy-based algorithm combine LICA with a monotonic mixing network; i.e., we make the following optimizations based on LICA:

1. Replace the policy mixing critic in LICA with **monotonic mixing critic**, as shown in Figure 10.
2. First, use **offline samples** to only train the critic network with 1-step TD error loss.
3. Then, use **online samples** to train actor end-to-end (by Eq.10) and critic with TD(λ).

This algorithm decomposes training into offline and online phases; it is named RIIT. Training actors with online samples improves learning stability [3]. Furthermore, the offline training phase improves sample efficiency for the critic network. Since RIIT is trained end-to-end, it can also be used for continuous control tasks. Figure 11 and 12 demonstrate that the monotonicity condition significantly improves the performance of RIIT, which also supports our speculation. Table 5 also shows that RIIT performs best among all policy-based multi-agent algorithms.

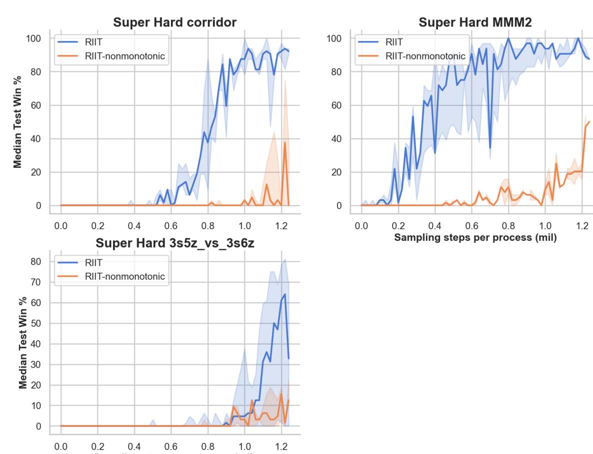

Figure 11: Comparing RIIT and RIIT without monotonicity condition (remove absolute value operation) on SMAC.

[2] VDN requires that $Q_{tot} = \sum_i^N Q_i$ holds.

[3] Cobbe et al. [2020] shows that actor-networks generally have a lower tolerance for sample reuse than the critic network

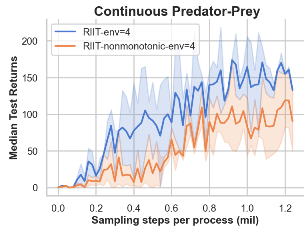

Figure 12: Comparing RIIT and RIIT without monotonicity condition (remove absolute value operation) on Continuous Predator-Prey de Witt et al. [2020].

5.3 THEORETICAL ANALYSIS

We find that the monotonicity condition is important in Super Hard scenarios of SMAC. To better understand this phenomenon, we performed a theoretical analysis of the monotonicity condition:

Definition 5.1. ***Cooperative tasks.*** *For a task with N agents ($N > 1$), all the agents have a common goal.*

Assumption 5.1. *For a cooperative task with N agents, marked as a set of agents $\mathbb{N}$. Given the true state s, the global Q_{tot} can be represented by a nonlinear mapping of individual $Q_i, i \in \mathbb{N}$, i.e., $Q_{tot} = f_\phi(s; Q_1, Q_2, ...Q_N)$.*

Definition 5.2. ***Hu's Cooperative tasks.*** *Given a cooperative task with a set of agents $\mathbb{N}$. For all states s of the task, if there is a subset $\mathbb{K} \subseteq \mathbb{N}$, $\mathbb{K} \neq \varnothing$, the $Q_i, i \in \mathbb{K}$ increases while the others $Q_j, j \notin \mathbb{K}$ are fixed, then this will lead to an increase in Q_{tot}.*

Intuitively, it's hard to find a cooperative task that isn't Hu's cooperative task in real life.

Definition 5.3. ***Competitive*** *For agents i and j, we say that agents i and j are competitive if an increase in Q_i leads to a decrease in Q_j or an increase in Q_j leads to a decrease in Q_i.*

Definition 5.4. ***Purely Cooperative Tasks.*** *The Hu's cooperative tasks without competitive cases.*

Proposition 5.1. *Purely Cooperative Tasks can be represented by the monotonic mixing networks.*

Proof. For a Hu's cooperative task, if there is a case (state s) that cannot be represented by a monotonic mixing network, i.e., $\frac{\partial Q_{tot}(s)}{\partial Q_i} < 0$. An increase in the Q_i must lead to a decrease in a $Q_j, j \neq i$ (since there is no Q_j decrease, by Def. 5.2 the condition $\frac{\partial Q_{tot}(s)}{\partial Q_i} < 0$ does not hold). Therefore, by Def. 5.3 this cooperative task has a competitive case which means it is not a Purely Cooperative Task. □

Since the SMAC gives agents rewards for hitting or killing enemies and for victory, the SMAC is a Purely Cooperative Task. Then, as shown in Figure 13, (1) the outermost circle indicates the parameter space without any constraints; (2) by Proposition 5.1, the optimal solutions of Purely Cooperative Tasks and the parameter space with the monotonicity condition are highly overlapping. Therefore, the monotonicity condition avoids searching for the optimal solution in invalid parameter space and significantly improves the sample efficiency.

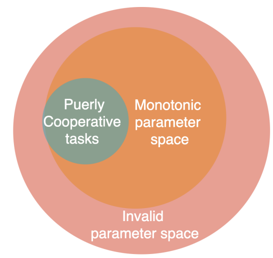

Figure 13: The relationship between monotonic parameter space (monotonic mixing network) and Puerly Cooperative Tasks.

6 RELATED WORKS

The work most closely related to our paper is probably Engstrom et al. [2020], which investigates code-level optimizations based on PPO Schulman et al. [2017] code and concludes that the majority of performance differences between PPO and TRPO originate from code tricks. Andrychowicz et al. [2020] investigates the influence of tricks on the performance of PPO and provides tuning optimizations.

7 CONCLUSION

In this study, we investigate the influence of tricks on the performance of QMIX and provides tuning optimizations. Furthermore, we find QMIX's monotonicity condition helps improve sample efficiency in some cooperative tasks, and we propose the new policy-based algorithm called: RIIT (Sec. 5.2) achieves SOTA among policy-based algorithms and also supports the importance of the monotonicity condition. At last, we prove theoretically that the Purely Cooperative Tasks (Def. 5.4) can be represented by the monotonic mixing networks.

A COOPERATIVE PREDATOR-PREY

de Witt et al. [2020] shows the monotonicity constraints improve the performance of FacMADDPG in the Continuous Predator-Prey de Witt et al. [2020], which is purely cooperative. However, the variant of Predator-Prey (from Böhmer et al. [2020]) in WQMIX is somewhat competitive (penalties are given if only one predator catches the prey

Algorithms	LICA	**OurLICA**	DOP	**OurDOP**	RIIT
Optimizer	Adam	**Adam**	RMSProp	**Adam**	Adam
Batch Size(episodes)	32	32	Off=32, On=32	**Off=64, On=32**	Off=64, On=32
Eligibility traces	TD(λ=0.8)	**TD(λ=0.6)**	TD(λ=0.8), TB(λ=0.93)	**TD(λ=0.6), TB(λ=0.9)**	TD(λ=0.6)
Exploration	Adapt Ent=0.06	Adapt Ent=0.06	Anneal Noise=500K steps	**Adapt Ent=0.0005**	Adapt Ent=0.03
Critic-Net Size	29696K	**208K**	122K	122K	69K
Rollout Processes	32	**8**	4	**8**	8

Table 6: Setting of Policy-based algorithms.

Algorithms	Vanilla-QMIX	**OurQMIX**	Qatten	**OurQatten**	QPLEX	**OurQPLEX**	WQMIX	**OurWQMIX**
Optimizer	RMSProp	**Adam**	RMSProp	**Adam**	RMSProp	**Adam**	RMSProp	**Adam**
Batch Size (epi.)	128	**128**	32	**128**	32	**128**	32	**128**
Q(λ)	0	**0.6**	0	**0.6**	0	**0.6**	0	**0.6**
Attention Heads	-	-	4	4	10	**4**	-	-
Mixing-Net Size	41K	41K	58K	58K	476K	**152K**	247K	247K
ε Anneal Steps				50K → **500K for** $6h\_vs\_8z$**, 100 K for others**				
Rollout Processes	8	**8**	1	**8**	1	**8**	1	**8**

Table 7: Setting of Value-based algorithm.

(not two predators at the same time)) [4]. For the Cooperative Predator-Prey, we remove the above penalties in the variant of Predator-Prey (from Böhmer et al. [2020]) to ensure that the environment is purely cooperative.

B OMITTED SETTINGS

B.1 EXPERIMENTAL FAIRNESS

The implementation tricks and comparison standards of these SOTA MADRL algorithms are inconsistent; some of these tricks are shown below:

1. DOP sets its number of processes to half that of QMIX to get more policy iterations
2. LICA uses Adam to optimize the network, while RMSProp is used in QMIX to optimize the network.
3. The enormous critic network of LICA is thousands of times larger than the mixing network of QMIX. Also, the mixing network of WQMIX and QPLEX are five and ten times larger, respectively, than that of QMIX.
4. LICA and DOP use eligibility traces to estimate TD target values but unfairly make a direct comparison with the performance of QMIX, which does not use eligibility traces.
5. QPLEX uses the 'buffer warmup', which means to start training the network after the specified number of samples in the replay buffer is reached.
6. These SOTA algorithms select test scenarios that specifically give them starting advantages or avoid the scenarios in which they fail.

We unify these settings for experimental fairness, and we avoided using the best hyperparameters of QMIX to compare with other algorithms. Table 6 and 7 shows our settings for the these algorithms. The network size is calculated under $6h\_vs\_8z$, and 'Our' denotes the new settings.

B.2 LEARNING RATE AND OTHER SETTINGS

For LICA, we set the learning rate of the agent network to 0.0025 and the critic network's learning rate to 0.0005. For DOP, we set the agent network's learning rate to 0.0005 and the learning rate of the critic network to 0.0001. For RIIT, we set the learning rates of neural networks to 0.001. For the Cooperative Predator-Prey, we set Adaptive Entropy to 0.06 for LICA and RIIT.

For all value-based algorithms, the neural networks are trained with 0.001 learning rate, and we use ε-greedy action selection, decreasing ε from 1 to 0.05 over n-time steps (n can be found in Table 7) for exploration. Also, we update the target network every 200 episodes. Specifically, we use OW-QMIX in WQMIX as the baseline.

All mixing networks and agent networks are the same as in QMIX Rashid et al. [2018]. For the discount factor, we set $\gamma = 0.99$. For SMAC, all the replay buffer size is set to 5000 episodes. For the Cooperative Predator-Prey, we set the buffer size to 1000 episodes and all λ to 0.5.

In the tuning stage, we experiment on more than five sets of settings for each algorithm. We use the StarCraft 2 Version: B75689 (SC2.4.10) in our experiments.

[4] The penalties make it necessary for two predators to capture or not to capture the prey at the same time. If a diligent predator prefers to capture the prey and the other lazy one does not, then their interests conflict.

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