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Bridging the performance-gap between target-free and target-based reinforcement learning

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Abstract

The use of target networks in deep reinforcement learning is a widely popular solution to mitigate the brittleness of semi-gradient approaches and stabilize learning. However, target networks notoriously require additional memory and delay the propagation of Bellman updates compared to an ideal target-free approach. In this work, we step out of the binary choice between target-free and target-based algorithms. We introduce a new method that uses a copy of the last linear layer of the online network as a target network, while sharing the remaining parameters with the up-to-date online network. This simple modification enables us to keep the target-free's low-memory footprint while leveraging the target-based literature. We find that combining our approach with the concept of iterated Q-learning, which consists of learning consecutive Bellman updates in parallel, helps improve the sample-efficiency of target-free approaches. Our proposed method, *iterated Shared Q-Learning* (iS-QL), bridges the performance gap between target-free and target-based approaches across various problems, while using a single Q-network, thus being a step forward towards resource-efficient reinforcement learning algorithms.

1 Introduction

Originally, Q-learning (Watkins & Dayan, 1992) was introduced as a reinforcement learning (RL) method that performs asynchronous dynamic programming using a single look-up table. By storing only one Q-estimate, Q-learning benefits from an up-to-date estimate and a low memory footprint. However, replacing look-up tables with non-linear function approximators and allowing off-policy samples to make the method more tractable introduces training instabilities (Sutton & Barto, 2018). To address this, Mnih et al. (2015) introduce Deep Q-Network (DQN), an algorithm that constructs the regression target from an older version of the online network, known as the *target network*, which is periodically updated to match the online network (see "Target Based" in Figure 1). This modification to the temporal-difference objective helps mitigate the negative effects of function approximation and bootstrapping (Zhang et al., 2021), two elements of the deadly triad (van Hasselt et al., 2018). Recently, new methods have demonstrated that increasing the size of the Q-network can enhance the learning speed and final performance of temporal difference methods (Espeholt et al., 2018; Schwarzer et al., 2023; Nauman et al., 2024; Lee et al., 2025). Numerous ablation studies highlight the crucial role of the target network in maintaining performance improvements over smaller networks (Figure 7 in Schwarzer et al. (2023), and Figure $9b$ in Nauman et al. (2024)). Interestingly, even methods initially introduced without a target network (Bhatt et al. (2024) and Kim et al. (2019)) benefit from its reintegration (Figure 5 in Palenicek et al. (2025) and Gan et al. (2021)).

While temporal difference methods clearly benefit from target networks, their utilization doubles the memory footprint dedicated to Q-networks. This ultimately limits the size of the online network due to the constrained Video Random Access Memory (VRAM) of GPUs. This limitation is not only problematic for learning on edge devices where memory is constrained, but also for applications that inherently require large network sizes, such as handling high-dimensional state spaces (Boukas et al., 2021; Pérez-Dattari et al., 2019), processing multi-modal inputs (Schneider et al., 2025), or constructing mixtures of experts (Obando Ceron et al., 2024; Hendawy et al., 2024). This motivates the development of target-free methods (see "Target Free" in Figure 1).

In this work, we introduce an alternative to the binary choice between target-free and target-based approaches. We propose storing only the smallest possible part of the target network, i.e., the

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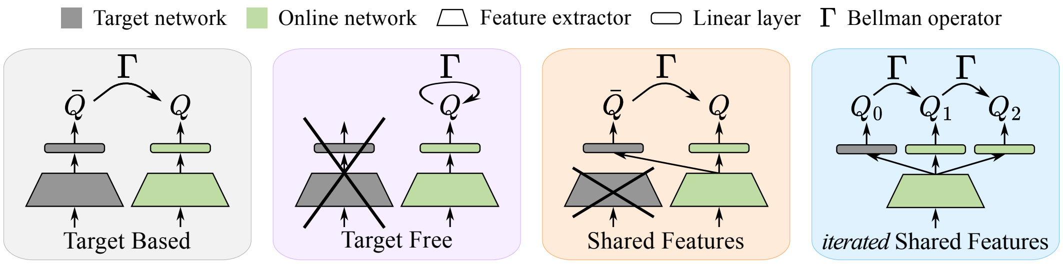

Figure 1: We propose a simple alternative to target-based/target-free approaches, where a linear layer represents the target network, sharing the rest of the parameters with the online network (Shared Features). We apply the concept of iterated Q-learning (Vincent et al., 2025), which consists of learning multiple Bellman updates in parallel, to reduce the performance gap between target-free and target-based approaches (*iterated* Shared Features).

parameters of the last linear layer, while using the parameters of the online network to substitute the other layers of the target network (see "Shared Features" in Figure 1). Although this simple modification alone helps reduce the performance gap between target-free and target-based DQN (see "iS-DQN $K = 1$" in Figure 4, right), we explain in this work how it opens up the possibility of leveraging the target-based literature to reduce this gap further, while maintaining a low memory footprint. Notably, this approach is also orthogonal to regularization techniques that have been shown to be effective for target-free algorithms (Kim et al., 2019; Bhatt et al., 2024; Gallici et al., 2025). Therefore, we will build upon these approaches to benefit from their performance gains.

In the following, we leverage the concept of iterated Q-learning (Vincent et al., 2025) to enhance the learning speed (in terms of number of environment interactions) of target-free algorithms. This concept, initially introduced as a target-based approach, aims at learning multiple Bellman iterations in parallel. This leads to a new algorithm, termed iterated Shared Q-Network (iS-QN), pronounced "ice-QN" to emphasize that it contains a frozen head. iS-QN utilizes a single network with multiple linear heads, where each head is trained to represent the Bellman target of the previous one (see "*iterated* Shared Features" in Figure 1). Our evaluation of iS-QN across various RL settings demonstrates that it improves the learning speed of target-free methods while maintaining a comparable memory footprint and training time.

2 Background

Deep Q-Network (Mnih et al., 2015) The optimal policy of a Markov Decision Process (MDP) with a discrete action space can be obtained by selecting for each state, the action that maximizes the optimal action-value function Q^*. This function represents the largest achievable expected sum of discounted rewards given a state-action pair. This is why Mnih et al. (2015) approximate the optimal action-value function with a neural network Q_θ, represented by a vector of parameters θ. This neural network is learned to approximate its Bellman iteration ΓQ_θ, leveraging the contraction property of the Bellman operator Γ to guide the optimization process toward the operator's fixed point, i.e., the optimal action-value function Q^*. In practice, a sample estimate of the Bellman iteration is used, where for a sample (s, a, r, s'), $\Gamma Q_\theta(s, a) = r + \gamma \max_{a'} Q_\theta(s', a')$, where γ is the discount factor linked to the MDP of interest. However, this learning procedure is unstable because the neural network Q_θ learns from its own values, which change at each optimization step due to function approximation, and because of the compound effect of the overestimation bias. To mitigate these issues, the authors introduce a target network with parameters $\bar{\theta}$ to stabilize the regression target $\Gamma Q_{\bar{\theta}}$, and periodically update these parameters to the online parameters θ every T steps. On the negative side, this doubles the memory footprint dedicated to Q-networks.

Iterated Q-Network (Vincent et al., 2025) By using a target network, DQN slows down the training process as multiple gradient steps are dedicated to each Bellman iteration, as $\Gamma Q_{\bar{\theta}}$ is delayed by some gradient steps compared to ΓQ_θ. To increase the learning speed, Vincent et al. (2025) propose to learn consecutive Bellman iterations in parallel. This approach uses a sequence of online parameters $(\theta_i)_{i=1}^K$ and a sequence of target parameters $(\bar{\theta}_i)_{i=0}^{K-1}$. Each online network $Q_{\theta_{i+1}}$ is trained to regress $\Gamma Q_{\bar{\theta}_i}$. Similarly to DQN, each target parameter $\bar{\theta}_i$ is updated to the online parameter θ_{i+1} every T steps. Importantly, the structure of a chain is enforced by setting each $\bar{\theta}_i$ to θ_i every

$D \ll T$ steps so that each $Q_{\theta_{i+1}}$, which is learned to regress $\Gamma Q_{\bar{\theta}_i}$, are forced to approximate ΓQ_{θ_i}. This results in $Q_{\theta_K} \approx \Gamma Q_{\theta_{K-1}} \approx \ldots \approx \Gamma^K Q_{\theta_0}$, thus learning K consecutive Bellman iterations in parallel. Importantly, DQN can be recovered by setting $K = 1$. While the feature representation can be shared across the online Q-networks, iterated Q-Network (i-QN) has the drawback of requiring an old copy of the online networks to stabilize training, significantly increasing the memory footprint. In the following, we will explain how the concept of i-QN can help reduce the performance gap between target-free and target-based approaches while maintaining a low memory footprint.

3 RELATED WORK

Other works have considered removing the target network in different RL scenarios. Vasan et al. (2024) introduce Action Value Gradient, an algorithm designed to work well in a streaming scenario where no replay buffer, no batch updates, and no target networks are available. Gallici et al. (2025) also develop a method for a streaming scenario, in which they rely on parallel environments to cope with the non-stationarity of the sample distribution. Gradient Temporal Difference learning is another line of work that does not use target networks (Sutton et al., 2009; Maei et al., 2009; Yang et al., 2021; Patterson et al., 2022; Elelimy et al., 2025). Instead, they compute the gradient w.r.t. the regression target as well as the gradient w.r.t. the predictions, which doubles the compute requirement. Additionally, to address the double sampling problem, another network is trained to approximate the temporal difference value, which also increases the memory footprint.

Alternatively, some works construct the regression target from the online network instead of the target network, but still use a target network in some other way. For example, Ohnishi et al. (2019) compute the TD(0) loss from the online network and add a term in the loss to constrain the predictions of the online network for the next state-action pair (s', a') to remain close to the one predicted by the target network. Piché et al. (2021; 2023) develop a similar approach, enforcing similar values for the state-action pair (s, a). Lindström et al. (2025) show that the target network can be removed after a pretraining phase in which they rely on expert demonstrations.

Many regularization techniques have been developed, attempting to combat the performance drop that occurs when removing the target network. We stress that our approach is orthogonal to these regularization techniques and we show in Section 5 that our method improves the performance of target-free methods equipped with these advancements. Li & Pathak (2021) encode the input of the Q-network with learned Fourier features. While this approach seems promising, the authors acknowledge that the performance degrades for high-dimensional problems. Shao et al. (2022) remove the target-network and search for an action that maximizes the Q-network predictions more than the action proposed by the policy. Searching for a better action requires additional resources and is only relevant for actor-critic algorithms. Kim et al. (2019) leverage the MellowMax operator to get rid of the target network. However, the temperature parameter needs to be tuned (Kim, 2020), which increases the compute budget, and a follow-up work demonstrates that the reintegration of the target network is beneficial (Gan et al., 2021). Finally, Bhatt et al. (2024) point out the importance of using batch normalization (Ioffe & Szegedy, 2015) to address the distribution shift of the input given to the critic. Our investigation reveals that it degrades the performance in a discrete action setting (see Figure 15, right).

The idea of learning multiple Bellman iterations has been introduced by Schmitt et al. (2022). They demonstrate convergence guarantees in the case of linear function approximation. Then, Vincent et al. (2024) used this approach to learn a recurrent hypernetwork generating a sequence of Q-functions where each Q-function approximates the Bellman iteration of the previous Q-function. Finally, Vincent et al. (2025) introduced iterated Q-Network as a far-sighted version of DQN that learns the K following Bellman iterations in parallel instead of only learning the following one. While promising, those approaches rely on a separate copy of the learnable parameters to stabilise the training process, which increases the memory footprint. In this work, we propose to leverage the potential of iterated Q-learning to boost the learning speed of target-free algorithms.

4 METHOD

Our goal is to design a new algorithm that improves the learning speed of target-free value-based RL methods without significantly increasing the number of parameters used by the Q-networks. To achieve this, we consider a *single* Q-network parameterized with $K + 1$ heads. We note ω_k the

Algorithm 1 *iterated* Shared Deep Q-Network (iS-DQN). Modifications to DQN are in purple.

Initialize a network Q_θ with $K+1$ heads, where each head is defined by the parameters ω_k. We note $\theta_k = (\omega, \omega_k)$, and ω the shared parameters such that $\theta = (\omega, \omega_0, .., \omega_K)$. $\mathcal{D}$ is an empty replay buffer.
Repeat
    Set $u \sim \texttt{Uniform}(\{1, .., K\})$.
    Take action $a \sim \epsilon$-greedy.$(Q_{\theta_u}(s, \cdot))$; Observe reward r, next state s'.
    Update $\mathcal{D} \leftarrow \mathcal{D} \bigcup \{(s, a, r, s')\}$.
    every G **steps**
        Sample a mini-batch $\mathcal{B} = \{(s, a, r, s')\}$ from $\mathcal{D}$.
        Store $[Q_0(s', \cdot), .., Q_K(s', \cdot)] \leftarrow Q_\theta(s', \cdot)$ and $[Q_0(s, a), .., Q_K(s, a)] \leftarrow Q_\theta(s, a)$.
        Compute the loss ▷ $\lceil \cdot \rceil$ indicates a stop gradient operation.
        $\mathcal{L}^{\text{iS-QN}} = \sum_{(s,a,r,s') \in \mathcal{B}} \sum_{k=1}^{K} (\lceil r + \gamma \max_{a'} Q_{k-1}(s', a') \rceil - Q_k(s, a))^2$.
        Update θ from $\nabla_\theta \mathcal{L}^{\text{iS-QN}}$.
    every T **steps**
        Update $\omega_k \leftarrow \omega_{k+1}$, for $k \in \{0, \ldots, K-1\}$.

parameters of the k^{th} head, ω the shared parameters, and define $\theta = (\omega, \omega_0, .., \omega_K)$ and $\theta_k = (\omega, \omega_k)$. Following Vincent et al. (2025), for a sample $d = (s, a, r, s')$, the training loss is

$$\mathcal{L}_d^{\text{iS-QN}}(\theta) = \sum_{k=1}^{K} \mathcal{L}_d^{\text{QN}}(\theta_k, \theta_{k-1}), \tag{1}$$

where $\mathcal{L}_d^{\text{QN}}$ can be chosen from any temporal-difference learning algorithm. For instance, DQN uses $\mathcal{L}_d^{\text{QN}}(\theta_k, \theta_{k-1}) = (\lceil r + \gamma \max_{a'} Q_{\theta_{k-1}}(s', a') \rceil - Q_{\theta_k}(s, a))^2$, where $\lceil \cdot \rceil$ indicates a stop gradient operation. We stress that ω_0 is not learned. However, every T steps, each ω_k is updated to ω_{k+1}, similarly to the target update step in DQN. This way, iS-QN allows to learn K Bellman iterations in parallel while only requiring a small amount of additional parameters on top of a target-free approach. Indeed, in the general case, the size of each head ω_k is negligible compared to the size of shared parameters ω. Algorithm 1 summarizes the changes brought to the pseudo-code of DQN to implement this approach.

In Figure 2, we compare the training paths defined by the Q-functions obtained after each target update of the proposed approach (top) and the target-based approach (bottom). For each given sample, the target-based approach learns only 1 Bellman iteration at a time and proceeds to the following one after T training steps. In contrast, the iterated Shared Features approach learns several consecutive Bellman iterations in parallel for each given sample. The considered window also moves forward every T training steps. As the window shifts, the network represents Q-functions that are closer to the optimal Q-function since every Q-function is learned to represent the Bellman iteration of the previous Q-function. Similarly to the target-based and target-free approaches, the online parameters are updated with the gradient computed through the forward pass of the state-action pair (s, a), as indicated with blue arrows. In Figure 2, we depict our approach with $K = 2$. However, the number of heads can be increased at minimal cost. We note that the first Q-function is considered fixed in this representation, even if the head is the only frozen element and the previous layers are shared with the other learned Q-estimates. We remark that iS-QN with $K = 1$ implements the "Shared Features" approach presented in Figure 1. Interestingly, the target-free approach can also be depicted in Figure 2. Indeed, not using a target network is equivalent to updating the target network to the online network after each gradient step. Consequently, the target-free approach can be understood as the target-based representation with a window shifting at every step. Therefore, the target-free approach passes through the Bellman iterations faster, creating instabilities as the optimization landscape may direct the training path toward undesirable Q-functions.

In the following, we apply iterated Shared Features to several target-based approaches on multiple RL settings, demonstrating that it reduces the gap between target-free and target-based methods. For each algorithm A, we note TB-A as its target-based version, TF-A as its target-free version, and iS-A as the iterated shared approach, where "iS" stands for iterated Shared. Importantly, we incorporate the insights provided by Gallici et al. (2025) to use LayerNorm (Ba et al., 2016) for the

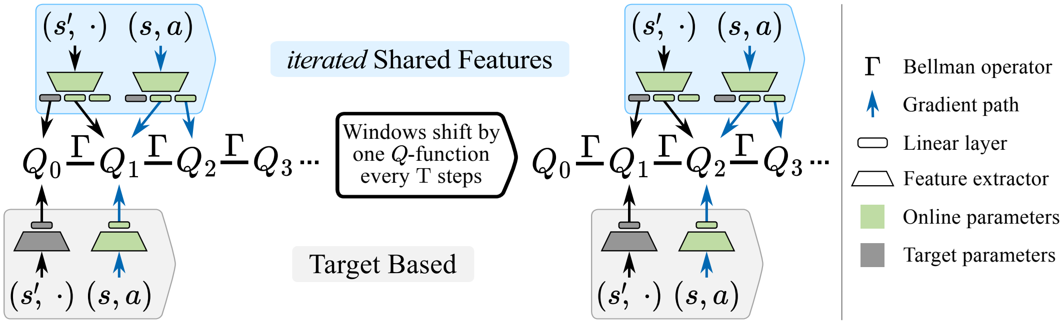

Figure 2: Comparison of the training path defined by the target networks obtained after each target update during training between the target-based approach (bottom) and the *iterated* Shared Features approach (top). While both approaches wait for T training steps before shifting their respective window by one Q-function, our approach already considers the following Bellman iterations using multiple heads, where each head represents the Bellman iteration of the previous head.

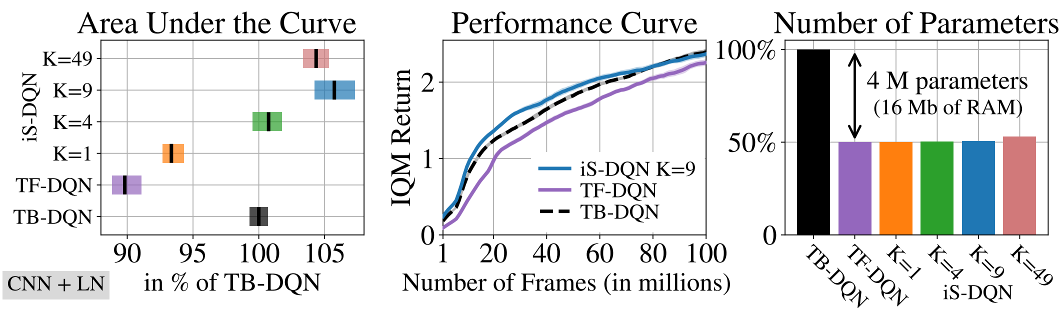

Figure 3: Reducing the performance gap in online RL on 15 **Atari** games with the CNN architecture and LayerNorm (LN). While removing the target network leads to a 10% drop in AUC (left), iS-DQN $K = 9$ (using 10 linear heads), not only closes the gap but improves over the target-based approach by 6%. Importantly, iS-DQN uses a comparable number of parameters to TF-DQN (right).

experiments with discrete action spaces, as we found it beneficial, even for the target-based approach. Similarly, we use BatchNorm (Ioffe & Szegedy, 2015), as suggested by Bhatt et al. (2024), to improve sample-efficiency in continuous action settings, except for the target-based approach, as it degrades performances (see Figure 19, right).

5 Experiments

We evaluate iS-QN in online, offline, continuous control, and language-based RL scenarios to demonstrate that it can enhance the learning speed of target-free methods. We focus on the learning speed because, in this work, we are interested in the sample efficiency of target-free methods. We use the Area Under the performance Curve (AUC) to measure the learning speed. The AUC has the benefit of depending less on the training length compared to the end performance, as it accounts for the performance during the entire training. It also favors algorithms that constantly improve during training over those that only emerge at the end of training, thus penalizing algorithms that require many samples to perform well. In each experiment, we report the AUC of each algorithm, normalized by the AUC of the target-based approach, to facilitate comparison. By normalizing the AUCs, the resulting metric can also be interpreted as the average performance gap observed during training between the considered approach and the target-based approach. We use the Inter-Quantile Mean (IQM) and 95% stratified bootstrapped confidence intervals to allow for more robust statistics as advocated by Agarwal et al. (2021). The IQMs are computed over 5 seeds per Atari game, 10 seeds per DMC Hard tasks, and 5 seeds for Wordle. 15 Atari games are used for the experiments on the CNN architecture, and 10 games for the experiments on the IMPALA architecture to reduce the computational budget. Importantly, all hyperparameters are kept untouched with respect to the standard values (Castro et al., 2018), only the architecture is modified, as described in Section 4. Extensive details about the selection process of the Atari games, the metrics computation, the hyperparameters, and the individual learning curves are reported in the appendix.

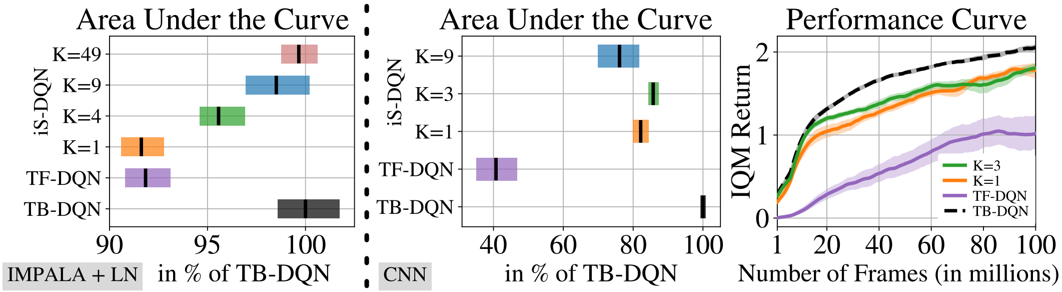

Figure 4: **Left**: Reducing the performance gap in online RL on 10 **Atari** games with the IMPALA architecture and LayerNorm (LN). Similar to the results with the CNN architecture, iS-DQN bridges the gap between the target-free and target-based approaches. **Middle** and **Right**: Reducing the performance gap in online RL on 15 **Atari** games with the CNN architecture. Removing the target network of the vanilla DQN algorithm results in a 60% performance drop ($100\% - 40\%$). By using iS-DQN with $K = 3$, the performance drop is divided by 4 ($100\% - 85\% = 15\% = 60\%/4$), thereby confirming the benefit of this approach.

5.1 Online Discrete Control

First, we evaluate iS-DQN on 15 Atari games (Bellemare et al., 2013) with the vanilla CNN architecture (Mnih et al., 2015) equipped with LayerNorm. As expected, the target-free approach yields an AUC 10% smaller than the target-based approach, as shown in Figure 3 (left). This performance drop is constant across the training, see Figure 3 (middle). Interestingly, iS-DQN $K = 1$ improves over TF-DQN by simply storing an old copy of the last linear head. As more Bellman iterations are learned in parallel, the performance gap between iS-DQN and TB-DQN shrinks. Remarkably, iS-DQN $K = 9$ even outperforms the target-based approach by 6% in AUC. We note a slight decline in performance for iS-DQN $K = 49$. We conjecture that this is due to the shared feature representation not being rich enough to enable the network to learn 49 Bellman iterations in parallel with linear approximations. Importantly, Figure 3 (right) testifies that this performance boost is achieved with approximately half of the parameters used by the target-based approach, truly reducing the memory footprint required by the Q-functions.

Our evaluation with the IMPALA architecture (Espeholt et al., 2018) with LayerNorm confirms the ability of iS-DQN to reduce the performance gap between target-free and target-based approaches. Indeed, Figure 4 (left) indicates that removing the target network leads to an 8% performance drop while iS-DQN annuls the performance gap as more Bellman iterations are learned in parallel, i.e., as K increases. Interestingly, as opposed to the CNN architecture, increasing the number of heads to learn 49 Bellman iterations in parallel is beneficial in this scenario. We believe this is due to IMPALA architecture's ability to produce a richer representation than the CNN architecture, thereby allowing more Bellman iterations to be approximated with a linear mapping. The plots of the performance curve and the number of parameters are similar to the ones for the CNN architecture, see Figure 13.

Finally, we confirm the benefit of the iterated Shared Features approach by removing the normalization layers for all algorithms with the CNN architecture in Figure 4 (right). We observe a major drop in performance for TF-DQN, leading to 60% performance gap ($100\% - 40\%$). Notably, iS-DQN $K = 1$ reduces this performance gap to 18% ($100\% - 82\%$). This highlights the potential of simply storing the last linear layer and using the features of the online network to build a lightweight regression target. While increasing the number of learned Bellman iterations to 3 brings a small benefit, the performances are slightly decreasing for higher values of K, indicating that LayerNorm is beneficial to provide useful representations when considering a higher number of linear heads.

5.2 Offline Discrete Control

We consider an offline RL setting in which the agent has access to 10% of the dataset collected by a vanilla DQN agent trained with a budget of 200 million frames (Agarwal et al., 2020), sampled uniformly. We adapt the loss for learning each Bellman iteration to the one proposed by Kumar et al. (2020b). This leads to an iterated version of Conservative Q-Learning (CQL). In Figure 5, iS-CQL $K = 9$ reduces the performance gap by 20 percentage points, ending up with a performance gap

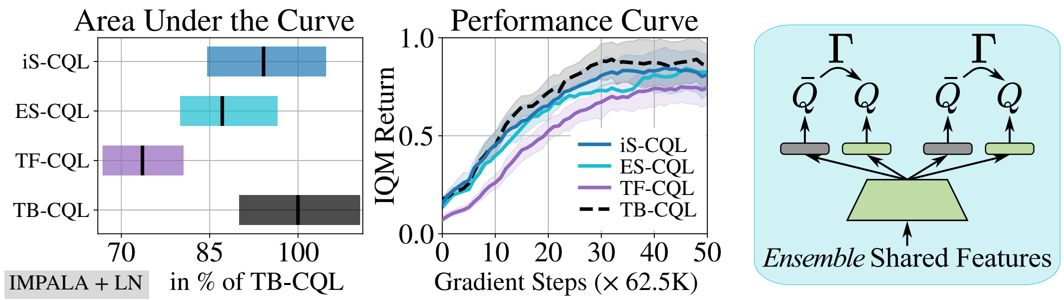

Figure 5: Reducing the performance gap in offline RL on 10 **Atari** games with the IMPALA architecture and LayerNorm (LN). iS-CQL shrinks the performance gap from 26% to 6%. Interestingly, applying the idea of sharing parameters to Ensemble DQN (*Ensemble* Shared Features, ES-CQL) also reduces the performance gap, demonstrating that this idea is not limited to iterated Q-learning and can be applied to other target-based approaches.

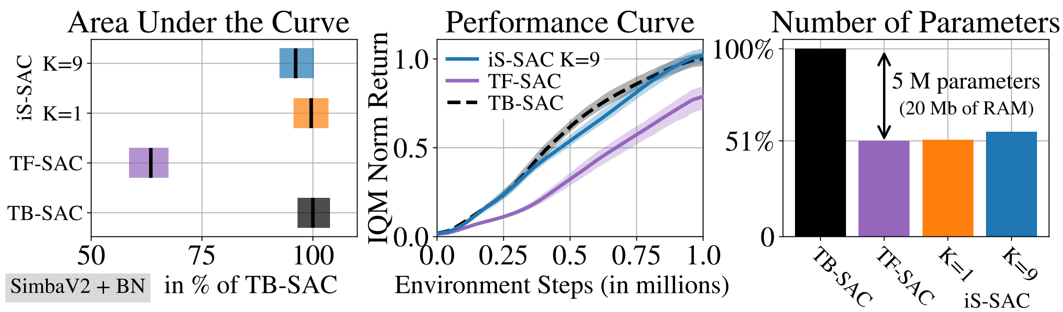

Figure 6: Reducing the performance gap in online RL on the 7 **DMC Hard** tasks with the SimbaV2 architecture and BatchNorm (BN). iS-SAC recovers the performance drop incurred by removing the target network (left). This performance boost is made while reducing the *total* number of parameters by 49% (right).

of 6% compared to 26% for TF-CQL. Additionally, we evaluate another way of sharing features to show that this idea is not limited to iterated Q-learning. Instead of building a chain of Q-functions represented by linear heads, we define an ensemble of pairs of linear heads. Each pair contains a frozen head representing a target network $\bar{Q}$ that is used to train the learned head representing the associated online network Q, as depicted in Figure 5 (right). We evaluate this variant that we call Ensemble Shared Features (ES-CQL), with 5 pairs of heads, i.e. 10 heads, to match the number of heads used by iS-CQL $K = 9$, as the number of heads of iS-QN is always equal to $K + 1$. Importantly, ES-CQL also outperforms TF-CQL, reinforcing the idea that sharing parameters and using linear heads is a fruitful direction.

5.3 Online Continuous Control

We investigate the behavior of iS-QN on the DeepMind Control suite (Tassa et al., 2018), focusing on the hard tasks. We select Soft Actor-Critic (SAC, Haarnoja et al. (2018)) as the base algorithm and adapt the architecture to the one proposed by Lee et al. (2025) (SimbaV2) so that the target-based approach corresponds to the state-of-the-art. This experiment allows us to test iS-QN on different learning dynamics, as the target updates are done with an exponentially moving average instead of a hard update, and the loss for the critic uses a categorical distribution to learn the distribution of the return. Interestingly, Figure 6 (left) shows that only using an old copy of the last layer of the critic to construct the regression target (iS-SAC $K = 1$) recovers the performance drop incurred by the target-free approach compared to the target-based approach. Importantly, Lee et al. (2025) design the critic with significantly more parameters than the actor, as commonly done in the actor-critic literature (Mysore et al., 2021; Mastikhina et al., 2025). This means that iS-SAC K=1 reduces the *total* number of parameters by 49%, see Figure 6 (right). When considering more heads to learn the following Bellman updates, we find it beneficial to give more importance to the first Bellman

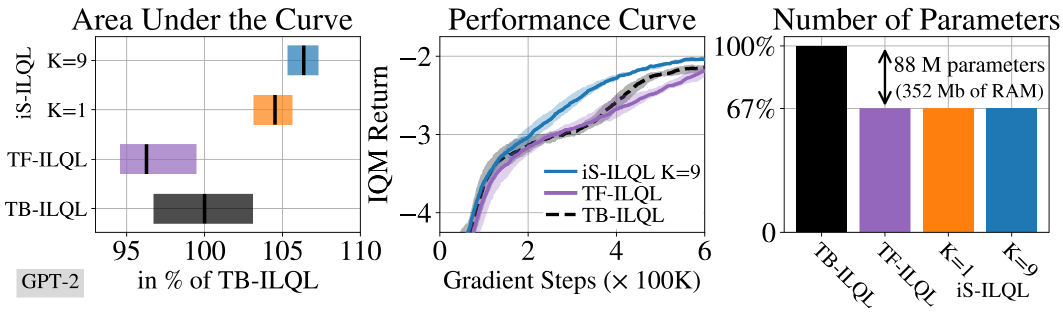

Figure 7: Reducing the performance gap in offline RL on **Wordle** with the GPT-2 small architecture. iS-ILQL $K = 9$, not only closes the gap but improves over the target-based approach by more than 5%. Importantly, iS-ILQL saves 33% of RAM compared to the target-based approach (right).

updates by scaling the future terms in the loss by a discounting factor of 0.25. We note that in this setting, iS-SAC $K = 9$ only performs on par with $K = 1$. Nonetheless, iS-SAC $K = 9$ is still performing better than the best target-free approach, having overlapping confidence intervals with the target-based approach, which serves as the goal standard, as it requires additional parameters.

5.4 Scaling Up to Language Models

In this experiment, we evaluate iS-QN on an offline RL language processing task. Specifically, we focus on Implicit Language Q-Learning (ILQL, Snell et al. (2023)), a method introduced with a target network. It adapts implicit Q-learning (Kostrikov et al., 2023) to the language domain by sampling action tokens from a policy, learned with supervised learning, and weighted by the advantage computed from the Q-function. We evaluate ILQL on the Wordle game (Lokshtanov & Subercaseaux, 2022), a multi-turn game where the agent guesses a hidden word and receives feedback after each attempt. As in Snell et al. (2023), we choose the GPT-2 small architecture, which results in TB-ILQL using 264 million parameters. In Figure 7 (left), we note that while a performance drop is noticeable, the target-free approach does not perform significantly worse than the target-based variant. Importantly, sharing parameters and learning $K = 9$ Bellman iterations in parallel improves the learning speed of the target-free approach by 10% without significantly increasing the memory footprint. This leads iS-QN to save 88 million parameters compared to the original approach.

5.5 Why is iS-QN improving over target-free approaches?

We now provide some insights to understand why iS-QN reduces the performance gap between target-free and target-based approaches. First, we investigate the change in the learning dynamics that happens when the features are shared between the online and the target heads ("Shared Features" or equivalently, "*iterated* Shared Features" with $K = 1$, see Figure 1). To evaluate the impact on the learning dynamics, we compute, for each gradient step of an iS-DQN $K = 1$ agent, the gradient with respect to the loss of iS-DQN, as well as the gradients that the target-based loss and the target-free loss would produce. These quantities determine how the parameters evolve during training. We then report the cosine similarity between the gradients w.r.t. the iS-QN loss and the TB-DQN loss, and the cosine similarity between the gradients w.r.t. the TF-DQN loss and the TB-DQN loss in Figure 8 (left) for 15 Atari games. Interestingly, the gradients obtained by the target-based approach are closer to the gradients of iS-DQN $K = 1$ than the gradients of the target-free approach, especially at the beginning of the training. This means that by simply using a copy of the last linear layer and sharing features, iS-DQN's learning dynamics become closer to those of the target-based approach.

At first sight, the fact that iS-QN uses frozen heads on top of features changing at each gradient step might seem like an uncommon practice in machine learning. However, this design choice is already part of the reinforcement learning literature. Indeed, in Deep Q-Network, the Q-network is designed with multiple heads, each one representing the prediction for a specific action. For each sample, only the selected head corresponding to the sampled action is updated, while the other heads, built on top of the features that are getting updated, remain frozen. This is likely to contribute to the policy churn phenomenon identified by Schaul et al. (2022), highlighting that the greedy-policy changes for a significant proportion of the states in the replay buffer after a single batch update. To measure the impact of sharing features, we introduce the notion of *target churn*, which we define as the absolute value of the difference between the regression target before and after each batch update. We report

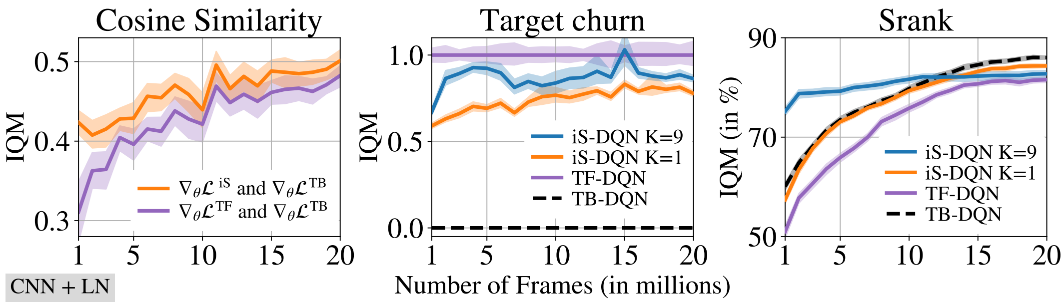

Figure 8: **Left**: The cosine similarity between the gradients w.r.t. the loss of iS-DQN and TB-DQN is larger than the cosine similarity between the gradients w.r.t. the loss of TF-DQN and TB-DQN. Therefore, iS-DQN brings the learning dynamics of the target-free approach closer to those of the target-based approach. **Middle**: The target churn is the difference between the regression targets computed before and after each batch update. The target predictions of iS-DQN are less influenced by batch updates than the ones computed from the target-free approach. **Right**: The effective rank (srank) of the features in the penultimate layer is higher for iS-QN, resulting in a higher expressivity.

the cumulative target churn of iS-DQN, reinitialized to zero after each target update, normalized by the target churn of TF-DQN in Figure 8 (middle). Conveniently, the target-based approach has a constant target churn of zero since the batch update does not influence the fully separated target network, and the normalization brings the target churn of the target-free approach to a constant value of 1. Remarkably, the target churn of iS-DQN $K = 1$ and 9 lies in between 0 and 1, indicating that iS-QN's targets are more stable than the ones of the target-free approach. We note that the target churn for $K = 9$ is larger than $K = 1$, due to the influence of the additional terms in the loss.

Beyond improving the learning dynamics of TF-DQN, iS-DQN also provides a richer state representation. We measure the representation expressivity by reporting the effective rank (srank) of the features in the penultimate layer (Kumar et al., 2020a) in Figure 8 (right). Interestingly, the srank obtained by iS-DQN $K = 1$ is closer to the srank of TB-DQN than the srank of TF-DQN, which further demonstrates the benefit of using the last linear layer to construct the target. Notably, learning $K = 9$ Bellman iterations in parallel increases the representation capacity of the network by a large margin. This behavior is also visible in the offline setting, where iS-CQL reaches a similar srank as the target-based approach at the end of the training (see Figure 17, middle). This confirms the benefit of iS-QN to foster a richer representational capacity.

6 Limitation and Conclusion

The proposed approach introduces the number of Bellman updates K to learn in parallel as a new hyperparameter and there seems to be a different optimal value for each setting. However, we observe that none of the values lead to a dramatic performance drop. In this work, we focus on reducing the memory footprint of the function approximators. Depending on the setting, other objects such as the replay buffer and the optimizer can occupy a large portion of the RAM. We remark that the proposed approach can be combined with other works addressing these issues (Vasan et al., 2024). Additionally, the proposed approach reduces the memory footprint during training but uses the same amount during inference, which is complementary to pruning methods that use more memory during training and less during inference (Graesser et al., 2022). As reported in Figure 10, iS-QN does not reduce the training time or the number of floating-point operations, except for the language processing task for which the temporal-difference error can be computed with a single pass through the network.

We introduced a simple yet efficient method for mitigating the performance drop that occurs when removing the target network in deep value-based reinforcement learning, while maintaining a low memory footprint. This is made possible by storing a copy of the last linear layer of the online network and using the features of the online network as input to this frozen linear head to construct the regression target. From there, more heads can be added to learn multiple Bellman iterations in parallel. We demonstrated that this new algorithm, iterated Shared Q-Networks, improves over the target-free approach and yields higher returns when the number of heads increases. We believe that combining iS-QN with pruning and/or quantization methods is a promising direction for future work to facilitate online learning on resource-constrained settings, without sacrificing performance.

REPRODUCIBILITY STATEMENT

Special care was taken to ensure this work is reproducible. **The code will be made open source upon acceptance** and is shared in the supplementary material. It contains the list of dependencies and their exact version that was used to generate the results. To ease reproducibility, all hyperparameters are listed in Appendix D, and the individual training curves are shown in Appendix E.

LARGE LANGUAGE MODEL USAGE

A large language model was helpful in polishing writing, improving reading flow, and identifying remaining typos.

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TABLE OF CONTENTS

A EXPERIMENT SETUP

Atari setup We build our codebase following Machado et al. (2018) standards and taking inspiration from Castro et al. (2018) codebase. Namely, we use the *game over* signal to terminate an episode instead of the life signal. The input given to the neural network is a concatenation of 4 frames in grayscale of dimension 84 by 84. To get a new frame, we sample 4 frames from the Gym environment (Brockman et al., 2016) configured with no frame-skip, and apply a max pooling operation on the 2 last grayscale frames. We use sticky actions to make the environment stochastic (with $p = 0.25$).

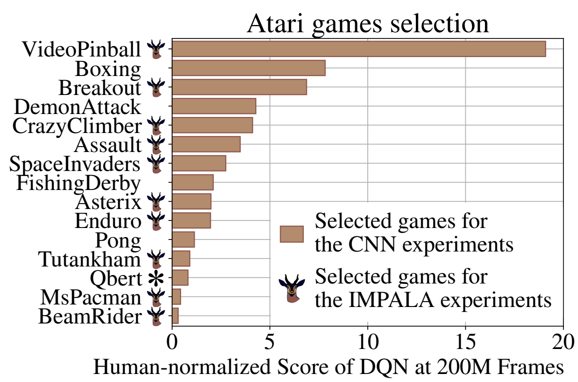

Figure 9: The Atari games selected for the experiments of this paper were chosen to cover a variety of normalized returns obtained by DQN after 200M frames. To lower the computational budget of the experiments with the IMPALA architecture, we reduced the set of games to 10 by removing 5 games, while maintaining diversity.

Atari games selection Our evaluations on the CNN architecture were performed on the 15 games recommended by Graesser et al. (2022). They were chosen for their diversity of Human-normalized score that DQN reaches after being trained on 200 million frames, as shown in Figure 9. As the IMPALA architecture increases the training length, we removed 5 games, while maintaining diversity in the final scores to reduce the computational budget. For the offline experiment, we used the datasets provided by Gulcehre et al. (2020). As the game *Tutankham* is not available in the released dataset, we replaced it with *Qbert*, indicated with an asterisk in Figure 9.

DeepMind Control suite setup Our codebase follows the implementation details of Lee et al. (2025). Before running the experiment presented in Section 5.3, we took special care that our codebase reproduces the evaluation performance shared by the authors. As a takeaway from this exercise, we note that the precision with which the state and reward are normalized matters, as using float32 leads to lower performance than using float64. We invite interested readers to examine our code for more details. We emphasize that the performances reported in this work correspond to those collected during training, not the ones obtained during a separate evaluation phase, as they are closer to the initial motivation behind online learning (Machado et al., 2018).

Wordle setup Our codebase is a fork of the repository shared by the authors (Snell et al., 2023), from which we implemented the target-free and the iterated Shared Features approaches. We refer to the original paper for extensive details about the setup.

Computing the Area Under the Curve For each experiment, we report the normalized IQM AUC. For that, we first compute the undiscounted return obtained for each epoch, averaged over the episodes, as advocated by Machado et al. (2018). Then, we sum the human-normalized returns over the epochs and compute the IQM and 95% stratified bootstrap confidence intervals over the seeds and games. Finally, we divide the obtained values by the IQM of the target-based approach to facilitate the comparison. The human-normalized scores are computed from human and random scores that were reported in Schrittwieser et al. (2020). As discussed in Section 5, the normalized AUCs can also be interpreted as the average performance gap between the considered algorithm and the target-based approach. Indeed, dividing the two sums of performances across the training is equivalent to dividing the two averages of performances across the training because the normalizing factors cancel out.

B Training Time and Floating-point Operations

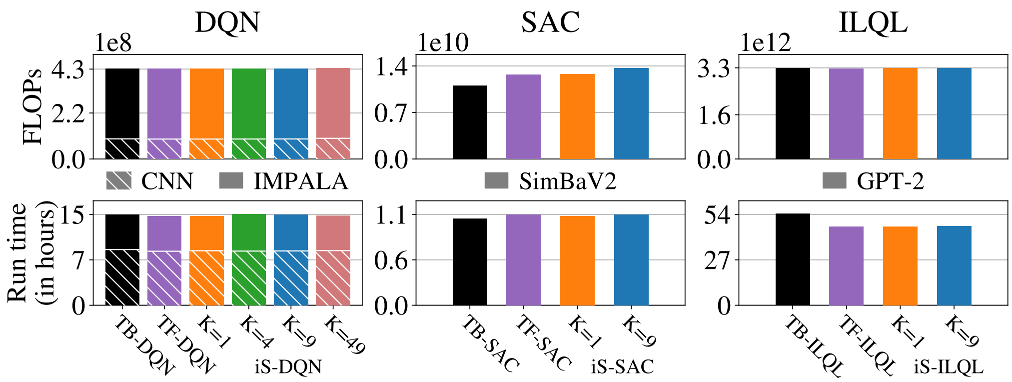

Figure 10: While TF-DQN and iS-DQN require fewer parameters, their training time is similar to TB-DQN since each algorithm uses a similar amount of computation, as indicated by the number of floating-point operations (FLOPs) per gradient steps. **Left**: All algorithms on the Atari benchmark require a similar amount of FLOPs and training time. **Middle**: As reported in Figure 19, the target-based approach does not benefit from BatchNorm for the DMC benchmark. This is why TB-SAC does not use BatchNorm and therefore has a lower amount of FLOPs compared to the other approaches. Importantly, the difference in training time between the algorithms is less visible across the algorithms. **Right**: Thanks to the way the embeddings are computed, the target-free approach and iS-ILQL can compute the TD error from a single pass through the neural network, which lowers the training time.

The presented approach is designed to reduce the memory footprint of target-based methods, while performing better than the target-free approach. In Figure 10 (bottom), we report the training time in hours required by all algorithms. On the top row, we report the number of floating-point operations (FLOPs) required by all algorithms to perform one gradient step. Computations were made on an NVIDIA GeForce RTX 4090 Ti with the game *Asterix* for the DQN experiments, and with the task *Dog-walk* for the SAC experiments. As expected, all algorithms require the same training time and FLOPs because the same amount of computation is needed. Indeed, a forward pass through the network for estimating the value of the next state is necessary to compute the temporal-difference error. We note two exceptions. First, for experiments with SAC, the amount of FLOPs is reduced for the target-based approach, as it does not use BatchNorm. However, the difference in training time remains small. Second, for the experiments with ILQL, the training time for the target-free approach and iS-ILQL is smaller than that of the target-based approach since only one forward pass is required for computing the temporal difference instead of two forward passes. This results in the target-free approach and iS-ILQL having a small training time. While this reduction is not visible in the amount of FLOPs per gradient steps, we verified that the amount of FLOPs per loss computation (forward pass only) is indeed lower: TB-ILQL: 3.3×10^{10} FLOPs, TF-ILQL: 2.0×10^{10} FLOPs, iS-ILQL $K = 1$: 2.1×10^{10} FLOPs, and iS-ILQL $K = 9$: 2.5×10^{10} FLOPs.

C Algorithmic Details

Aggregating individual losses In Equation 1, we define the loss of iS-QN as the sum of losses over each Bellman iteration. Other ways of aggregating the losses are possible. Nonetheless, we decided to stick to the version proposed by Vincent et al. (2025) and leave this investigation for future work. We provide a first alternative in Section 5.3 that provides a performance boost by discounting the following terms by a factor of 0.25. While it is true that taking the sum of temporal differences increases the magnitude of the loss, it has a different impact on the updates than simply multiplying the learning rate by the number of terms in the loss. Indeed, the Adam optimizer (Kingma & Ba, 2015) first normalizes the gradient with a running statistic before applying the learning rate. Therefore, changing the aggregation mechanism has a greater impact on the direction of the update than on its magnitude. This is why we do not compare iS-QN against baselines instantiated with different learning rates.

Sampling actions Following Vincent et al. (2025), at each environment interaction, an action is sampled from a single head chosen uniformly as shown in Line 3 in Algorithm 1. The authors motivate this choice by arguing that it allows each Q-function to interact with the environment, thereby avoiding passive learning, identified by Ostrovski et al. (2021). This choice is further justified by an ablation study (see Figure 19 in Vincent et al. (2025)) demonstrating a stronger performance against another sampling strategy consisting of sampling one head for each episode, as proposed in Osband et al. (2016).

In the experiment on continuous control (Section 5.3), the policy network is used to sample actions. To align with the choice of computing the discounted sum of temporal differences, the critic estimate in the policy loss is calculated as the average discounted prediction over the sequence of Q-predictions given by the heads. The experiment on the language task (Section 6) also uses a policy network to sample actions, but weighs each prediction with the predicted advantage from the critic. To align with the choice made for the experiment on continuous control, the average over the weights corresponding to each head is computed to obtain a single scalar value to weight each action probability.

D LIST OF HYPERPARAMETERS

Our codebase is written in Jax (Bradbury et al., 2018). The details of hyperparameters used for the experiments are provided in Table 1 (Atari), Table 2 (DMC Hard), and Table 3 (Wordle). In each experiment, the same hyperparameters as those provided in the original target-based approaches are used without further tuning. We note $\text{Conv}_{a,b}^{d}C$ a $2D$ convolutional layer with C filters of size $a \times b$ and stride d, and FC E a fully connected layer with E neurons. When added, LayerNorm is placed before each activation function, and BatchNorm is placed after the activation function. Additionally, when BatchNorm is used, the state-action and next state-next action pairs are first concatenated and then passed as a single batch to the network as suggested by the authors of CrossQ and CrossQ + WN (Bhatt et al., 2024; Palenicek et al., 2025).

Table 1: Summary of the shared hyperparameters used for the **Atari** experiments. The CNN architecture is described here. We used three stacked layers of size 32, 64, and 64 with a last linear layer of size 512 for the IMPALA architecture (Espeholt et al., 2018).

Shared hyperparameters	
Discount factor γ	0.99
Horizon H	27 000
Full action space	No
Reward clipping	clip$(-1, 1)$
Batch size	32
Torso architecture	$\text{Conv}_{8,8}^{4}32$ $-\text{Conv}_{4,4}^{2}64$ $-\text{Conv}_{3,3}^{1}64$
Head architecture	FC 512 $-$FC $n_{\mathcal{A}}$ [TB-QN, TF-QN] $-$FC $(K+1) \cdot n_{\mathcal{A}}$ [iS-QN]
Activations	ReLU

CQL hyperparameters	
Number of gradient steps per epoch	62 500
Target update period T	2 000
Dataset size	5 000 000
Learning rate	5×10^{-5}
Adam ϵ	3.125×10^{-4}
CQL weight α	0.1

DQN hyperparameters	
Number of training steps per epoch	250 000
Target update period T	8 000
Type of the replay buffer $\mathcal{D}$	FIFO
Initial number of samples in $\mathcal{D}$	20 000
Maximum number of samples in $\mathcal{D}$	1 000 000
Gradient step period G	4
Starting ϵ	1
Ending ϵ	0.01
ϵ linear decay duration	250 000
Batch size	32
Learning rate	6.25×10^{-5}
Adam ϵ	1.5×10^{-4}

Table 2: Summary of the shared hyperparameters used for the **DMC Hard** experiments.

Environment	
Discount factor γ	0.99
Horizon H	1000
Action repeat	2
Experiments	
Batch size	256
Policy architecture	SimbaV2 Actor
Critic Torso architecture	SimbaV2 Critic
Critic Head architecture	FC 512 $-$FC n_{atoms} [TB-SAC, TF-SAC] $-$FC $(K+1)\cdot n_{\text{atoms}}$ [iS-SAC]
Activations	ReLU
BatchNorm	TF-SAC, iS-SAC
Number of training steps	$500\,000$
Soft target update τ	5×10^{-3}
Initial number of samples in $\mathcal{D}$	$5\,000$
Maximum number of samples in $\mathcal{D}$	$1\,000\,000$
Initial learning rate	1×10^{-4}
Final learning rate	3×10^{-4}
Optimizer	Adam
SimbaV2 hyperparameters	
Double Q	No
Distributional critic bins n_{atoms}	101

Table 3: Summary of the shared hyperparameters used for the **Wordle** experiments.

Environment	
Dataset	Wordle Twitter dataset
Discount factor γ	0.99
Number of tokens	35 (alphabet + colors)
Rewards	-1 for incorrect guess, 0 for correct guess
Experiments	
Batch size	1024
Policy architecture	GPT-2 small (Dropout $p=0.1$)
Torso architecture Q, V	GPT-2 small (Dropout $p=0.1$)
Head architecture Q	FC 1536 $-$FC $n_{\mathcal{A}}$ [TB-ILQL, TF-ILQL] $-$FC $(K+1)\cdot n_{\mathcal{A}}$ [iS-ILQL]
Head architecture V	FC 1536 $-$FC 1 [TB-ILQL, TF-ILQL] $-$FC $(K+1)\cdot 1$ [iS-ILQL]
Activations	ReLU
Number of gradient steps	$800\,000$
Soft target update τ	5×10^{-3}
Learning rate	1×10^{-5}
Optimizer	Adam
ILQL hyperparameters	
Inverse temperature β	4.0
CQL weight α	1×10^{-4}

E INDIVIDUAL LEARNING CURVES

E.1 DEEP Q-NETWORK WITH CNN AND LAYERNORM

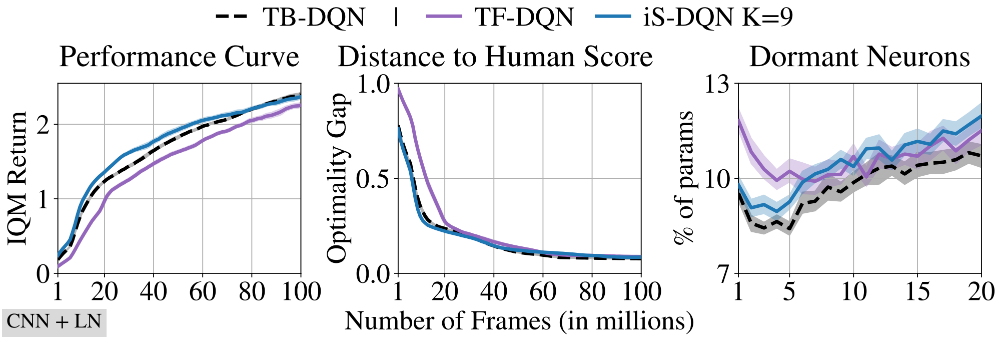

Figure 11: Reducing the performance gap in online RL on 15 **Atari** games with the CNN architecture and LayerNorm. **Left**: iS-DQN $K = 9$ not only reduces the performance gap but outperforms the target-based approach. **Middle**: iS-DQN annuls the performance gap for the games where the score is below the human level. **Right**: iS-DQN exhibits a lower amount of dormant neurons at the beginning of the training compared to the target-free approach.

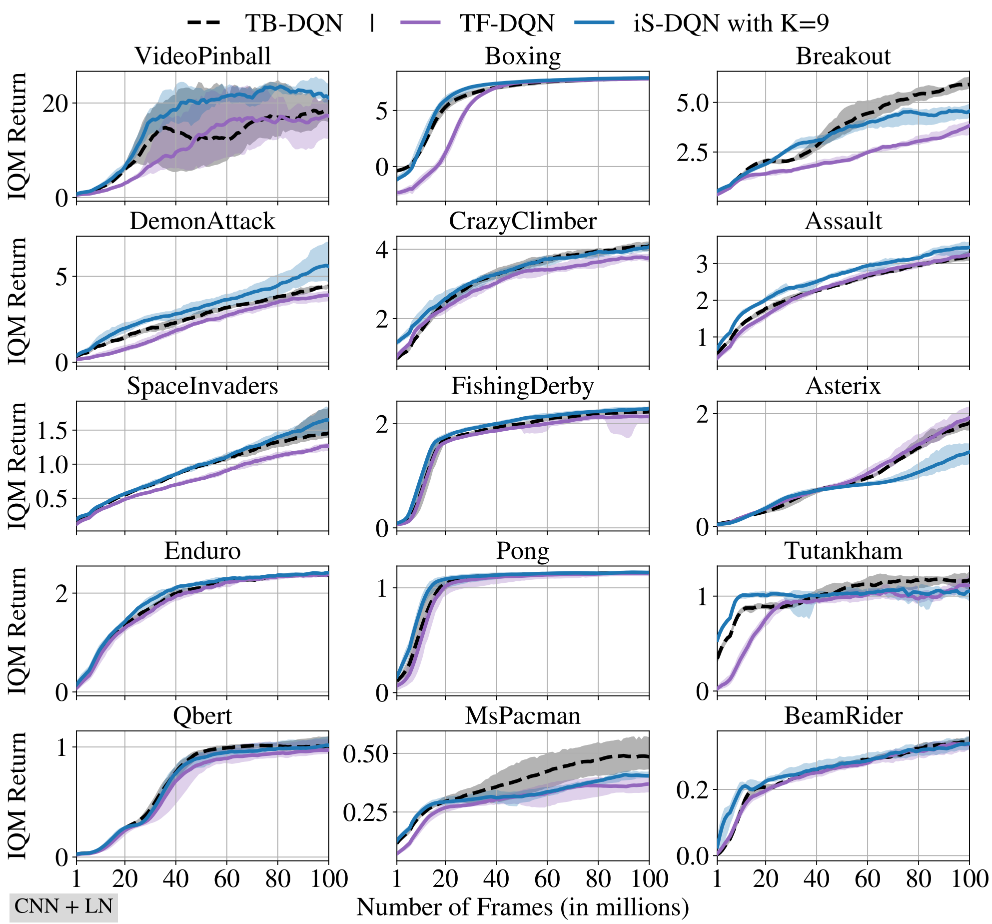

Figure 12: Per game training curves of iS-DQN, TF-DQN, and TB-DQN with the CNN architecture and LayerNorm. Except on *Asterix*, iS-DQN outperforms or is on par with the target-free approach (TF-DQN).

E.2 DEEP Q-NETWORK WITH IMPALA AND LAYERNORM

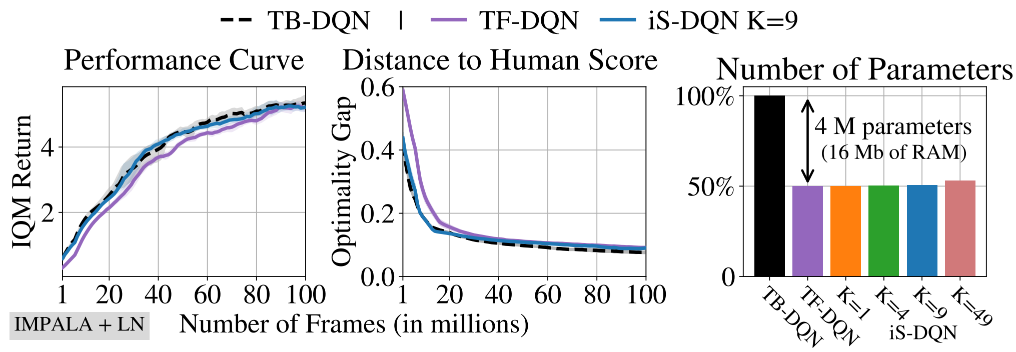

Figure 13: Reducing the performance gap in online RL on 10 **Atari** games with the IMPALA architecture and LayerNorm. **Left**: iS-DQN $K = 9$ is outperforms the target-free approach. **Middle**: iS-DQN annuls the performance gap for the games where the score is below the human level. **Right**: iS-DQN requires significantly fewer parameters than the target-based approach while reaching similar performance.

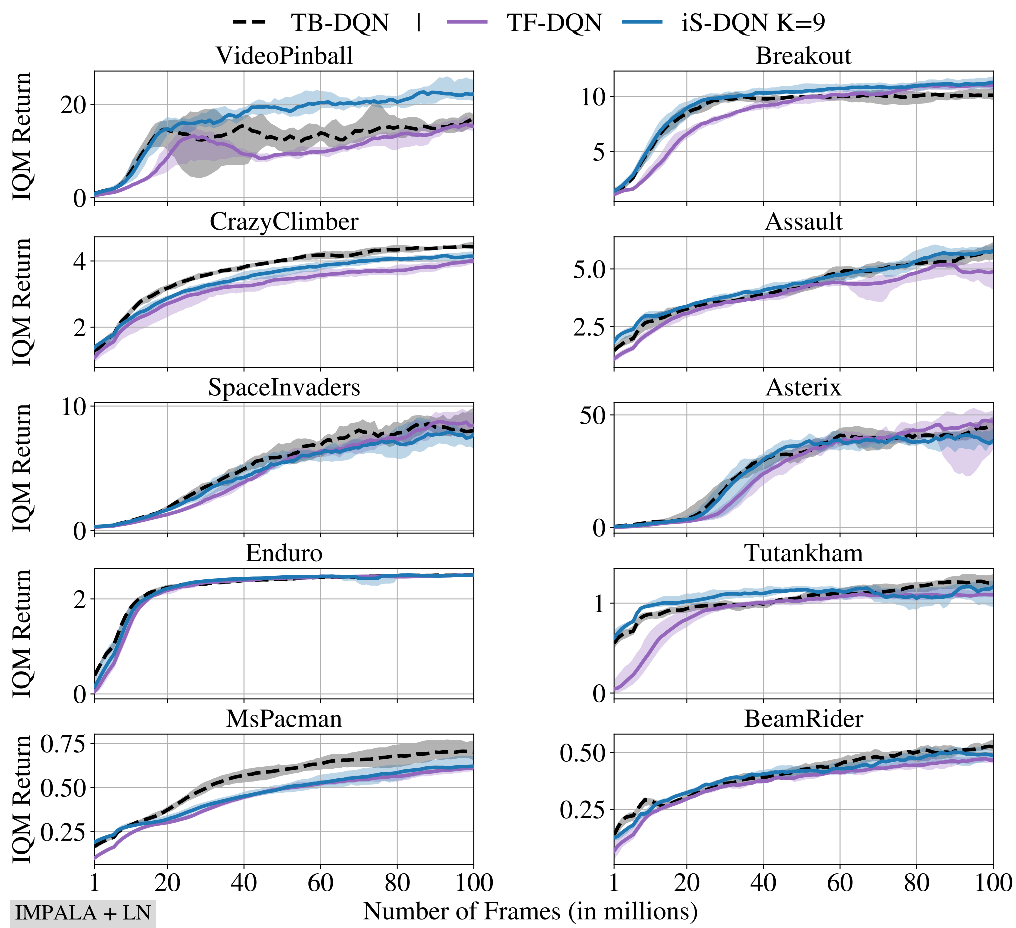

Figure 14: Per game training curves of iS-DQN, TF-DQN, and TB-DQN with the IMPALA architecture and LayerNorm. Our approach outperforms or is on par with the target-free approach (TF-DQN) on all games.

E.3 Deep Q-Network with CNN

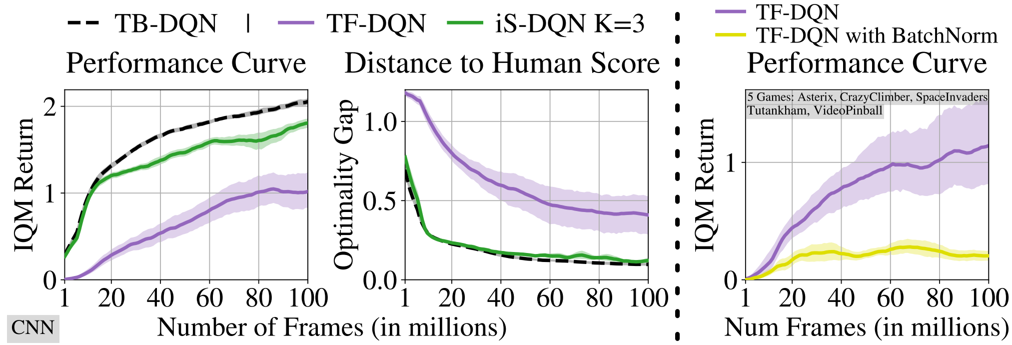

Figure 15: Reducing the performance gap in online RL on 15 **Atari** games with the CNN architecture. **Left**: iS-DQN $K = 3$ significantly reduces the performance gap between the target-free and target-based approaches. **Middle**: iS-DQN annuls the performance gap for the games where the score is below the human level. **Right**: Including BatchNorm in the architecture damages the performance on the 5 considered games of the target-based approach. This is why BatchNorm is not included for the experiments with TB-DQN.

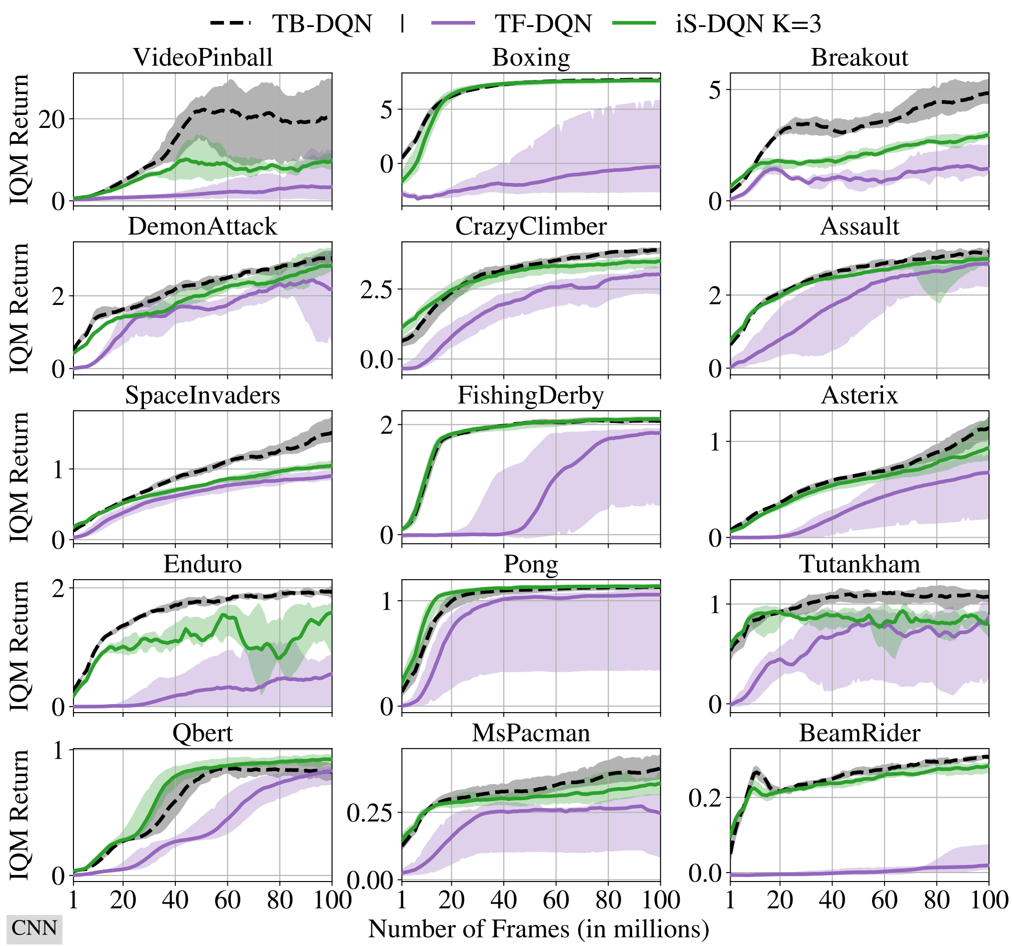

Figure 16: Per game training curves of iS-DQN, TF-DQN, and TB-DQN with the CNN architecture. Remarkably, iS-DQN outperforms the target-free approach (TF-DQN) on all games.

E.4 Conservative Q-Learning with IMPALA and LayerNorm

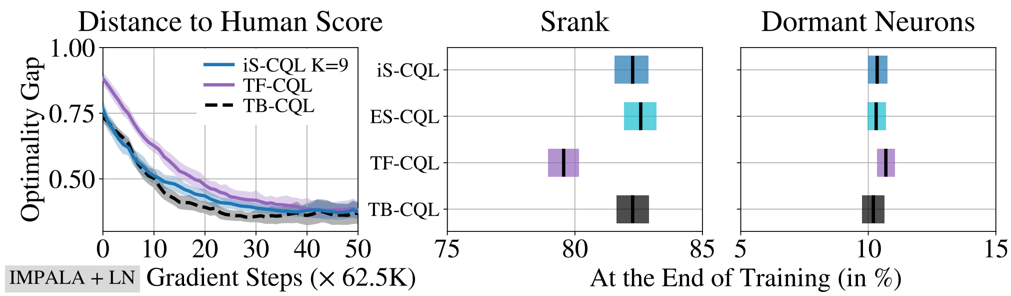

Figure 17: Reducing the performance gap in offline RL on 10 **Atari** games with the IMPALA architecture and LayerNorm. **Left**: iS-CQL significantly reduces the performance gap for the gameS where the score is below the human level. **Middle**: At the end of the training, iS-CQL and ES-CQL lead to a higher srank than the target-free approach, which indicates a higher representation capability. **Right**: All methods converge to a low amount of dormant neurons at the end of the training.

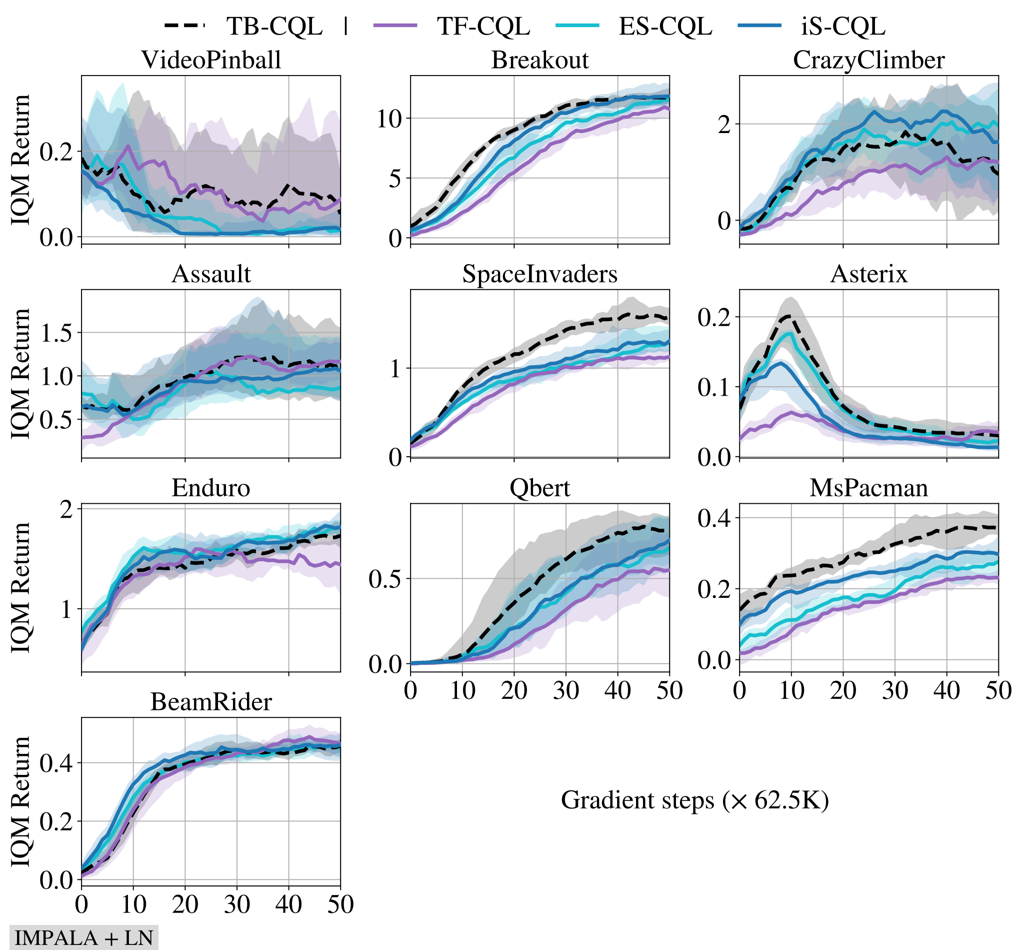

Figure 18: Per game training curves of iS-CQL, TF-CQL, and TB-CQL with the IMPALA architecture and LayerNorm. Except on *VideoPinball*, iS-CQL outperforms or is on par with the target-free approach (TF-CQL).

E.5 SOFT ACTOR-CRITIC WITH SIMBAV2 AND BATCHNORM

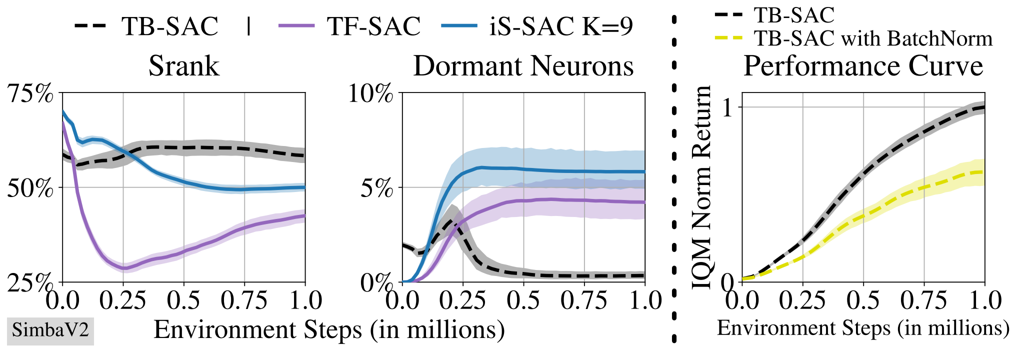

Figure 19: Reducing the performance gap in online RL on the 7 **DMC Hard** tasks with the SimbaV2 architecture and BatchNorm. **Left**: As opposed to iS-SAC, the target-free approach suffers from a low srank, which indicates a lower representation capability. **Middle**: The percentage of dormant neurons remains low during training for all methods, not exceeding 7%. **Right**: The target-based approach does not benefit from BatchNorm. This is why it is not included in the experiments with TB-SAC.

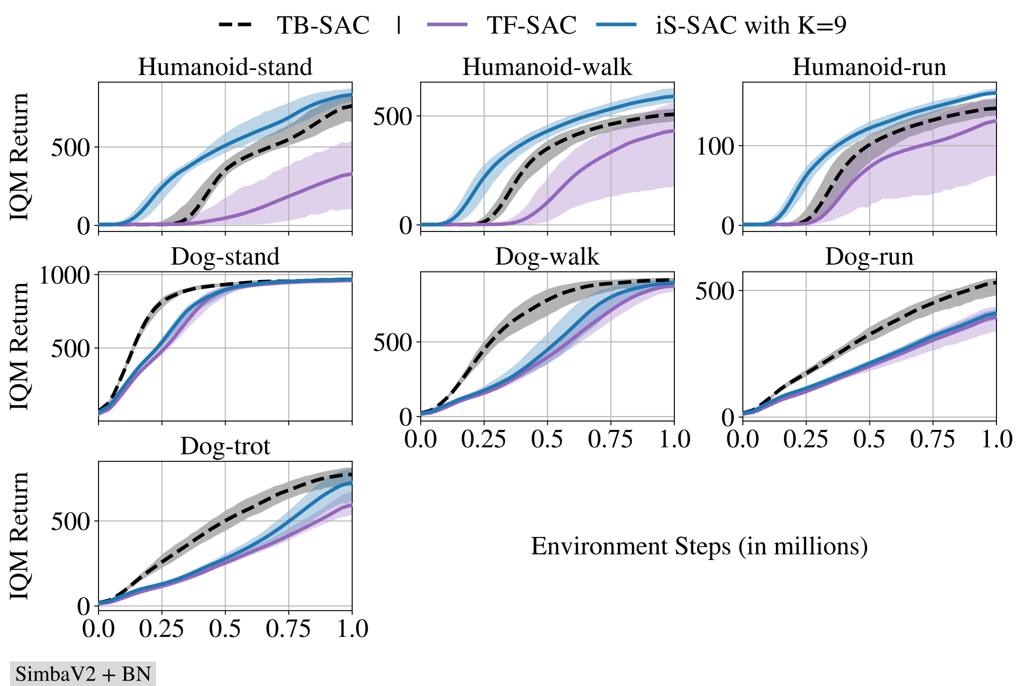

Figure 20: Per game training curves of iS-SAC, TF-SAC, and TB-SAC with the SimbaV2 architecture and BatchNorm. iS-SAC consistently performs better than or on par with the target-free approach. Interestingly, iS-SAC even outperforms the target-based approach on the humanoid tasks.