TTN: A DOMAIN-SHIFT AWARE BATCH NORMALIZATION IN TEST-TIME ADAPTATION

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Paper under double-blind review

ABSTRACT

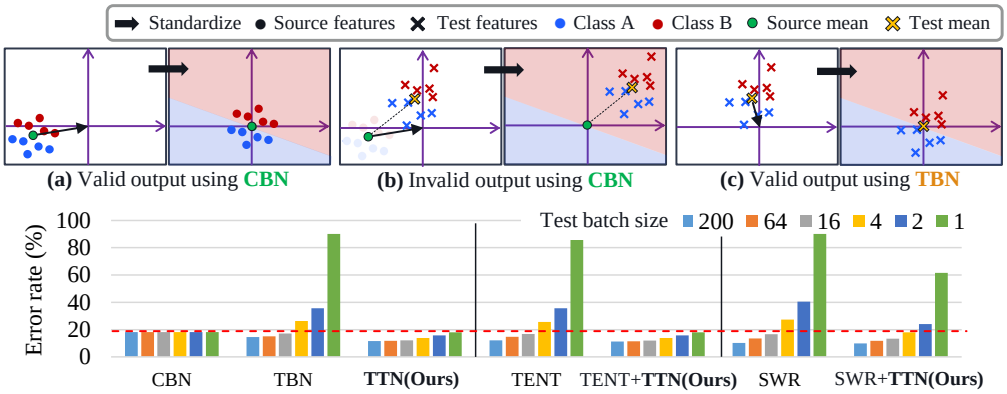
This paper proposes a novel batch normalization strategy for test-time adaptation. Recent test-time adaptation methods heavily rely on the modified batch normalization, *i.e.,* transductive batch normalization (TBN), which calculates the mean and the variance from the current test batch rather than using the running mean and variance obtained from source data, *i.e.,* conventional batch normalization (CBN). Adopting TBN that employs test batch statistics mitigates the performance degradation caused by the domain shift. However, re-estimating normalization statistics using test data depends on impractical assumptions that a test batch should be large enough and be drawn from i.i.d. stream, and we observed that the previous methods with TBN show critical performance drop without assumptions. In this paper, we identify that CBN and TBN are in a trade-off relationship and present a new *test-time normalization* (TTN) method that interpolates the standardization statistics by adjusting the importance between CBN and TBN according to the *domain-shift sensitivity* of each BN layer. Our proposed TTN improves model robustness to shifted domains across a wide range of batch sizes and in various realistic evaluation scenarios. TTN is widely applicable to other test-time adaptation methods that rely on updating model parameters via backpropagation. We demonstrate that adopting TTN further improves their performance and achieves state-of-the-art performance in various standard benchmarks.

1 INTRODUCTION

When we deploy deep neural networks (DNNs) trained on the source domain into test environments (*i.e.,* target domains), the model performance on the target domain deteriorates due to the domain shift from the source domain. For instance, in autonomous driving, a well-trained DNNs model may exhibit significant performance degradation at test time due to environmental changes, such as camera sensors, weather, and region (Choi et al., 2021; Lee et al., 2022; Kim et al., 2022b).

Test-time adaptation (TTA) has emerged to tackle the distribution shift between source and target domains during test time (Sun et al., 2020; Wang et al., 2020). Recent TTA approaches (Wang et al., 2020; Choi et al., 2022; Liu et al., 2021) address this issue by 1) (re-)estimating normalization statistics from current test input and 2) optimizing model parameters in unsupervised manner, such as entropy minimization (Grandvalet & Bengio, 2004; Long et al., 2016; Vu et al., 2019) and self-supervised losses (Sun et al., 2020; Liu et al., 2021). In particular, the former focused on the weakness of conventional batch normalization (CBN) (Ioffe & Szegedy, 2015) for domain shift in a test time. As described in Fig. 1(b), when standardizing target feature activations using source statistics, which are collected from the training data, the activations can be transformed into an unintended feature space, resulting in misclassification. To this end, the TTA approaches (Wang et al., 2020; Choi et al., 2022; Wang et al., 2022) have heavily depended on the direct use of test batch statistics to fix such an invalid transformation in BN layers, called transductive BN (TBN (Schneider et al., 2020; Nado et al., 2020; Bronskill et al., 2020) (see Fig. 1(c)).

The approaches utilizing TBN showed promising results but have mainly been assessed in limited evaluation settings (Wang et al., 2020; Choi et al., 2022; Liu et al., 2021). For instance, such evaluation settings assume large test batch sizes (*e.g.,* 200 or more) and a single stationary distribution shift (*i.e.,* single corruption). Recent studies suggest more practical evaluation scenarios based on small batch sizes (Mirza et al., 2022; Hu et al., 2021; Khurana et al., 2021) or continuously changing data



(d) Performance drops in small test batches using **TBN**

Figure 1: **Trade-off between CBN & TBN.** In conceptual illustrations (a), (b), and (c), the depicted standardization only considers making the feature distribution have a zero mean, disregarding making it have unit variance. When the source and test distributions are different, and the test batch size is large, **(b)** test features can be wrongly standardized when using CBN, but **(c)** TBN can provide a valid output. **(d)** Error rates (↓) on shifted domains (CIFAR-10-C). TBN and TBN applied (TENT (Wang et al., 2020), SWR (Choi et al., 2022)) methods suffer from severe performance drop when the batch size becomes small, while TTN (Ours) improves overall performance.

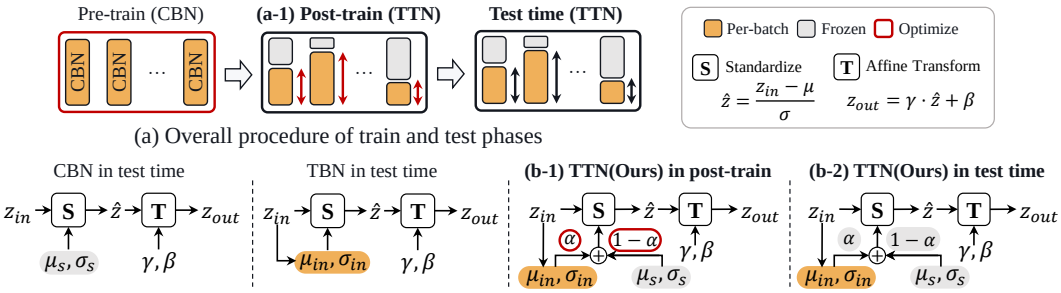
distribution during test time (Wang et al., 2022). We show that the performance of existing methods significantly drops once their impractical assumptions of the evaluation settings are violated. For example, as shown in Fig. 1(d), TBN and TBN applied methods suffer from severe performance drop when the test batch size becomes small, while CBN is irrelevant to the test batch sizes. We identify that CBN and TBN are in a trade-off relationship (Fig. 1), in the sense that one of each shows its strength when the other falls apart.

To tackle this problem, we present a novel *test-time normalization (TTN)* strategy that controls the trade-off between CBN and TBN by adjusting the importance of source and test batch statistics according to the *domain-shift sensitivity* of each BN layer. Intuitively, we linearly interpolate between CBN and TBN so that TBN has a larger weight than CBN if the standardization needs to be adapted toward the test data. We optimize the interpolating weight after the pre-training but before the test time, which we refer to as the post-training phase. Specifically, given a pre-trained model, we first estimate channel-wise sensitivity of the affine parameters in BN layers to domain shift by analyzing the gradients from the back-propagation of two input images, clean input and its augmented one (simulating unseen distribution). Afterward, we optimize the interpolating weight using the channel-wise sensitivity replacing BN with the TTN layers. It is noteworthy that none of the pre-trained model weights are modified, but we only train our newly added interpolating weight for TTN layers.

We empirically show that TTN outperforms existing TTA methods in realistic evaluation settings, *i.e.,* with a wide range of test batch sizes for single, mixed, and continuously changing domain adaptation through extensive experiments on image classification and semantic segmentation tasks. TTN as a stand-alone method shows compatible results with the state-of-the-art methods and combining our TTN with the baselines even boosts their performance in overall scenarios. Moreover, TTN applied methods flexibly adapt to new target domains while sufficiently preserving the source knowledge. No action other than computing per batch statistics (which can be done simultaneously to the inference) is needed in test-time; TTN is compatible with other TTA methods without requiring additional computation cost.

Our contributions are summarized as follows:

- We propose a novel domain-shift aware test-time normalization (TTN) layer that combines source and test batch statistics using channel-wise interpolating weights considering the sensitivity to domain shift in order to flexibly adapt to new target domains while preserving the well-trained source knowledge.
- To show the broad applicability of our proposed TTN, which does not alter training or test-time schemes, we show that adding TTN to existing TTA methods significantly improves



(a) Overall procedure of train and test phases

(b) Comparison of BN layers

Figure 2: **Method overview. (a)** We introduce an additional training phase between pre-train and test time called **(a-1)** post-training phase. **(b)** Our proposed TTN layer combines per-batch statistics and frozen source statistics with interpolating weight α, which is **(b-1)** optimized in post-training phase and **(b-2)** fixed in test time.

the performance across a wide range of test batch sizes (from 200 to 1) and in three realistic evaluation scenarios; stationary, continuously changing, and mixed domain adaptation.

- We evaluate our method through extensive experiments on image classification using CIFAR-10/100-C, and ImageNet-C (Hendrycks & Dietterich, 2018) and semantic segmentation task using CityScapes (Cordts et al., 2016), BDD-100K (Yu et al., 2020), Mapillary (Neuhold et al., 2017), GTAV (Richter et al., 2016), and SYNTHIA (Ros et al., 2016).

2 Methodology

In this section, we describe our method, the *Test-Time Normalization* (TTN) layer, whose design is suitable for test-time adaptation (TTA) in practical usages out of the large batch size and i.i.d assumptions during a test time. We first define the problem setup in Section 2.1 and present our proposed TTN layers in Section 2.2. Finally, we discuss how we optimize TTN layers in Sections 2.3.

2.1 Problem Setup

Let the train and test data be $\mathcal{D}_S$ and $\mathcal{D}_T$ and the corresponding probability distributions be P_S and P_T, respectively, where $\mathcal{D}_S$ and $\mathcal{D}_T$ share the output space, *i.e.*, $\{y_i\} \sim \mathcal{D}_S = \{y_i\} \sim \mathcal{D}_T$. The covariate shift in TTA is defined as $P_S(x) \neq P_T(x)$ where $P_S(y|x) = P_T(y|x)$ (Quinonero-Candela et al., 2008). A model, f_θ, with parameters θ, is trained with a mini-batch, $\mathcal{B}^S = \{(x_i, y_i)\}_{i=1}^{|\mathcal{B}^S|}$, from source data $\mathcal{D}_S$, where x_i is an example and y_i is the corresponding label. During the test, f_θ encounters a test batch $\mathcal{B}^T \sim \mathcal{D}_T$, and the objective of TTA is correctly managing the test batch from the different distribution.

To simulate more practical TTA, we mainly consider two modifications: (1) various test batch sizes, $|\mathcal{B}^T|$, where small batch size indicates small latency while handling the test data online, (2) multi, N-target domains, $\mathcal{D}_\mathcal{T} = \{\mathcal{D}_{T,i}\}_{i=1}^N$. Under this setting, each test batch $\mathcal{B}^T$ is drawn by one of the test domains in $\mathcal{D}_T$, where $\mathcal{D}_T$ may consist of a single target domain, multiple target domains, or cyclically repeating target domains.

2.2 Test-Time Normalization Layer

We denote an input of a BN layer as $\mathbf{z} \in \mathbb{R}^{BCHW}$, forming a mini-batch size of B. The mean and variance of $\mathbf{z}$ are μ and σ^2, respectively, which are computed as follows:

$$\mu_c = \frac{1}{BHW} \sum_b^B \sum_h^H \sum_w^W \mathbf{z}_{bchw}, \quad \sigma_c^2 = \frac{1}{BHW} \sum_b^B \sum_h^H \sum_w^W (\mathbf{z}_{bchw} - \mu_c)^2, \tag{1}$$

where μ and σ^2 are in $\mathbb{R}^C$, and C, H, and W stand for the number of channels, dimension of height, and that of width, respectively. Based on μ and σ^2, the source statistics $\mu_s, \sigma_s^2 \in \mathbb{R}^C$ are usually estimated with exponential moving average over the training data.

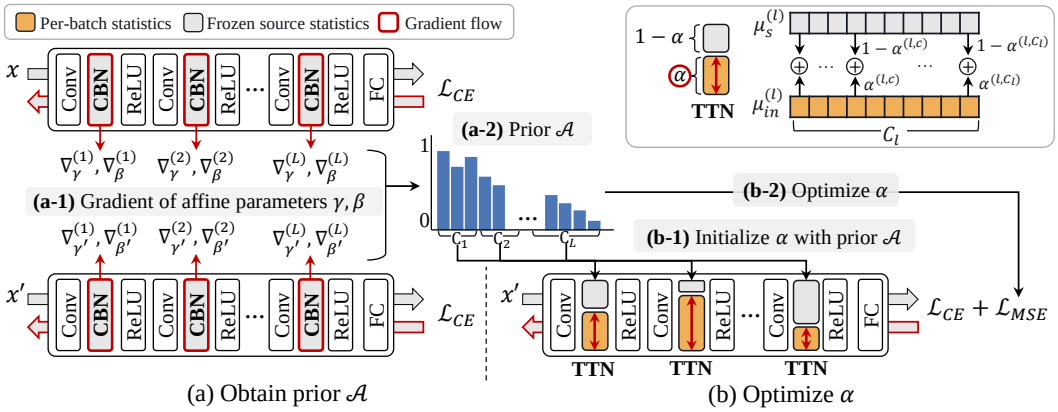


Figure 3: **Two stages in post-training phase. (a)** Given a pre-trained model, which uses CBN, and its training data, we obtain prior knowledge of each BN layer. **(a-1)** We first compute gradients of affine parameters in each BN layer from clean x and augmented input x' and obtain the gradient distance score (Eq. 4). **(a-2)** For BN layers with larger distance score, we put more importance on current batch statistics than source statistics (*i.e.,* large α), and we define prior $\mathcal{A}$ accordingly (Eq. 5). **(b)** After obtaining prior $\mathcal{A}$, we substitute BN layers from CBN to TTN. **(b-1)** Initializing α with prior $\mathcal{A}$, **(b-2)** we optimize α using CE and MSE loss (Eq. 6) with augmented training data x'.

In BN layers, input $\mathbf{z}$ is first standardized with statistics μ and σ^2 and then is scaled and shifted with learnable parameters γ and β in $\mathbb{R}^C$. The standardization use current input batch statistics during training and use estimated source statistics μ_s and σ_s^2 at test time (Fig. 2(b)). To address a domain shift in a test time, we adjust the source statistics by combining source and test mini-batch statistics (Singh & Shrivastava, 2019; Summers & Dinneen, 2019) with a learnable interpolating weight $\alpha \in \mathbb{R}^C$ ranges $[0, 1]$. Precisely, TTN standardizes a feature with

$$\tilde{\mu} = \alpha\mu + (1-\alpha)\mu_s, \quad \tilde{\sigma}^2 = \alpha\sigma^2 + (1-\alpha)\sigma_s^2 + \alpha(1-\alpha)(\mu - \mu_s)^2, \tag{2}$$

while using same affine parameters, γ and β. Note that we have different mixing ratio α_c for every layer and channel.

2.3 Post Training

Like Choi et al. (2022), we introduce an additional training phase, post-training (after pre-training but before testing), to optimize the mixing parameters α in Eq. 2 (Fig. 2(a)). Note that all parameters except α are frozen and we have access to the labeled source data during the post-training. We first obtain prior knowledge $\mathcal{A}$ of α by identifying which layers and their channels are sensitive to domain shift. Then, we optimize α with prior knowledge and an additional objective term. The overall procedure is depicted in Fig. 3 and the pseudo code is provided in appendix A.3.

Obtain Prior $\mathcal{A}$. To identify which BN layers and corresponding channels are sensitive to domain shift, we simulate the domain shift by augmenting the clean image, *i.e.,* original training data, and make a pair of (clean x, domain-shifted x') images, where the semantic information is shared. To analyze in which layer and channel the standardization statistics should be corrected, we consider the standardized features $\hat{z}^{(l,c)}$ of $z^{(l,c)}$, for a channel index c at a layer l, whose input is clean x. We compare $\hat{z}^{(l,c)}$ to that of domain-shifted one, $\hat{z}'^{(l,c)}$ from x'. While the pre-trained CBN uses the same $\mu_s^{(l,c)}$ and $\sigma_s^{(l,c)}$ for both inputs, the difference between $\hat{z}^{(l,c)}$ and $\hat{z}'^{(l,c)}$ is caused by the simulated domain shift. We argue that if the difference is significant, the parameter at (l, c) is sensitive to the domain shift, *i.e.,* intensely affected by the domain shift, and hence the standardization statistics at (l, c) should be adapted towards the shifted input.

Drawing inspiration from Choi et al. (2022), we measure the domain-shift sensitivity by comparing gradients. Since the standardized feature $\hat{z}$ is scaled and shifted by γ and β in each BN layer, we compare the gradients of affine parameters γ and β, ∇_γ and ∇_β, respectively, to measure the dissimilarity of $\hat{z}$ and $\hat{z}'$. As described in Fig. 3(a-1), we collect the ∇_γ and ∇_β using cross-entropy loss, $\mathcal{L}_{\text{CE}}$. To this end, we introduce a *gradient distance score*, $d^{(l,c)} \in \mathbb{R}$ for each channel c at layer

l as follows:

$$s = \frac{1}{N}\sum_{i=1}^{N}\frac{g_i \cdot g_i'}{\|g_i\|\|g_i'\|}, \tag{3}$$

$$d^{(l,c)} = 1 - \frac{1}{2}\big(s_\gamma^{(l,c)} + s_\beta^{(l,c)}\big), \tag{4}$$

where (g, g') is $(\nabla_\gamma^{(l,c)}, \nabla_{\gamma'}^{(l,c)})$ and $(\nabla_\beta^{(l,c)}, \nabla_{\beta'}^{(l,c)})$ for $s_\gamma^{(l,c)}$ and $s_\beta^{(l,c)}$, respectively, N is the number of training data, and the resulting $d^{(l,c)} \in [0, 1]$.

Finally, we conduct min-max normalization $\nu(\cdot)$ over all $d^{(l,c)}$. To magnify the relative difference, we take the square as a final step and we call the result as a prior $\mathcal{A}$ (Fig. 3(a-2)):

$$\mathcal{A} = \big\{\nu([d^{(1,\cdot)}, d^{(2,\cdot)}, \ldots, d^{(L,\cdot)}])\big\}^2, \tag{5}$$

where $d^{(l,\cdot)} = [d^{(l,c)}]_{c=1}^{C_l}$.

Optimize α. The goal of optimizing α is to make the combined statistics correctly standardize the features when the input is sampled from arbitrary target domain. After obtaining the prior $\mathcal{A}$, we replace CBN with TTN layers while keeping the affine parameters. Then, we initialize the interpolating weights α with $\mathcal{A}$, which represents in which layer and channel the standardization statistics need to be adopted using test batch statistics (see Fig. 3(b-1)). To simulate distribution shift, we use the augmented training data. Expecting the model to make consistent prediction either given clean or augmented inputs, we use cross-entropy loss $\mathcal{L}_{\text{CE}}$. Furthermore, to prevent α from moving too far from the initial value $\mathcal{A}$, we use mean-squared error loss $\mathcal{L}_{\text{MSE}}$ between α and the prior $\mathcal{A}$, *i.e.,* $\mathcal{L}_{\text{MSE}} = \|\alpha - \mathcal{A}\|^2$ as a constraint. Total loss $\mathcal{L}$ can be written as

$$\mathcal{L} = \mathcal{L}_{\text{CE}} + \lambda\mathcal{L}_{\text{MSE}}, \tag{6}$$

where λ is a weighting hyperparameter.

3 Experiments

In image classification, we evaluate TTN for corruption robustness in realistic evaluation settings, *i.e.,* where test batch size can be variant and where the target domain can be either stationary, continuously changing, or mixed with multiple domains. Additionally, we further validate TTN on domain generalization benchmarks incorporating natural domain shift (*e.g.,* changes in camera sensors, weather, time, and region) in semantic segmentation.

3.1 Experimental Setup

Given models pre-trained on clean source data, we optimize TTN parameter α with augmented source data in the post-training phase. Afterward, we evaluate our post-trained model on corrupted target data. **Implementation details are provided in the appendix A.1.**

Datasets and models. We use corruption benchmark datasets CIFAR-10/100-C and ImageNet-C, which consist of 15 types of common corruptions at five severity levels (Hendrycks & Dietterich, 2018). Each corruption is applied to test images of clean datasets, *i.e.,* CIFAR-10/100 and ImageNet. We use a train set of the clean dataset for post-training and a corrupted dataset for evaluation. As backbone models, we used WideResNet-40-2 (Hendrycks et al., 2019) trained on CIFAR-10/100, and ResNet-50 (He et al., 2016) trained on ImageNet. To validate our method in semantic segmentation, we conduct experiments on Cityscapes (Cordts et al., 2016), BDD-100K (Yu et al., 2020), Mapillary (Neuhold et al., 2017), GTAV Richter et al. (2016), and SYNTHIA (Ros et al., 2016) datasets, in accordance with the experimental setup for domain generalization proposed in RobustNet (Choi et al., 2021).

Baselines. To demonstrate that TTN successfully controls the trade-off between CBN and TBN, we compare TTN with (1) α-BN You et al. (2021) and (2) MixNorm (Hu et al., 2021), which combines or takes the moving average of source and test batch statistics with a pre-defined hyperparameter (*i.e.,* a constant α). The following baselines are suggested on top of TBN; (3) TENT (Wang et al., 2020) optimizes affine parameters via entropy minimization. (4) SWR (Choi et al., 2022) updates the entire model parameter considering the domain-shift sensitivity. (5) CoTTA (Wang et al., 2022)

Table 1: **Single domain adaptation on corruption benchmark.** Error rate (↓) averaged over 15 corruptions with severity level 5 is reported for each test batch size. * denotes the reported results from the original paper and the others are reproduced. We used MixNorm with fixed parameters.

	Method	CIFAR-10-C 200	64	16	4	2	1	Avg.	CIFAR-100-C 200	64	16	4	2	1	Avg.
	Source	18.27	18.27	18.27	18.27	18.27	18.27	18.27	46.75	46.75	46.75	46.75	46.75	46.75	46.75
Norm	TBN	14.49	15.02	17.10	26.28	35.65	90.00	33.09	39.25	40.21	44.03	59.10	80.65	99.04	60.38
Norm	α-BN	13.78	13.77	13.89	14.54	**15.16**	15.47	14.44	39.72	39.85	39.99	41.34	**42.66**	**45.64**	**41.53**
Norm	MixNorm*	13.85	14.41	14.23	14.60 (B=5)	-	**15.09**	14.44	-	-	-	-	-	-	-
Norm	**Ours (TTN)**	**11.67**	**11.80**	**12.13**	**13.93**	15.83	17.99	**13.89**	**35.58**	**35.84**	**36.73**	**41.08**	46.67	57.71	42.27
Optim.	TENT	12.08	14.78	16.90	25.61	35.69	90.00	32.51	35.52	39.90	43.78	59.02	80.68	99.02	59.65
Optim.	**+Ours (TTN)**	**11.28**	**11.52**	**12.04**	**13.95**	**15.84**	**17.94**	**13.77**	**35.16**	**35.57**	**36.55**	**41.18**	**46.63**	**58.33**	**42.24**
Optim.	SWR	10.26	13.51	16.61	27.33	40.48	90.04	33.04	**32.68**	37.41	43.15	59.90	87.07	99.05	59.88
Optim.	**+Ours (TTN)**	**9.92**	**11.77**	**13.41**	**18.02**	**24.09**	**61.56**	**23.13**	32.86	**35.13**	**38.66**	**49.80**	**60.72**	**80.90**	**49.68**

Table 2: **Continuously changing domain adaptation on corruption benchmark.** Error rate (↓) averaged over 15 corruption types with severity level 5 is reported for each test batch size.

	Method	CIFAR-10-C 200	64	16	4	2	1	Avg.	CIFAR-100-C 200	64	16	4	2	1	Avg.
	Source	18.27	18.27	18.27	18.27	18.27	18.27	18.27	46.75	46.75	46.75	46.75	46.75	46.75	46.75
	Ours (TTN)	**11.67**	**11.80**	**12.13**	**13.93**	**15.83**	**17.99**	**13.89**	**35.58**	**35.84**	**36.73**	**41.08**	**46.67**	**57.71**	**42.27**
Optim.	CoTTA	12.46	14.60	21.26	45.69	58.87	90.00	40.48	39.75	42.20	52.94	73.69	87.66	98.99	65.87
Optim.	TENT	12.54	13.52	15.69	26.23	35.77	90.00	32.29	**36.11**	37.90	43.78	58.71	81.76	99.04	59.55
Optim.	**+Ours (TTN)**	**11.44**	**11.60**	**12.08**	**16.14**	**18.36**	**22.40**	**15.33**	43.50	**37.60**	**38.28**	**44.60**	**54.29**	**80.63**	**49.82**
Optim.	SWR	11.04	11.53	13.90	23.99	34.02	90.00	30.75	34.16	35.79	40.71	58.15	80.55	99.03	62.56
Optim.	**+Ours (TTN)**	**10.09**	**10.51**	**11.28**	**14.29**	**16.67**	**84.12**	**24.49**	**33.09**	**34.07**	**36.15**	**42.41**	**53.63**	**93.08**	**48.74**

ensembles the output of augmented test inputs, updates the entire model parameter using a consistency loss between student and teacher models, and stochastically restores the pre-trained model. We refer to TBN, (1) and (2) as *normalization*-based methods (Norm), the other as *optimization*-based methods (Optim.), and denote the pre-trained model using CBN as 'source'.

Evaluation scenarios. To show that TTN performs robust on various test batch sizes, we conduct experiments with test batch sizes of 200, 64, 16, 4, 2, and 1. Note that the α is shared across the settings. We report the error rate (lower the better) for each test batch size, averaging over 15 corruption types (See the appendix Table 10 for the results of each).

For optimization-based methods, we conduct experiments in three evaluation scenarios; *single*, *continuously changing*, and *mixed* domain adaptation. In single domain adaptation, the model is optimized for one corruption type and then reset before adapting to the subsequent corruption, following TENT and SWR. In continuously changing adaptation (Wang et al., 2022), the model is continuously adapted to 15 corruption types (w/o the reset), which is more realistic because it is impractical to precisely indicate when the data distribution has shifted in the real world. Finally, to simulate the non-stationary target domain where the domain frequently changes in the short term, we introduce a new evaluation setting, called mixed domain adaptation, whose corruption type changes over the test batch (Details are in the appendix A.2). We cyclically repeat 15 corruption types to comprise each test batch. We used a severity level of 5 (Hendrycks & Dietterich, 2018) for all experiments.

3.2 Experiments on Image Classification

Tables 1, 2, and 3 show error rates on corruption benchmark datasets in three different evaluation scenarios; single domain, continual, and mixed domain adaptation, respectively. Note that the performance of normalization-based methods is the same for all scenarios. Tables 4 and 5 show the adaptation performance on the source and class imbalanced target domains, respectively. See the supplementary material for more results, including results of ImageNet-C and analysis.

Robustness to practical settings. In Table 1, 2, and 3, TTN and TTN applied methods show robust performance over the test batch size ranges from 200 to 1. Comparing with normalization-based baselines, we demonstrate that TTN, which uses channel-wisely optimized combining rate α, shows better results than defining α as a constant hyperparameter, which can be considered as a special case

Table 3: **Mixed domain adaptation on corruption benchmark.** Error rate (↓) of mixed domain with severity level 5 is reported for each test batch size.

	Method	CIFAR-10-C 200	64	16	4	2	1	Avg.	CIFAR-100-C 200	64	16	4	2	1	Avg.
	Source	18.27	18.27	18.27	18.27	18.27	18.27	18.27	46.75	46.75	46.75	46.75	46.75	46.75	46.75
	Ours (TTN)	**11.67**	**11.80**	**12.13**	**13.93**	**15.83**	**17.99**	**13.89**	**35.58**	**35.84**	**36.73**	**41.08**	**46.67**	**57.71**	**42.27**
Optim.	TENT	14.27	15.25	16.82	26.13	35.95	90.00	33.07	36.86	40.28	43.47	59.52	80.29	98.97	59.90
	+Ours (TTN)	**11.73**	**12.11**	**11.97**	**13.67**	**16.06**	**17.80**	**13.89**	**35.90**	**36.17**	**36.39**	**41.86**	**46.95**	**59.08**	**42.73**
	SWR	12.96	12.70	14.47	24.26	34.43	90.00	31.47	36.60	36.99	40.18	57.76	78.86	99.07	58.24
	+Ours (TTN)	**11.65**	**11.44**	**12.08**	**14.14**	**17.15**	**19.55**	**14.34**	**35.67**	**35.59**	**36.90**	**42.20**	**48.60**	**69.29**	**44.71**

Table 4: **Adaptation on source domain test set.** Error rate (↓) on test split of CIFAR-10 using WideResNet-40-2 is reported for each test batch size.

	Method	Test batch size 200	64	16	4	2	1	Avg.
	Source	4.92	4.92	4.92	4.92	4.92	4.92	4.92
Norm	TBN	6.41	6.60	8.64	17.65	26.08	90.00	25.90
	Ours (TTN)	**4.88**	**5.11**	**5.35**	**7.27**	**9.45**	**9.96**	**7.00**
Optim.	TENT	6.15	6.45	8.61	17.61	26.20	90.00	32.2
	+Ours (TTN)	**4.93**	**5.11**	**5.32**	**7.22**	**9.38**	**10.21**	**7.02**
	SWR	5.63	6.01	8.25	17.49	26.32	90.00	25.62
	+Ours (TTN)	**4.79**	**5.02**	**5.51**	**6.68**	**7.91**	**9.34**	**6.54**

of TTN; $\alpha = 1$ is equal to TBN, and $\alpha = 0.1$ corresponds to α-BN. It is noteworthy that TTN as a stand-alone method favorably compares with optimization-based baselines in all three scenarios.

Adopting TTN improves other TTA methods. We compare optimization-based methods with and without TTN layers. Since TENT, SWR, and CoTTA use TBN layers as default, they also suffer from performance drops when the test batch size becomes small. Adopting TTN reduces the dependency on large test batch size, *i.e.,* makes robust to small batch size, and even improves their performance when using large test batch. Furthermore, in continual (Table 2) and mixed domain (Table 3) adaptation scenario, TENT and SWR shows higher error rate than in single domain (Table 1) adaptation. We interpret that because they update the model parameters based on the current output and predict the next input batch using the updated model, the model will not perform well if the consecutive batches have different corruption types (*i.e.,* mixed domain adaptation). Moreover, the error from the previous input batch propagates to the future input stream, and thus they may fall apart rapidly once they have a strongly wrong signal, which can happen in continual adaptation (*i.e.,* long-term adaptation without resetting). Applying TTN significantly accelerates their model performance regardless of the evaluation scenarios.

TTN preserves knowledge on source domain. In practice, data-driven from the source domain (or a merely different domain) can be re-encountered in test time. We used clean domain test data in a single domain adaptation scenario to show how TTN and other TTA methods adapt to the seen source domain data (but unseen instance). As shown in Table 4, all baseline methods using TBN layers, show performance drops even with large batch sizes. We can conclude that it is still better to rely on source statistics collected from large training data than using only current input statistics, even if its batch size is large enough to obtain reliable statistics (*i.e.,* 200). However, since TTN utilizes source statistics while leveraging the current input, TTN itself and TTN adopted methods well preserve the source knowledge overall compared to the TBN-based methods. With a batch

Table 5: **Adaptation on class imbalanced target domain.** Error rate (↓) averaged over 15 corruptions of CIFAR-10-C where test data is sorted in class label order and composed into test batches.

Method	Test batch size 200	64	16	4	2	1	Avg.
Source	18.27	18.27	18.27	18.27	18.27	18.27	18.27
TBN	77.60	76.66	77.72	78.59	77.84	90.00	79.74
Ours (TTN)	**35.75**	**35.13**	**34.92**	**32.51**	**28.60**	**17.99**	**30.82**

Table 6: **Adaptation on DG benchmarks in semantic segmentation.** mIoU(↑) comparison on four unseen domains with ResNet-50 based DeepLabV3+ model pre-trained on Cityscapes.

Method (Cityscapes→)	BDD-100K	Mapillary	GTAV	SYNTHIA	Cityscapes
Source (Chen et al., 2018)	44.28	50.68	43.04	23.23	**77.66**
TBN	43.95	46.14	41.41	25.88	74.56
Ours (TTN)	**48.62**	**54.14**	**43.51**	**26.93**	77.08

size of 200, we can observe that combining the source with a current test batch can improve the performance of the source model (see 3rd row of Table 4).

TTN is robust to class imbalanced scenario. Heavily depending on current test batch statistics are especially vulnerable when the class labels are imbalanced (Boudiaf et al., 2022; Gong et al., 2022). To simulate this situation, we sorted test images in class label order and then sampled test batches following the sorted data order. In Table 5, we can observe that TTN is more robust to class imbalanced scenario than utilizing only test batch statistics (*i.e.,* TBN). As explained in Section 3.5, we are putting more importance on CBN than TBN, where semantic information is mainly handled, *i.e.,* in deeper layers, so we can understand that TTN is less impacted by skewed label distribution.

3.3 Experiments on Semantic Segmentation

We additionally conduct experiments on domain generalization (DG) benchmarks (Choi et al., 2021; Pan et al., 2018) for semantic segmentation, including natural domain shifts (*e.g.,* Cityscapes→BDD-100K), to demonstrate the broad applicability of our proposed method. Table 6 shows the results of evaluating the ResNet-50-based DeepLabV3+ (Chen et al., 2018) model trained on the Cityscapes training set using the validation set of real-world datasets such as Cityscapes, BDD-100K, and Mapillary, and synthetic datasets including GTAV and SYNTHIA, respectively. We employ a test batch size of 2 for test-time adaptation in semantic segmentation. TBN performs worse than the source model on most datasets, except for SYNTHIA, which has a large domain gap. Despite such a small test batch size, TTN significantly outperforms the other methods on both synthetic (*i.e.,* large domain gap) and real-world datasets (*i.e.,* small domain gap).

3.4 Ablation Studies

Prior $\mathcal{A}$ regularizes α to be robust to overall test batch sizes. We conducted an ablation study on the importance of each proposed component, *i.e.,* initializing α with prior $\mathcal{A}$, optimizing α using CE and MSE loss, and the results are shown in Table 7. Initialization and MSE loss using $\mathcal{A}$ both aim to optimize α following our intuition that we discussed in Section 2.3. Optimizing α using CE loss improves the overall performance, but without regularizing with MSE loss, α may overfit to large batch size (see rows 2 & 3). Initialization with $\mathcal{A}$ or not does not show a significant difference, but we can see that $\mathcal{A}$ provides a better starting point than random initialization when comparing the left and right of the 2nd row. We observe that when using MSE loss, with or without $\mathcal{A}$, the optimized α sufficiently reflects our intuition resulting in a low error rate to overall batch sizes (see row 3).

Table 7: **Ablation study on importance of each component**

Method			**Test batch size**						**Avg.**	**Method**			**Test batch size**						**Avg.**
Init.	CE	MSE	200	64	16	4	2	1		Init.	CE	MSE	200	64	16	4	2	1	
-	-	✓	**11.64**	**11.73**	12.26	14.46	16.94	19.88	14.49	✓	-	-	11.73	12.03	13.22	18.81	23.92	42.70	20.40
-	✓	-	13.36	13.43	13.85	15.50	17.43	20.07	15.61	✓	✓	-	11.73	11.82	12.23	14.18	16.41	19.27	14.27
-	✓	✓	**11.64**	11.78	12.21	13.97	15.86	18.00	13.91	✓	✓	✓	11.67	11.80	**12.13**	**13.93**	**15.83**	**17.99**	**13.89**

3.5 Visualization of α

Fig. 4 shows the visualization of optimized α for CIFAR-10 with backbone WRN-40. We observe that α decreases from shallow to deep layers (left to right), which means CBN is more active in deeper layers, and TBN is vice versa. As shown in Table 4 and 6, CBN employing source statistics is superior to TBN when the distribution shift between source and target domains is small. Assuming that the α we obtained is optimal, we can conjecture that CBN is more active (*i.e.,* α closer to 0) in deeper layers because domain information causing distribution shift is diminished, whereas TBN has

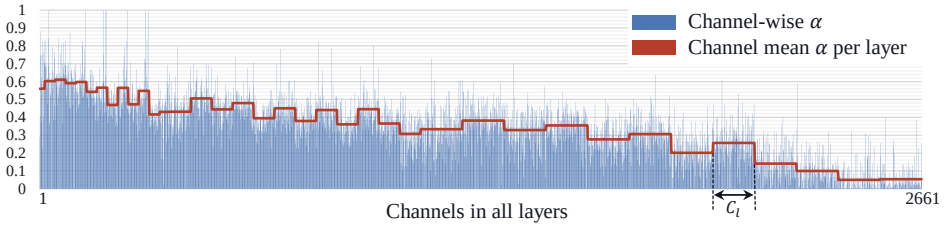


Figure 4: **Optimized α.** x- and y-axes indicate all channels in order from shallow to deep layers and the interpolating weight α, respectively. C_l denotes the channel size of layer l.

a larger weight (*i.e.,* α closer to 1) in shallower layers since the domain information induces large distribution shift. This interpretation is consistent with the observations of previous studies (Pan et al., 2018; Wang et al., 2021; Kim et al., 2022a) that style (or domain) information mainly exists in shallower layers, whereas only content information remains in deeper layers.

4 Related Work

Test-time adaptation/training (TTA) aims to adapt models towards test data to overcome the performance degradation caused by distribution shift (Sun et al., 2020; Wang et al., 2020). There are other related problems, unsupervised domain adaptation (UDA) (Sun & Saenko, 2016; Ganin et al., 2016) and source-free domain adaptation (SFDA) (Liang et al., 2020; Huang et al., 2021). Both UDA and SFDA have access to sufficiently large enough unlabeled target datasets, and their objective is to achieve high performance on that particular target domain. Unlike UDA and SFDA, TTA utilizes test data in an online manner. There are two key factors of recent approaches: adapting standardization statistics in normalization layers and adapting model parameters.

Normalization in Test Time. Schneider et al. (2020) introduced adapting BN statistics by combining source and test batch statistics considering the the test batch size to mitigate the intermediate covariate shift. Similarly, You et al. (2021) and Khurana et al. (2021) also mix the statistics using predefined hyperparameter. Also, Mirza et al. (2022) and Hu et al. (2021) adapt the statistics using moving average while augmenting the input to form a pseudo test batch when only a single instance is given. The primary difference with the existing approaches is that we consider the channel-wise domain-shift sensitivity of BN layers to optimize the interpolating weights between CBN and TBN.

Optimization in Test Time. TENT (Wang et al., 2020), SWR (Choi et al., 2022), CoTTA (Wang et al., 2022) update model parameters while using TBN. TENT optimized affine parameters in BN layers using entropy minimization while freezing the others. To maximize the adaptability, SWR updated the entire model parameters minimizing the entropy loss based on the domain-shift sensitivity. To stabilize the adaptation in continuously changing domains, CoTTA used consistency loss between student and teacher models and stochastically restore random part of the pre-trained model.

We focus on correcting the standardization statistics using domain-shift aware interpolating weight α. Similar to Choi et al. (2022), we measure the domain-shift sensitivity by comparing gradients. The principle difference is that we use channel-wise sensitivity when optimizing α in post-training, while SWR uses layer-wise sensitivity regularizing the entire model update in test time.

5 Conclusions

This paper proposes TTN, a novel domain-shift aware batch normalization layer, which combines the benefits of CBN and TBN that have a trade-off relationship. We present a strategy for mixing CBN and TBN based on the interpolating weight derived from the optimization procedure utilizing the sensitivity to domain shift and show that our method significantly outperforms other normalization techniques in various realistic evaluation settings. Additionally, our method is highly practical because it can complement other optimization-based TTA methods. The oracle mixing ratio between CBN and TBN can vary depending on the domain gap difference. However, our proposed method employs a fixed mixing ratio during test time, although the mixing ratio is optimized before model deployment. If we adjust the mixing ratio according to the distribution shift during test time, we can expect a further performance improvement. We consider it as future work. In this regard, our efforts encourage this field to become more practical and inspire new lines of research.

REPRODUCIBILITY STATEMENT

To ensure the reproducibility of our method, we provide the experimental setup in Section 3.1. Moreover, the details on implementation and evaluation settings can be found in Appendix A.1 and A.2, respectively. The pseudo code for overall training and testing scheme is provided in Appendix A.3. Together with related references and publicly available codes, we believe our paper contains sufficient information for reimplementation.

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A APPENDIX: FOR REPRODUCIBILITY

This section provides supplemental material for Section 2 and 3.1.

A.1 IMPLEMENTATION DETAILS

Datasets and Models. For CIFAR-10/100-C, we optimized α using augmented CIFAR-10/100 training set on the pre-trained WideResNet-40-2 (Hendrycks et al., 2019). For ImageNet-C, we used augmented ImageNet training set (randomly sampled 64000 instances per epoch) on the pre-trained ResNet-50.

Augmentation. Following the setting of SWR (Choi et al., 2022), we used color jittering, random invert and random grayscale when obtaining the prior $\mathcal{A}$. When optimizing α, we followed the augmentation choice of CoTTA (Wang et al., 2022), which are color jittering, padding, random affine, gaussian blur, center crop and random horizontal flip. We excluded for gaussian noise to avoid any overlap with corruption type of common corruptions Hendrycks & Dietterich (2018). For ImageNet, we only used the same augmentation both for obtaining $\mathcal{A}$ and optimizing α following the SWR augmentation choices.

Post-training. We used Adam (Kingma & Ba, 2015) optimizer using a learning rate (LR) of 1e-3, which is decayed with cosine schedule (Loshchilov & Hutter, 2017) for 30 epochs and used 200 training batch for CIFAR-10/100. For ImageNet, we lowered LR to 2.5e-4 and used 64 batch size. We can terminate the training when MSE loss saturates (We observed that α does not show great difference after the MSE loss is saturated). We used the weighting hyperparmeter to MSE loss λ as 1.

Test time. For optimization-based TTA methods, we followed default setting in TENT, SWR, and CoTTA for test-time adaptation. We used LR of 1e-3 to test batch size of 200 for CIFAR-10/100-C in single domain (TENT, SWR) and continuously changing domain (CoTTA) scenarios. For smaller batch sizes in single domain adaptation scenario and all batch sizes for the other two scenarios, we lowered the LR to 1e-4, to avoid rapid error accumulation. For all TTN applied experiments, we used LR of 1e-4, since TTN already mitigates the distribution shift, so we let baselines update less rigorously. Moreover, in continuously changing and mixed domain scenarios, we used the stable version of SWR, which updates the model parameter based on the frozen source parameters instead of previously updated parameters (original SWR). For ImageNet-C, we used LR of 2.5e-4 for all test batch sizes. For all test-time adaptaion, we used constant learning rate without scheduling.

A.2 EVALUATION SCENARIO DETAILS

Mixed domain scenario. We introduce a mixed domain scenario, which we cyclically repeat 15 corruption types to comprise each test batch. A batch consists of the same corruption type, but the corruption types of consecutive batches differ. In other words, the corruption sequence is repeated as *domain 1 (batch 1)* $\rightarrow$ *domain 2 (batch 2)* $\rightarrow \ldots \rightarrow$ *domain 14 (batch 14)* $\rightarrow$ *domain 0 (batch 15)* $\rightarrow$ *domain 1 (batch 16)* $\rightarrow \ldots \rightarrow$ *domain N%15 (batch N)*. The total number of test images is same as the total number of the test split of clean dataset *i.e.,* 10,000 test images for CIFAR-10-C in mixed domain scenario.

Class imbalanced setting In the main paper Table 5, we show the results under class imbalanced settings. In the setting, we sorted the test dataset of each corruption in the order of class labels, i.e., from class 0 to 9 for CIFAR-10-C. Then, we comprised test batches following the sorted order. Therefore, most batches consist of single class input data, which leads to biased test batch statistics. For larger batch size, the statistics are more likely to be extremely skewed, and that explains why error rates are higher with larger batch sizes than with the small ones.

A.3 PSEUDO CODE

Pseudo code for post-training, *i.e.,* obtaining $\mathcal{A}$ and optimizing α, is provided in Algorithms 1 and 2, respectively, and that for test time is in Algorithm 3. Please see Section 2 for equations and terminologies used in the algorithms.

Algorithm 1 Obtain prior $\mathcal{A}$

Require: Pre-trained model f_θ; source training data $\mathcal{D}_S = (X, Y)$
Output: Prior $\mathcal{A}$
for all (x, y) in $\mathcal{D}_S$ **do**
  Augment x: x'
  Collect gradients $(\nabla_\gamma, \nabla_{\gamma'})$ and $(\nabla_\beta, \nabla_{\beta'})$ from f_θ using clean x and augmented x'
end for
Compute gradient distance score d using Eq. 4
Define prior $\mathcal{A}$ using Eq. 5

Algorithm 2 Post-train

Require: Pre-trained model f_θ; source training data $\mathcal{D}_S = (X, Y)$;
step size hyperparameter η; regularization weight hyperparameter λ
Output: Optimized interpolating weight α
Obtain prior $\mathcal{A}$ using Algorithm 1
Initialize α with prior $\mathcal{A}$
Replace all BN layers of f_θ to TTN layers using α and Eq. 2
while not done **do**
  Sample minibatches $\mathcal{B}^S$ from $\mathcal{D}_S$
  for all minibatches **do**
    Augment all x in $\mathcal{B}^S$: x'
    Evaluate $\nabla_\alpha \mathcal{L}$ using f_θ given $\{(x'_i, y_i)\}_{i=1}^{|\mathcal{B}^S|}$ using Eq. 6 while adapting standardization statistics using Eq. 2
    Update $\alpha \leftarrow \alpha - \eta \nabla_\alpha \mathcal{L}$
  end for
end while

Algorithm 3 Inference (Test time)

Require: Pre-trained model f_θ; optimized α, target test data $\mathcal{D}_T = (X)$;
Replace all BN layers of f_θ to TTN layers using α and Eq. 2
Sample minibatches $\mathcal{B}^T$ from $\mathcal{D}_T$
for all minibatches **do**
  Make prediction using f_θ given $\mathcal{B}^T$ while adapting standardization statistics using Eq. 2
end for

B Appendix: Experimental Results

This section provides additional experimental results supplementing the Section 3.2 and 3.4.

B.1 Ablation Studies

Channel-wise α. In Table 8, we compared different granularity levels of interpolating weight α, *i.e.,* channel-wise, layer-wise, and a constant value with CIFAR-10-C and backbone WRN-40-2. We observed that channel-wise optimized α shows the best performance. We take average of the channel-wisely optimized α (the 1st row) over channels to make a layer-wise α (the 2nd row), and take average over all channels and layers to make a constant value (the 3rd row). α of the 1st and 2nd rows are visualized in the main paper Table 4 colored in blue and red, respectively. The constant value α (the 3rd row) is 0.3988. We also optimized α layer-wisely (the 4th row).

B.2 Results on ImageNet-C

Table 9 shows the experimental results using ResNet-50 (He et al., 2016) on ImageNet-C (Hendrycks & Dietterich, 2018) dataset. TTN shows more robust and better performance than TBN and α-BN (You et al., 2021).

Table 8: **Ablation study on granularity level of α**

#	Method	Test batch size						Avg.
		200	64	16	4	2	1	
1	**Channel-wise (Optimized)**	**11.67**	**11.80**	**12.13**	**13.93**	**15.83**	**17.99**	**13.89**
2	Layer-wise (Channel mean)	12.75	12.84	13.16	14.66	16.40	18.82	14.77
3	Constant (Mean)	12.07	12.21	13.05	16.72	20.04	21.26	15.89
4	Layer-wise (Optimized)	13.11	13.21	13.51	14.84	16.46	18.62	14.96

Table 9: **Single domain adaptation on ImageNet-C (ResNet-50).** Error rate (↓) averaged over 15 corruption types with severity level 5 is reported for each test batch size.

	Method	Test batch size					Avg. Error
		64	16	4	2	1	
	CBN	93.34	93.34	93.34	93.34	93.34	93.34
Norm	TBN	74.24	76.81	85.74	95.35	99.86	86.40
Norm	α-BN	86.06	86.32	87.16	88.33	90.45	87.66
Norm	**Ours (TTN)**	**72.81**	**73.80**	**77.68**	**82.16**	**90.56**	**79.40**

B.3 Error Rates of Each Corruption

In Table 10, we shows the error rates of TTN per each corruption of CIFAR-10-C. Here we exploit the WRN-40-2 backbone. The averaged results over the corruptions are in the main manuscript, Table 1.

Table 10: **Results of each corruption (CIFAR-10-C)**

batch size	gauss.	shot	impulse	defocus	glass	motion	zoom	snow	frost	fog	brightness	contrast	elastic	pixel.	jpeg.	Avg.
200	14.81	12.78	17.32	7.37	17.87	8.51	7.23	10.29	9.88	11.29	6.06	8.36	13.42	14.89	14.94	11.67
64	14.81	12.81	17.42	7.41	18.21	8.66	7.41	10.44	9.93	11.63	6.11	8.35	13.59	15.18	15.02	11.80
16	15.23	13.00	17.98	7.71	18.46	8.95	7.68	10.85	10.17	12.21	6.25	8.54	13.95	15.67	15.34	12.13
4	17.03	15.29	19.75	9.26	20.93	10.01	9.62	12.58	11.85	13.65	7.69	9.25	16.21	18.08	17.70	13.93
2	19.21	16.80	21.86	10.70	23.74	11.39	11.92	14.00	13.39	15.38	8.95	10.13	18.92	20.68	20.40	15.83
1	22.03	19.97	25.24	12.41	26.99	12.22	14.39	14.73	14.60	17.27	10.16	9.51	22.10	24.12	24.09	17.99