

Is Synthetic Data all We Need?

Benchmarking the Robustness of Models Trained with Synthetic Images

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Abstract

A long-standing challenge in developing machine learning approaches has been the lack of high-quality labeled data. Recently, models trained with purely synthetic data, here termed synthetic clones, generated using large-scale pre-trained diffusion models have shown promising results in overcoming this annotation bottleneck. As these synthetic clone models progress, they are likely to be deployed in challenging real-world settings, yet their suitability remains understudied. Our work addresses this gap by providing the first benchmark for three classes of synthetic clone models, namely supervised, self-supervised, and multi-modal ones, across a range of robustness measures. We show that existing synthetic self-supervised and multi-modal clones are comparable to or outperform state-of-the-art real-image baselines for a range of robustness metrics – shape bias, background bias, calibration, etc. However, we also find that synthetic clones are much more susceptible to adversarial and real-world noise than models trained with real data. To address this, we find that combining both real and synthetic data further increases the robustness, and that the choice of prompt used for generating synthetic images plays an important part in the robustness of synthetic clones.

1. Introduction

Most modern machine learning methods are bottlenecked in performance by the quality and quantity of labeled data. Several works [5, 39, 43] have shown that the generalization error of neural networks follows the neural scaling law with respect to the dataset size, *i.e.* the test error reduces linearly with the log of the dataset size. Moreover, the datasets’ diversity [53] and fairness [63] are also factors that play an important role in the generalization performance of modern

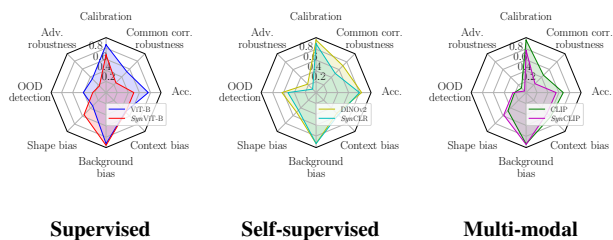


Figure 1. **Robustness of synthetic clones vs. real-image baselines** for different model classes. Self-supervised and multi-modal synthetic clones are close in performance on various robustness measures to baseline models trained on real images. All synthetic clones suffer in performance w.r.t. adversarial and common corruption robustness.

neural networks. Unfortunately, curating diverse, fair, and large datasets is time-consuming and expensive.

The advent of large-scale image generation models like Stable Diffusion [64] has revived the interest in utilizing generated images to train models for various downstream tasks in hopes of alleviating the need for high-quality annotations. Models like [22, 67, 89] use only generated images from Stable Diffusion for supervised training of a downstream classifier. [22, 31, 73] show that it is also possible to train self-supervised models like SimCLR [14] and multi-modal models like CLIP [60] using *only* synthetic images and prompts. These models can match or outperform their counterparts trained on real data for downstream tasks like classification and segmentation. We term such models that are trained using only generated data as *synthetic clones*.

Modern machine learning models are increasingly employed in solving real-world problems like autonomous driving and automated medical assistance [9]. With the rapid progress of using synthetic data for training models, it is imperative that we understand how robust these models are before deploying them in the real world. Recent work on synthetic clones [22, 67, 73] has not focused on evaluating the robustness of these models. Yet, models trained

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on synthetic or generated datasets have been known to suffer from shortcomings such as model collapse [19, 70], *i.e.* when the model forgets the long tail classes or learns a different distribution than the training dataset.

Our work aims to provide a comprehensive benchmark for the robustness of synthetic clone models compared to state-of-the-art (SOTA) baseline models that are trained on real image datasets. We benchmark three classes of synthetic clone models – supervised [22, 67], self-supervised [73], and multi-modal [22] ones – against nine strong baseline models trained using real images. We evaluate robustness metrics regarding shape, background, and context bias. We also benchmark these models against adversarial and common image corruptions. Finally, we test how well these models are calibrated in comparison to models trained with real data. Our results are visually summarized in Fig. 1.

To overcome some of the drawbacks of using synthetic data alone, we conduct extensive ablations regarding how the robustness of synthetic clones changes with (i) joint training with synthetic and real data, (ii) increasing the number of synthetic samples, and (iii) the effect of prompts when generating images with Stable Diffusion.

Let us summarize our findings: (i) On many robustness metrics (calibration, background bias, shape bias, *etc.*) self-supervised and multi-modal models trained on synthetic data perform on par with their counterparts trained on real imagery. (ii) Supervised synthetic models, on the other hand, lag behind baselines trained on real datasets w.r.t. several key robustness measures like calibration, OOD detection, adversarial robustness, *etc.* (iii) Synthetic clones are much more vulnerable to adversarial and common corruption than models trained with real images. (iv) A mixture of real and synthetic data is the best combination for obtaining robustness. (v) The choice of prompt for image generation plays a crucial role in the robustness of synthetic clones.

2. Related Work

Self-supervised learning (SSL) methods [7, 12, 33, 34] have emerged as promising alternatives to solve the data annotation bottleneck. These models learn by solving pretext tasks like context prediction [18], image denoising [79], patch prediction [18], and many others [11, 56, 59, 86, 87]. In recent years, they have come increasingly close to supervised models. For example, the downstream classification accuracy for DINOv2 [57] with supervised linear probing is 84.5% (using ViT-B) while that of EfficientNet [84], a strong supervised model, is 88.4% on the ImageNet-1K dataset [15]. However, SSL methods suffer from scaling issues, *i.e.* augmenting an already large-scale dataset in size has little effect on the model performance [29]. Another approach is using large-scale uncurated multimodal web data [60]. However, this data is often noisy, biased, and limited in diversity (*e.g.*, certain concepts may have only a few data

points [24, 58]).

Generative neural networks are a class of models that, given random noise samples, learn to transform these noise samples into data. Modern generative models can broadly be categorized into *implicit models*, such as GANs [3, 10, 27, 45] and diffusion-based models [40, 72], or *explicit models* like normalizing flows [13, 17] and VAEs [48, 77]. Diffusion models are SOTA for image generation since they address the limited diversity and image quality issues, which impaired the use of previous generative models [83].

Synthetic data has found usage in a myriad of computer vision tasks or applications like semantic segmentation [61], object detection [65], and autonomous driving [1]. Recently, generated data from large-scale pre-trained diffusion models was used to train better object classification models [4]. Particularly, [35, 67] showed that synthetic data is extremely useful in transfer learning, zero-shot, and few-shot classification. [22, 31, 74] show that even training of large-scale self-supervised models, such as CLIP [60] and SimCLR [14], is possible with synthetic data. Our work focuses on such synthetic clone models where the training data was generated using large-scale pre-trained diffusion models. We use diffusion models because of the superior quality and diversity of the generated data.

Robustness. An often overlooked aspect when evaluating models trained with synthetic datasets is evaluating them for robustness. Recently, some efforts have been made to benchmark models trained with synthetic data for adversarial robustness [69] and out-of-distribution (OOD) detection [6]. Still, no comprehensive robustness evaluation of these models exists. In our work, we aim to benchmark synthetic clone models in a more comprehensive manner and on various robustness benchmarks. Besides adversarial robustness [28] and OOD detection, we also benchmark these models on common 2D and 3D image corruptions [36, 44], and w.r.t. shape bias [25], context bias [46], background bias [52], and calibration [30]. Previous works [6, 69] have only benchmarked small-scale supervised synthetic models, while we analyze synthetic clones trained with 100s of millions of synthetic images across three classes of models, namely supervised, self-supervised, and multi-modal ones.

3. Background: Synthetic Clones

Before analyzing various synthetic clone models below, let us briefly recapitulate how synthetic images can be generated using diffusion models and how various classes of models have been trained on these synthetic images.

Synthetic data generation. The synthetic images in synthetic clone models [22, 31, 67, 73] are typically generated using large-scale pre-trained image generation models, *e.g.*, Stable Diffusion [64] or Imagen [66]. The input to the generation model is Gaussian noise and a conditional text

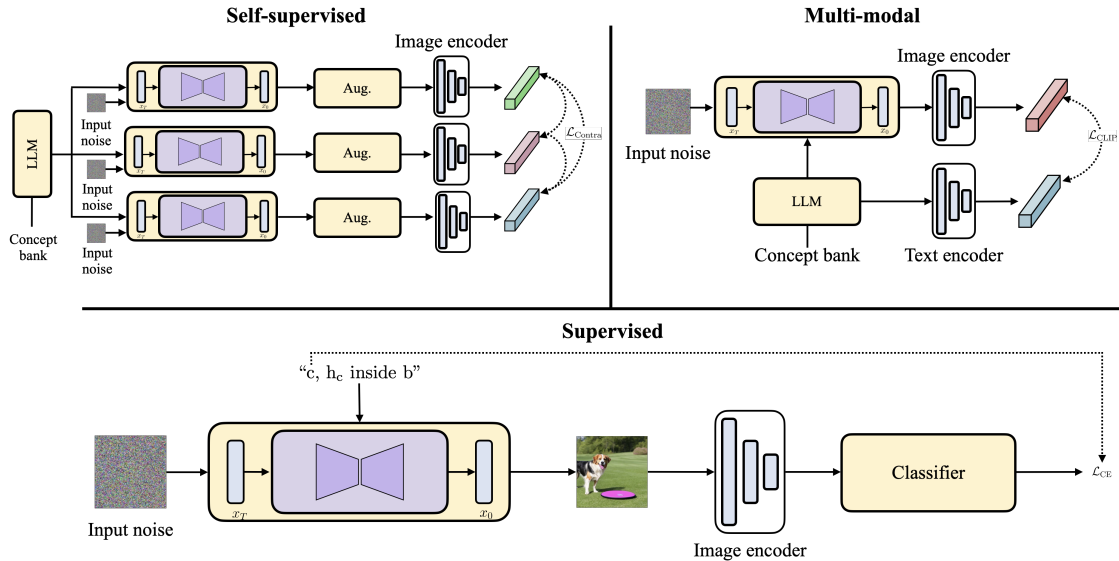


Figure 2. **Setups for training different classes of models using synthetic images.** Supervised learning (*bottom*) uses the ground-truth label for conditionally generating a synthetic image, while self-supervised (*top left*) and multi-modal methods (*top right*) make use of a concept bank along with a large language model (LLM) for prompt generation. Please see text for more details.

prompt. Synthetic clones can be divided into three categories, namely supervised synthetic models, self-supervised synthetic models, and multi-modal synthetic models. We now describe how each model creates the prompt for generating the image and which losses are used to train the model.

Supervised models using generated data. For training a supervised classifier, Saryıldız et al. [67] first generate an image using Stable Diffusion conditioned on the prompt “ c, h_c inside b ”. Here, c is the ground-truth class name sampled from all class labels of a dataset (e.g., ImageNet-1K [15]), h_c is the hypernym associated with c , and b denotes one of the 365 classes from the Places365 [88] dataset. A hypernym of c is the parent node of c in the WordNet [23] hierarchy. The classifier is then trained end to end with the cross-entropy loss (\mathcal{L}_{CE}) between the predicted label of the generated image and the sampled ground-truth class label used for generating the image; see Fig. 2 (*bottom*). Saryıldız et al. [67] created 1.2M such prompts and generated corresponding images to train a ResNet50 model. Similarly, Fan et al. [22] used just class names “ c ” for generating 16M images. They then train a ViT-B model on the generated images and ground-truth class labels.

Self-supervised models using generated data. Synthetic self-supervised models, namely *SynCLR* [73] and *StableRep* [74], first sample a concept label from a concept bank. The concept bank is typically constructed using extracted synsets of WordNet [23] or common unigrams, bigrams, and titles from Wikipedia [85]. This sampled concept label is then fed into a large language model (LLM) [2, 42, 76] for generating extra contextual information. The

final prompt is formed by concatenating the concept label and the contextual information. This prompt is then used to generate n images. After this, several augmentations (Aug.) also used in the SimCLR model [14] are applied. The *SynCLR* model is trained using a multi-positive contrastive loss (\mathcal{L}_{Contra}) [47, 73], see in Fig. 2 (*upper left*).

Multi-modal model using generated data. The multi-modal synthetic CLIP [22, 31] models also use a concept label sampled from a concept bank. This concept label, along with a random place label sampled from the classes of Places365 dataset, is fed into an LLM [2] for generating a caption, which is subsequently used for conditional image generation. These images are used to train a CLIP model [60] using a contrastive loss between the generated image and the prompt that was used for generating the image. The architecture is shown in Fig. 2 (*upper right*).

4. Robustness Analysis

Setup. We divide the models to be analyzed into supervised, self-supervised, and multi-modal models. For synthetic supervised models, we use a ResNet50 from [67] and a ViT-B model from [22], which were trained on approx. 1M images generated using prompts as described in Sec. 3. The class labels used for creating the prompts were sampled from the classes of the ImageNet-1K dataset [15]. For clarity of notation, we term them *SynResNet50* and *SynViT-B* for all our experiments. We compare these models against strong supervised models trained on the real ImageNet-1K dataset like ResNet50 [32], ViT-B [20], DeiT-III [75], Swin transformer [50], and ConvNeXt [51]. All baselines are

from the PyTorch Image Models library [80].

For the self-supervised case, we use the *SynCLR* model [73], which has been trained on 600M synthetic images. We use SOTA self-supervised models like DINOv2 [57], MAE [34], and MOCOv3 [33] trained on ImageNet-1K as self-supervised baselines. All checkpoints for the baseline models were obtained from the timm library. For a fair comparison, we use the ViT-B [20] backbone with a patch size of 16 for all models. We perform linear probing on all self-supervised models, training a single-layer linear classification head on the top of these models for 90 epochs using the ImageNet-1k [15] dataset. We searched over ten learning rates to find the optimal linear classifier for each model.

Finally, for the multi-modal case, we analyze the synthetic CLIP model from [22], which we term as *SynCLIP*, trained on 371M synthetic images. We compare this model with the CLIP implementation from OpenCLIP [41], trained on 400M real images. We used the ViT-B backbone for these models to allow for a fair comparison. For CLIP and *SynCLIP* we report the zero-shot results.

4.1. Calibration

As neural networks become adopted for safety-critical tasks like autonomous driving and healthcare, it is not only important to predict accurate results, but also to accurately report the confidence in their prediction [30]. Calibration can help to understand how reliable the model’s prediction is and whether an end user can trust the model’s output. The calibration of neural networks is commonly measured using the Expected Calibration Error (ECE) [55]. The ECE measures the expected absolute difference between the model confidence and the model accuracy. In our work, we study the effect that training on synthetic images has on the calibration of a model compared to training with real data.

We report the results for the ECE metric with 20 bins for all models. Fig. 3 shows the results for both in-distribution (ID) calibration (train and test splits are from the same dataset) on the ImageNet-1k dataset [15] and for out-of-distribution (OOD) calibration (train and test split are from different datasets) on the ImageNet-R [37] and ImageNet-A [38] datasets. We can conclude the following:

Observation 1: *Synthetic clones are mostly well calibrated for the in-distribution case and even to some extent out-of-distribution on ImageNet-R. The OOD calibration of synthetic clones suffers on ImageNet-A.*

This may be because the synthetic data generated from pre-trained diffusion models (trained on data scraped from the web) already captures the distribution of the ImageNet (images scraped from the web) and ImageNet-R (consisting of cartoons and sketches, which are abundant on the internet) datasets. ImageNet-A, on the other hand, consists of

naturally adversarial examples that are hard to find on the internet; hence, synthetic clones and even baseline models trained on real images exhibit a rather poor calibration for this dataset. However, models trained with real datasets are generally better calibrated for ImageNet-A, likely due to the inherent noise in the dataset (see also Sec. 4.2).

Out of distribution (OOD) detection deals with finding out how well a model can distinguish between samples from the training data distribution (ID – in distribution) and samples from another distribution. OOD detection is critical to increasing an end users’ trust in the safety and reliability of the model. We thus aim to evaluate how training on synthetic data affects a model’s capability for OOD detection.

The OOD detection task can be formulated as a binary classification task on the model’s predictive probability. A model F with weights θ classifies an input sample x_i as ID if the maximum predictive probability of the sample is higher than a pre-defined threshold value τ , *i.e.* $\max F_\theta(x_i) \geq \tau$, and as OOD if $\max F_\theta(x_i) < \tau$. OOD detection can be evaluated using standard metrics for binary classification, such as the area under the receiver operating characteristic curve (AUROC). We also report the false positive rate of OOD samples when the true positive rate of in-distribution samples is at 95% (FPR@95). Tab. 1 shows the results of all models on three OOD datasets, namely SUN397 [81], Places365 [88], and iNaturalist [78], where ImageNet-1K is the ID dataset. We conclude the following:

Observation 2: *SynCLR and SynCLIP are comparable to the baseline models in their category for OOD detection. Even with 16 times more data than the baseline, SynViT-B clearly lags behind supervised models trained with real data.*

4.2. Robustness

Adversarial robustness. Adversarial learning aims to understand model robustness to examples manipulated by an adversary in a way that the examples seem similar to the human eye but change the model’s predictions. In our work, we want to explore whether models trained on synthetic data are more susceptible to adversarial attacks. We use two popular white-box attacks, the Fast Gradient Sign Method (FGSM) [28] and the Projected Gradient Descent (PGD) attack [52]. These white-box attacks require that the model’s gradient be known to the adversary. The FGSM attack perturbs the input image with the gradient of the model’s prediction w.r.t. its input, scaled by a small step ϵ . This can be written as $\hat{x}_i = x_i + \epsilon \nabla_{x_i} J(\theta, x_i, y_i)$, where x_i denotes the input image, $\nabla_{x_i} J$ denotes the gradient of the loss function w.r.t. x_i , and y_i denotes the label for the input image x_i .

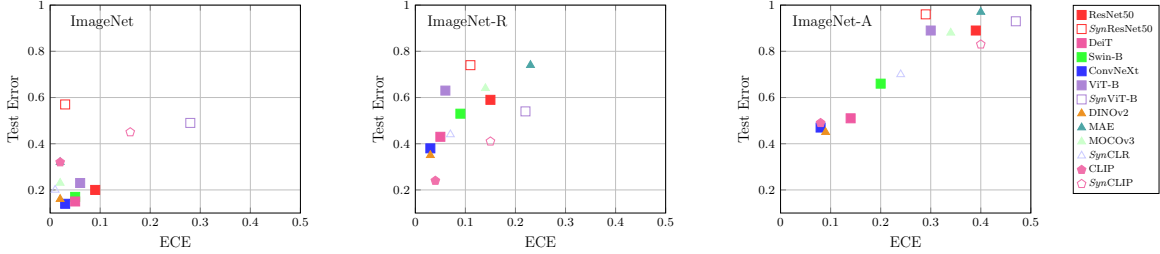


Figure 3. **Test error vs. ECE for ID and OOD datasets.** We report the resulting ECE metric and test error metrics for both ID (ImageNet) and OOD datasets (ImageNet-{R,A}). Filled markers indicate real models, empty markers indicate synthetic clones.

Table 1. **OOD detection with ImageNet-1K being in-domain (ID).** We report the AUROC and FPR@95 metrics for the OOD detection task on the three OOD datasets, namely SUN, iNaturalist, and Places. In addition, we also report the avg. performance of all models on all three datasets. The best performing model in each category is highlighted in **bold**.

Model	No. of training images	SUN		iNaturalist		Places		Avg.	
		AUROC (\uparrow)	FPR@95 (\downarrow)	AUROC (\uparrow)	FPR@95 (\downarrow)	AUROC (\uparrow)	FPR@95 (\downarrow)	AUROC (\uparrow)	FPR@95 (\downarrow)
ResNet50	1.2M	0.84	0.65	0.91	0.47	0.82	0.69	0.86	0.60
SynResNet50	1.2M	0.70	0.83	0.72	0.89	0.67	0.87	0.70	0.86
Swin-B	1.2M	0.79	0.63	0.86	0.45	0.77	0.69	0.81	0.59
ConvNeXt	1.2M	0.76	0.68	0.89	0.45	0.74	0.71	0.80	0.61
DeiT	1.2M	0.80	0.66	0.89	0.48	0.80	0.68	0.83	0.61
ViT-B	1.2M	0.81	0.64	0.90	0.45	0.80	0.67	0.84	0.59
SynViT-B	16M	0.76	0.74	0.75	0.75	0.72	0.79	0.74	0.76
MAE	1.2M	0.76	0.84	0.87	0.71	0.75	0.86	0.79	0.80
DINOv2	142M	0.88	0.49	0.98	0.09	0.87	0.53	0.91	0.37
MOCOv3	1.2M	0.84	0.65	0.94	0.35	0.84	0.66	0.87	0.55
SynCLR	600M	0.85	0.58	0.95	0.24	0.83	0.63	0.88	0.48
CLIP	400M	0.82	0.74	0.68	0.88	0.78	0.76	0.76	0.79
SynCLIP	371M	0.73	0.75	0.74	0.75	0.70	0.79	0.72	0.76

The PGD attack is an iterative version of the FGSM attack, followed by a projection of the adversarial input to an ϵ ball around the input x . The ϵ value denotes the maximum perturbation allowed. We use ϵ values of $1/255$ for the PGD and FGSM attacks. The number of steps is set to 20 for the PGD attack. We report the accuracy of the clean and the adversarial examples from the test set. We define the adversarial robustness metric, R_{adv} , as the relative accuracy between adversarial and clean samples as $R_{adv} = \frac{Acc_{adv}}{Acc_{clean}}$, where Acc_{adv} is the accuracy on the adversarial samples and the Acc_{clean} is the accuracy on the clean samples. Tab. 2 shows the results. We can conclude the following:

Observation 3: *Synthetic clone models are significantly more vulnerable to adversarial examples, particularly supervised synthetic clones, than models trained with real data. The self-supervised synthetic clone model trained with large amounts of synthetic data, i.e. SynCLR, is loosely comparable to real-image baseline models in its respective category.*

We find that MAE [34] performs the worst among all models (synthetic and real) regarding adversarial robustness, indicating that the training objective along with the training dataset size are important factors in determining a model’s adversarial robustness.

Table 2. **Adversarial robustness results (in %).** We report the clean and adversarial accuracy. Also, we report the relative adversarial robustness (R_{adv}) metric for each model.

Model	FGSM			PGD	
	$Acc_{clean}(\uparrow)$	$Acc_{adv}(\uparrow)$	$R_{adv}(\uparrow)$	$Acc_{adv}(\uparrow)$	$R_{adv}(\uparrow)$
ResNet50	80.12	26.95	33.64	16.71	20.85
SynResNet50	42.89	2.12	4.95	1.27	2.96
Swin-B	83.08	48.59	58.49	23.71	28.54
ConvNext	85.52	42.19	49.33	17.51	20.47
DeiT	84.59	53.22	62.92	35.51	41.98
ViT-B	76.78	27.39	35.67	20.45	26.64
SynViT-B	50.96	8.84	17.35	5.06	9.92
MAE	67.59	0.67	0.99	1.34	1.98
DINOv2	84.49	19.10	22.61	18.71	22.14
MOCOv3	76.66	13.21	17.23	9.11	11.88
SynCLR	80.46	7.31	9.08	6.18	7.68
CLIP	68.27	8.75	12.82	6.31	9.24
SynCLIP	55.11	2.40	4.35	2.02	3.67

Robustness against common corruptions. Next, we evaluate the performance of all models on real-world noise corruptions that occur frequently. For this, we evaluate on the ImageNet-C [36] and ImageNet-3DCC [44] datasets. ImageNet-C consists of 19 naturally occurring image corruptions like Gaussian noise, shot noise, motion blur, elastic transforms, *etc.* ImageNet-3DCC includes 12 common corruptions that take depth into account, *e.g.*, z -axis blur,

Table 3. **Common corruptions robustness results** (in %). We report the individual and average accuracy for various 2D and 3D common corruptions. We also report the relative drop in average accuracy (Avg. R_{cc}) for all models.

Noise	ResNet50	SynResNet50	Swin-B	ConvNeXt	DeiT	ViT-B	SynViT-B	MAE	DINOv2	MOCov3	SynCLR	CLIP	SynCLIP
AccClean	80.12	42.89	83.08	85.52	84.59	76.78	50.96	67.59	84.49	76.66	80.46	68.27	55.11
Shot noise	56.31	5.11	66.33	72.31	75.41	57.95	29.03	34.47	73.45	57.14	43.23	44.13	19.85
Motion blur	47.55	5.56	59.87	67.30	70.85	49.58	19.91	27.70	67.24	48.68	37.47	38.63	16.67
Snow	44.32	7.07	57.62	65.38	69.02	45.71	18.33	25.87	67.17	46.27	40.38	38.22	16.64
Pixelate	45.32	7.38	58.11	66.07	69.66	46.95	19.96	27.89	69.06	48.47	41.33	40.14	17.26
JPEG compression	47.03	7.09	58.92	67.51	70.37	49.82	20.91	30.38	70.70	51.60	39.66	41.81	16.34
Near focus	64.55	27.28	69.11	75.23	75.82	63.17	33.98	47.18	77.33	65.14	67.57	56.90	34.64
Far focus	60.94	24.76	65.93	72.53	73.28	60.13	31.34	43.96	75.35	61.77	63.85	53.89	32.04
Fog 3D	58.80	23.22	63.67	70.17	71.00	58.11	30.57	40.17	72.87	58.64	60.48	51.29	30.88
XY motion blur	54.30	19.42	60.12	66.86	67.94	53.95	26.71	35.25	69.11	54.43	54.78	47.20	27.05
Z motion blur	50.43	16.77	56.85	64.28	65.52	50.12	22.97	32.07	66.59	50.65	50.10	43.90	23.64
Avg. Acc _{cc} (↑)	52.96	14.37	61.65	68.76	70.89	53.55	25.37	34.50	70.89	54.28	49.88	45.61	23.50
Avg. R_{cc} (↑)	66.10	33.50	74.21	80.40	83.80	69.74	49.78	51.04	83.90	70.81	61.99	66.81	42.64

far and near focus errors, *etc.* Due to time and resource constraints, we report the results only on ten common corruption tasks (five each from ImageNet-C and ImageNet-3DCC). We report the accuracy of the clean and corrupted samples and the average accuracy over all corruptions. We also report the Avg. R_{cc} metric, which is defined as the relative accuracy between the clean samples and the average accuracy over all corruptions, *i.e.* $Avg. R_{cc} = \frac{Avg. Acc_{cc}}{Acc_{clean}}$. The results are given in Tab. 3 and yield the following conclusion:

Observation 4: *Synthetic clones are significantly less robust to common corruptions in images than baselines trained with real images.*

The Avg. R_{cc} is significantly lower for synthetic clones across all categories of models. Real datasets inherently have these common corruptions present in the imagery, hence training on real data already makes the resulting models more robust to noise. Synthetic images currently lack these corruptions, making synthetic clones highly susceptible to common image corruptions.

4.3. Biases

Context bias. We define context bias as the affinity of a model to use contextual cues, *e.g.*, location for classifying objects, rather than actually using the object appearance. This context bias exists because most large-scale datasets consist of uncurated data scraped from the internet. For example, images of airplanes in a forest are highly unlikely when compared to airplanes on a taxiway. We use the FOCUS (Familiar Objects in Common and Uncommon Settings) dataset [46] to evaluate the context bias, which consists of around 21K images. Each image in the dataset is annotated with the object class, the time of day, location, and weather labels. FOCUS subdivides the dataset into a subset of common and uncommon samples. Uncommon samples are uncommon in the real world, like “airplane in forest”

Table 4. **Context bias results** (in %). CB_k denotes the context bias with k uncommon attributes.

Model	CB_1 (↑)	CB_2 (↑)
ResNet50	61.27	38.70
SynResNet50	62.33	44.49
Swin-B	68.83	54.85
ConvNext	70.20	55.57
DeiT	68.19	55.19
ViT-B	67.21	49.71
SynViT-B	66.13	50.29
MAE	59.75	46.53
DINOv2	69.11	54.46
MOCov3	62.29	44.95
SynCLR	70.04	58.42
CLIP	76.77	63.09
SynCLIP	71.47	54.39

or uncommon in the ImageNet dataset due to labels used for its construction (*e.g.*, there is no label for seaplane in ImageNet). The dataset is partitioned into mutually exclusive partitions P_k where k is the number of uncommon attributes. The total dataset is divided into four partitions, P_0 (containing only common objects) to P_3 (containing three uncommon attributes). We report the CB_k metrics (Context Bias with k uncommon attributes), which is defined as the relative accuracy between the accuracy on the partition with no uncommon attributes P_0 and a partition with k uncommon attributes P_k , *i.e.* $CB_k = \frac{Acc_{P_k}}{Acc_{P_0}}$. For example, CB_2 measures the relative accuracy between P_0 and P_2 . The results are given in Tab. 4 and yield the following:

Observation 5: *Self-supervised synthetic clones are robust to changes in context compared to baseline supervised and self-supervised models trained with real data. The supervised synthetic clone SynViT-B is comparable in performance to the ViT-B model trained on real data. Meanwhile, SynCLIP is more prone to changes in context compared to CLIP, but it is still comparable to models like DINOv2 and ConvNeXt.*

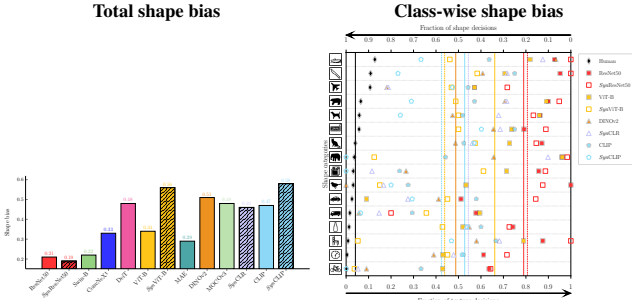


Figure 4. **Shape bias.** (left) Average shape bias of models trained with synthetic (dashed bars) and real data. Synthetic clones are generally more biased toward shape than texture compared to models trained with real datasets. (right) Class-wise shape bias of synthetic clones and their counterparts trained using real data. Solid and dashed lines represent the mean shape bias of models trained with real images and synthetic images, respectively.

Shape-texture bias. Children learn to recognize and organize objects based on shape and are more biased towards object shape rather than color and textures [16, 71]. It has been shown [25, 54] that biasing a network towards shape increases its robustness against common corruptions. This suggests that the robustness of neural networks generally benefits from biasing towards categorizing objects by shape rather than textures. Generated images from GANs typically have high-frequency artifacts (indicating high texture bias) [21, 68]. Diffusion models also exhibit similar patterns, though these are more muted [62]. Such artifacts contrast with real images that do not contain these high-frequency artifacts. To understand if training on synthetic images from Stable Diffusion biases the networks towards texture, we use the cue conflict dataset [25]. This dataset consists of about 1200 images of 16 classes where the texture and shape of an image are in conflict with each other. Fig. 4 shows the shape bias of all the models averaged across all classes. We also show the class-wise shape bias results for synthetic clones and some baseline models. We conclude the following:

Observation 6: *Synthetic clones tend to be more shape-biased than texture-biased.* In particular, *SynCLIP* outperforms all models on the shape bias metric, while *SynViT-B* outperforms all classification and self-supervised models. The *SynCLR* model has comparable performance to the *MOCOv3* model and outperforms the *MAE* model on the shape-bias metric.

A similar result was observed in [8] with synthetic data from StyleGANv2 [45] models. Our results indicate that synthetic data is diverse in terms of shape, leading to a higher shape bias of synthetic clone models, but this could indicate that the generated images lack texture diversity,

Table 5. **Background bias results** (in %). BG-Gap metric reports the drop in performance by just changing the background to a different class than the foreground class.

Model	Original Acc. (IN-9L, ↑)	Mix-Same Acc. (↑)	Mix-Rand Acc. (↑)	BG-Gap (↓)
ResNet50	95.43	87.04	81.36	5.68
SynResNet50	66.44	44.35	35.83	8.52
Swin-B	96.57	88.32	82.57	5.75
ConvNeXt	97.98	93.95	90.40	3.56
DeiT	97.70	93.28	89.98	3.31
ViT-B	95.98	87.53	79.63	7.90
SynViT-B	87.70	77.01	71.60	5.41
MAE	57.36	46.47	40.57	5.90
DINOv2	97.95	91.93	85.95	5.98
MOCOv3	95.01	83.63	74.17	9.46
SynCLR	96.22	86.59	80.37	6.22
CLIP	93.31	83.09	77.19	5.90
SynCLIP	84.79	71.16	65.83	5.33

making the network rely more on shape for classification.

Background bias. The background bias of models can be used to identify if the model is using the background of the image to make the classification decision instead of using the object itself. Learning if a model is biased towards the background is an effective way to understand if the model has learned shortcuts [26] instead of learning good features for the given category. For evaluating a model’s background bias, we utilize the Mixed-Rand and Mixed-Same partitions from the IN-9L dataset [82]. The Mixed-Rand dataset segments the foreground object in an image and switches the original background with a random background from a different class label, while the Mixed-Same partition places the segmented foreground object on a random background from the same class label. Tab. 5 shows the accuracy of all models on the original, Mixed-Rand, and Mixed-Same partitions from the IN-9L dataset, along with BG-Gap. The BG-Gap measures the difference in performance between accuracies on the Mixed-Rand and Mixed-Same datasets and assesses how decisions can be manipulated just by changing the background to a different foreground. We conclude the following:

Observation 7: *Synthetic clones perform on par in terms of background bias with a SOTA baseline model trained with real data.*

In general, we found all models (synthetic and real) to be very robust to background changes.

4.4. Ablations

We now look at three important factors that affect the robustness of synthetic clone models. We use the models from [22] for these ablations (including all the CLIP models).

Effect of prompts. Here, we analyze the effect that the prompt has on the robustness of the synthetic clone models.

Table 6. **Effect of prompt type and dataset size on various performance metrics for the supervised *SynViT-B* model.** R_{adv} (FGSM) denotes the adversarial robustness for the FGSM attack, and R_{cc} (2DCC) the robustness for 2D common corruptions. **Bold** indicates the best performance within a prompt type, and **color** indicates the best performance across all prompts and dataset sizes.

Metric	Class name				Captions				CLIP templates			
	1M	4M	8M	16M	1M	4M	8M	16M	1M	4M	8M	16M
Acc. (\uparrow)	0.44	0.49	0.50	0.51	0.50	0.58	0.59	0.60	0.45	0.53	0.54	0.55
R_{adv} (FGSM, \uparrow)	0.14	0.18	0.17	0.17	0.12	0.16	0.16	0.17	0.15	0.17	0.18	0.18
R_{cc} (2D-CC, \uparrow)	0.39	0.42	0.43	0.42	0.37	0.43	0.44	0.44	0.44	0.51	0.54	0.54
CB ₂ (\uparrow)	0.47	0.47	0.47	0.50	0.52	0.58	0.58	0.59	0.47	0.53	0.50	0.50
Shape Bias (\uparrow)	0.39	0.55	0.56	0.56	0.33	0.42	0.47	0.45	0.57	0.71	0.71	0.69
BG-Gap (\downarrow)	0.71	0.66	0.61	0.54	0.85	0.54	0.53	0.52	0.63	0.42	0.37	0.46
FPR@95 (SUN, \downarrow)	0.81	0.74	0.75	0.74	0.77	0.74	0.73	0.74	0.84	0.82	0.81	0.80
ECE (\downarrow)	0.33	0.31	0.29	0.28	0.25	0.18	0.17	0.16	0.30	0.24	0.23	0.23

Table 7. **Effect of dataset composition and size on various performance metrics for the *SynCLIP* model.** **Bold** indicates the best performance within a prompt type, and **color** indicates the best performance across all dataset compositions and sizes.

Metric	Real				Synthetic				Synthetic + Real			
	64M	128M	256M	371M	64M	128M	256M	371M	64M	128M	256M	371M
Acc. (\uparrow)	0.55	0.60	0.65	0.66	0.47	0.51	0.54	0.55	0.56	0.62	0.65	0.66
R_{adv} (FGSM, \uparrow)	0.09	0.07	0.10	0.12	0.05	0.03	0.04	0.04	0.09	0.08	0.10	0.12
R_{cc} (2D-CC, \uparrow)	0.44	0.46	0.51	0.52	0.29	0.28	0.31	0.31	0.46	0.48	0.52	0.52
CB ₂ (\uparrow)	0.52	0.52	0.57	0.61	0.58	0.53	0.55	0.54	0.61	0.58	0.63	0.61
Shape Bias (\uparrow)	0.51	0.51	0.51	0.52	0.54	0.55	0.59	0.58	0.54	0.51	0.56	0.60
BG-Gap (\downarrow)	0.73	0.76	0.57	0.72	0.65	0.51	0.57	0.53	0.73	0.63	0.63	0.56
FPR@95 (SUN, \downarrow)	0.92	0.84	0.81	0.82	0.86	0.75	0.75	0.75	0.86	0.81	0.82	0.78
ECE (\downarrow)	0.22	0.19	0.16	0.14	0.25	0.20	0.17	0.16	0.16	0.13	0.11	0.11

Tab. 6 shows results for a *SynViT-B* model [22] trained on synthetic images generated using different prompts such as (i) class names, (ii) 80 CLIP templates, e.g. “high-quality photo of {class name}”, used in evaluating the zero-shot classification performance of the CLIP model, and (iii) class names combined with a generated caption from BLIP2 [49], e.g. “Tench [class label], a man holding a fish”. As can be seen in Tab. 6, captions and CLIP templates are much better for creating robust synthetic clones compared to just using class names. This can be attributed to more diverse images being generated with more descriptive text.

Effect of adding real data. Next, we study the effect of using a mixture of real and synthetic image data on the robustness of the CLIP model. Fan et al. [22] trained the CLIP model with a fixed dataset size (for example, 371M images) where the real and synthetic images are picked randomly to create a subset containing both real and synthetic images, which are then used for training the CLIP model. Tab. 7 shows that adding real data as suggested by [22] improves the performance on many key metrics (ECE, adversarial accuracy, shape bias) while remaining comparable on others. Also, we see that training with just synthetic images or a combination of synthetic and real images creates more robust models compared to models trained just on real data.

Size of generated data. We evaluate the effect of dataset size on the training of synthetic clones. As seen in Tabs. 6 and 7, adding more data, in general, helps with the robustness of both *SynViT-B* and *SynCLIP* models. In some cases, adding more data may slightly decrease performance, which

can be due to less dataset diversity with increasing dataset size and overfitting of the model with less diverse data.

5. Conclusion

Our work is the first to perform a detailed analysis of models trained with synthetic data across different robustness measures. Specifically, we show that certain synthetic clones, namely *SynCLIP* and *SynCLR*, perform within tolerable limits of their counterparts trained on real images; this holds for all robustness metrics except for common corruptions and OOD detection. Supervised models, namely *SynViT-B*, on the other hand, are outperformed by their real-image counterparts on all metrics except shape bias, which clearly shows the need for better supervised synthetic clones. Through detailed ablations, we find that using captions or CLIP templates produces more robust synthetic clones. Importantly, we find that mixing real data with synthetic data can improve the robustness measures across most metrics. We hope our work encourages the development of more robust synthetic clones.

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References

- [1] Hassan Abu Alhaija, Siva Karthik Mustikovela, Lars Mescheder, Andreas Geiger, and Carsten Rother. Augmented reality meets computer vision: Efficient data generation for urban driving scenes. *IJCV*, pages 961–972, 2018.
- [2] Josh Achiam, Steven Adler, Sandhini Agarwal, Lama Ahmad, Ilge Akkaya, Florencia Leoni Aleman, Diogo Almeida, Janko Altschmidt, Sam Altman, Shyamal Anadkat, et al. GPT-4 technical report. *arXiv:2303.08774 [cs.CL]*, 2023.
- [3] Martin Arjovsky, Soumith Chintala, and Léon Bottou. Wasserstein generative adversarial networks. In *ICML*, pages 214–223, 2017.
- [4] Shekoofeh Azizi, Simon Kornblith, Chitwan Saharia, Mohammad Norouzi, and David J. Fleet. Synthetic data from diffusion models improves ImageNet classification. *TMLR*, 2023.
- [5] Yasaman Bahri, Ethan Dyer, Jared Kaplan, Jaehoon Lee, and Utkarsh Sharma. Explaining scaling laws of neural network generalization. *arXiv:2102.06701 [cs.LG]*, 2021.
- [6] Hritik Bansal and Aditya Grover. Leaving reality to imagination: Robust classification via generated datasets. *arXiv:2302.02503 [cs.CV]*, 2023.
- [7] Hangbo Bao, Li Dong, Songhao Piao, and Furu Wei. BEiT: Bert pre-training of image transformers. In *ICLR*, 2022.
- [8] Elior Benarous, Sotiris Anagnostidis, Luca Biggio, and Thomas Hofmann. Harnessing synthetic datasets: The role of shape bias in deep neural network generalization. *arXiv:2311.06224 [cs.CV]*, 2023.
- [9] Md Rafiul Biswas, Ashhadul Islam, Zubair Shah, Wajdi Zaghrouani, and Samir Brahim Belhaouari. Can ChatGPT be your personal medical assistant? In *SNAMS*, pages 1–5, 2023.
- [10] Andrew Brock, Jeff Donahue, and Karen Simonyan. Large scale GAN training for high fidelity natural image synthesis. In *ICLR*, 2019.
- [11] Mathilde Caron, Ishan Misra, Julien Mairal, Priya Goyal, Piotr Bojanowski, and Armand Joulin. Unsupervised learning of visual features by contrasting cluster assignments. *NeurIPS*, pages 9912–9924, 2020.
- [12] Mathilde Caron, Hugo Touvron, Ishan Misra, Hervé Jégou, Julien Mairal, Piotr Bojanowski, and Armand Joulin. Emerging properties in self-supervised vision transformers. In *ICCV*, pages 9650–9660, 2021.
- [13] Ricky T. Q. Chen, Yulia Rubanova, Jesse Bettencourt, and David K. Duvenaud. Neural ordinary differential equations. *NeurIPS*, pages 6572–6583, 2018.
- [14] Ting Chen, Simon Kornblith, Mohammad Norouzi, and Geoffrey Hinton. A simple framework for contrastive learning of visual representations. In *ICML*, pages 1597–1607, 2020.
- [15] Jia Deng, Wei Dong, Richard Socher, Li-Jia Li, Kai Li, and Li Fei-Fei. ImageNet: A large-scale hierarchical image database. In *CVPR*, pages 248–255, 2009.
- [16] Gil Diesendruck and Paul Bloom. How specific is the shape bias? *Child development*, pages 168–178, 2003.
- [17] Laurent Dinh, Jascha Sohl-Dickstein, and Samy Bengio. Density estimation using Real NVP. In *ICLR*, 2016.
- [18] Carl Doersch, Abhinav Gupta, and Alexei A Efros. Unsupervised visual representation learning by context prediction. In *ICCV*, pages 1422–1430, 2015.
- [19] Elvis Dohmatob, Yunzhen Feng, Pu Yang, Francois Charton, and Julia Kempe. A tale of tails: Model collapse as a change of scaling laws. *arXiv:2402.07043 [cs.LG]*, 2024.
- [20] Alexey Dosovitskiy, Lucas Beyer, Alexander Kolesnikov, Dirk Weissenborn, Xiaohua Zhai, Thomas Unterthiner, Mostafa Dehghani, Matthias Minderer, Georg Heigold, Sylvain Gelly, et al. An image is worth 16x16 words: Transformers for image recognition at scale. In *ICLR*, 2020.
- [21] Ricard Durall, Margret Keuper, and Janis Keuper. Watch your up-convolution: CNN based generative deep neural networks are failing to reproduce spectral distributions. In *CVPR*, pages 7890–7899, 2020.
- [22] Lijie Fan, Kaifeng Chen, Dilip Krishnan, Dina Katabi, Phillip Isola, and Yonglong Tian. Scaling laws of synthetic images for model training ...for now. *arXiv:2312.04567 [cs.CV]*, 2023.
- [23] Christiane Fellbaum. WordNet. In *Theory and Applications of Ontology: Computer Applications*, pages 231–243. Springer, 2010.
- [24] Felix Friedrich, Manuel Brack, Lukas Struppek, Dominik Hintersdorf, Patrick Schramowski, Sasha Luccioni, and Kristian Kersting. Fair Diffusion: Instructing text-to-image generation models on fairness. *arXiv:2302.10893 [cs.LG]*, 2023.
- [25] Robert Geirhos, Patricia Rubisch, Claudio Michaelis, Matthias Bethge, Felix A. Wichmann, and Wieland Brendel. ImageNet-trained CNNs are biased towards texture; increasing shape bias improves accuracy and robustness. In *ICLR*, 2018.
- [26] Robert Geirhos, Jörn-Henrik Jacobsen, Claudio Michaelis, Richard Zemel, Wieland Brendel, Matthias Bethge, and Felix A Wichmann. Shortcut learning in deep neural networks. *Nature Machine Intelligence*, pages 665–673, 2020.
- [27] Ian Goodfellow, Jean Pouget-Abadie, Mehdi Mirza, Bing Xu, David Warde-Farley, Sherjil Ozair, Aaron Courville, and Yoshua Bengio. Generative adversarial nets. *NIPS*, pages 2672–2680, 2014.
- [28] Ian J. Goodfellow, Jonathon Shlens, and Christian Szegedy. Explaining and harnessing adversarial examples. In *ICLR*, 2015.
- [29] Priya Goyal, Dhruv Mahajan, Abhinav Gupta, and Ishan Misra. Scaling and benchmarking self-supervised visual representation learning. In *ICCV*, pages 6391–6400, 2019.
- [30] Chuan Guo, Geoff Pleiss, Yu Sun, and Kilian Q. Weinberger. On calibration of modern neural networks. In *ICML*, pages 1321–1330, 2017.
- [31] Hasan Abed Al Kader Hammoud, Hani Itani, Fabio Pizzati, Philip Torr, Adel Bibi, and Bernard Ghanem. SynthCLIP: Are we ready for a fully synthetic CLIP training? *arXiv:2402.01832 [cs.CV]*, 2024.
- [32] Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Deep residual learning for image recognition. In *CVPR*, pages 770–778, 2016.

- [33] Kaiming He, Haoqi Fan, Yuxin Wu, Saining Xie, and Ross Girshick. Momentum contrast for unsupervised visual representation learning. In *CVPR*, pages 9729–9738, 2020.
- [34] Kaiming He, Xinlei Chen, Saining Xie, Yanghao Li, Piotr Dollár, and Ross Girshick. Masked autoencoders are scalable vision learners. In *CVPR*, pages 16000–16009, 2022.
- [35] Ruifei He, Shuyang Sun, Xin Yu, Chuhui Xue, Wenqing Zhang, Philip Torr, Song Bai, and Xiaojuan Qi. Is synthetic data from generative models ready for image recognition? In *ICLR*, 2022.
- [36] Dan Hendrycks and Thomas Dietterich. Benchmarking neural network robustness to common corruptions and perturbations. In *ICLR*, 2018.
- [37] Dan Hendrycks, Steven Basart, Norman Mu, et al. The many faces of robustness: A critical analysis of out-of-distribution generalization. In *ICCV*, pages 8340–8349, 2021.
- [38] Dan Hendrycks, Kevin Zhao, Steven Basart, Jacob Steinhardt, and Dawn Song. Natural adversarial examples. In *CVPR*, pages 15262–15271, 2021.
- [39] Joel Hestness, Sharan Narang, Newsha Ardalani, Gregory Diamos, Heewoo Jun, Hassan Kianinejad, Md Mostofa Ali Patwary, Yang Yang, and Yanqi Zhou. Deep learning scaling is predictable, empirically. *arXiv:1712.00409 [cs.LG]*, 2017.
- [40] Jonathan Ho, Ajay Jain, and Pieter Abbeel. Denoising diffusion probabilistic models. *NeurIPS*, pages 6840–6851, 2020.
- [41] Gabriel Ilharco, Mitchell Wortsman, Ross Wightman, Cade Gordon, Nicholas Carlini, Rohan Taori, Achal Dave, Vaishaal Shankar, Hongseok Namkoong, John Miller, Hananeh Hajishirzi, Ali Farhadi, and Ludwig Schmidt. OpenCLIP, 2021.
- [42] Albert Q. Jiang, Alexandre Sablayrolles, Arthur Mensch, Chris Bamford, Devendra Singh Chaplot, Diego de las Casas, Florian Bressand, Gianna Lengyel, Guillaume Lample, Lucile Saulnier, et al. Mistral 7B. *arXiv:2310.06825 [cs.CL]*, 2023.
- [43] Jared Kaplan, Sam McCandlish, Tom Henighan, Tom B. Brown, Benjamin Chess, Rewon Child, Scott Gray, Alec Radford, Jeffrey Wu, and Dario Amodei. Scaling laws for neural language models. *arXiv:2001.08361 [cs.LG]*, 2020.
- [44] Oğuzhan Fatih Kar, Teresa Yeo, Andrei Atanov, and Amir Zamir. 3D common corruptions and data augmentation. In *CVPR*, pages 18963–18974, 2022.
- [45] Tero Karras, Samuli Laine, Miika Aittala, Janne Hellsten, Jaakko Lehtinen, and Timo Aila. Analyzing and improving the image quality of StyleGAN. In *CVPR*, pages 8110–8119, 2020.
- [46] Priyatham Kattakinda and Soheil Feizi. FOCUS: Familiar objects in common and uncommon settings. In *ICML*, pages 10825–10847, 2022.
- [47] Prannay Khosla, Piotr Teterwak, Chen Wang, Aaron Sarna, Yonglong Tian, Phillip Isola, Aaron Maschinot, Ce Liu, and Dilip Krishnan. Supervised contrastive learning. *NeurIPS*, pages 18661–18673, 2020.
- [48] Diederik P. Kingma and Max Welling. Auto-encoding variational bayes. In *ICLR*, 2014.
- [49] Junnan Li, Dongxu Li, Silvio Savarese, and Steven Hoi. BLIP-2: Bootstrapping language-image pre-training with frozen image encoders and large language models. In *ICML*, pages 19730–19742, 2023.
- [50] Ze Liu, Yutong Lin, Yue Cao, Han Hu, Yixuan Wei, Zheng Zhang, Stephen Lin, and Baining Guo. Swin Transformer: Hierarchical vision transformer using shifted windows. In *ICCV*, pages 10012–10022, 2021.
- [51] Zhuang Liu, Hanzi Mao, Chao-Yuan Wu, Christoph Feichtenhofer, Trevor Darrell, and Saining Xie. A ConvNet for the 2020s. In *CVPR*, pages 11976–11986, 2022.
- [52] Aleksander Madry, Aleksandar Makelov, Ludwig Schmidt, Dimitris Tsipras, and Adrian Vladu. Towards deep learning models resistant to adversarial attacks. In *ICLR*, 2018.
- [53] Pranshu Malviya and Arjun Vaithilingam Sudhakar. Feature diversity in self-supervised learning. *arXiv:2209.01275 [cs.LG]*, 2022.
- [54] Claudio Michaelis, Benjamin Mitzkus, Robert Geirhos, Evgenia Rusak, Oliver Bringmann, Alexander S. Ecker, Matthias Bethge, and Wieland Brendel. Benchmarking robustness in object detection: Autonomous driving when winter is coming. *arXiv:1907.07484 [cs.CV]*, 2019.
- [55] Mahdi Pakdaman Naeini, Gregory Cooper, and Milos Hauskrecht. Obtaining well calibrated probabilities using Bayesian binning. In *AAAI*, pages 2901–2907, 2015.
- [56] Mehdi Noroozi and Paolo Favaro. Unsupervised learning of visual representations by solving jigsaw puzzles. In *ECCV*, pages 69–84, 2016.
- [57] Maxime Oquab, Timothée Darcet, Théo Moutakanni, et al. DINOv2: Learning robust visual features without supervision. *TMLR*, 2024.
- [58] Shubham Parashar, Zhiqiu Lin, Tian Liu, Xiangjue Dong, Yanan Li, Deva Ramanan, James Caverlee, and Shu Kong. The neglected tails of vision-language models. *arXiv:2401.12425 [cs.CV]*, 2024.
- [59] Senthil Purushwalkam and Abhinav Gupta. Demystifying contrastive self-supervised learning: Invariances, augmentations and dataset biases. *NeurIPS*, pages 3407–3418, 2020.
- [60] Alec Radford, Jong Wook Kim, Chris Hallacy, et al. Learning transferable visual models from natural language supervision. In *ICML*, pages 8748–8763, 2021.
- [61] Stephan R. Richter, Vibhav Vineet, Stefan Roth, and Vladlen Koltun. Playing for Data: Ground truth from computer games. In *ECCV*, pages 102–118, 2016.
- [62] Jonas Ricker, Simon Damm, Thorsten Holz, and Asja Fischer. Towards the detection of diffusion model deepfakes. *arXiv:2210.14571 [cs.CV]*, 2022.
- [63] Esther Rolf, Theodora T. Worledge, Benjamin Recht, and Michael Jordan. Representation matters: Assessing the importance of subgroup allocations in training data. In *ICML*, pages 9040–9051, 2021.
- [64] Robin Rombach, Andreas Blattmann, Dominik Lorenz, Patrick Esser, and Björn Ommer. High-resolution image synthesis with latent diffusion models. In *CVPR*, pages 10684–10695, 2022.
- [65] Artem Rozantsev, Vincent Lepetit, and Pascal Fua. On rendering synthetic images for training an object detector. *CVIU*, pages 24–37, 2015.

- [66] Chitwan Saharia, William Chan, Saurabh Saxena, et al. Photorealistic text-to-image diffusion models with deep language understanding. *NeurIPS*, pages 36479–36494, 2022.
- [67] Mert Bülent Sarıyıldız, Karteek Alahari, Diane Larlus, and Yannis Kalantidis. Fake it till you make it: Learning transferable representations from synthetic ImageNet clones. In *CVPR*, pages 8011–8021, 2023.
- [68] Katja Schwarz, Yiyi Liao, and Andreas Geiger. On the frequency bias of generative models. *NeurIPS*, pages 18126–18136, 2021.
- [69] Vikash Sehwal, Saeed Mahloujifar, Tinashe Handina, Sihui Dai, Chong Xiang, Mung Chiang, and Prateek Mittal. Robust learning meets generative models: Can proxy distributions improve adversarial robustness? In *ICLR*, 2021.
- [70] Iliia Shumailov, Zakhar Shumaylov, Yiren Zhao, Yarin Gal, Nicolas Papernot, and Ross Anderson. The curse of recursion: Training on generated data makes models forget. *arXiv:2305.17493 [cs.LG]*, 2023.
- [71] Linda B. Smith, Susan S. Jones, Barbara Landau, Lisa Gershkoff-Stowe, and Larissa Samuelson. Object name learning provides on-the-job training for attention. *Psychological Science*, pages 13–19, 2002.
- [72] Jascha Sohl-Dickstein, Eric Weiss, Niru Maheswaranathan, and Surya Ganguli. Deep unsupervised learning using nonequilibrium thermodynamics. In *ICML*, pages 2256–2265, 2015.
- [73] Yonglong Tian, Lijie Fan, Kaifeng Chen, Dina Katabi, Dilip Krishnan, and Phillip Isola. Learning vision from models rivals learning vision from data. *arXiv:2312.17742 [cs.CV]*, 2023.
- [74] Yonglong Tian, Lijie Fan, Phillip Isola, Huiwen Chang, and Dilip Krishnan. StableRep: Synthetic images from text-to-image models make strong visual representation learners. *NeurIPS*, 2023.
- [75] Hugo Touvron, Matthieu Cord, and Hervé Jégou. DeiT III: Revenge of the ViT. In *ECCV*, pages 516–533, 2022.
- [76] Hugo Touvron, Louis Martin, Kevin Stone, et al. Llama 2: Open foundation and fine-tuned chat models. *arXiv:2307.09288 [cs.CL]*, 2023.
- [77] Aaron Van Den Oord, Oriol Vinyals, et al. Neural discrete representation learning. *NIPS*, pages 6306–6315, 2017.
- [78] Grant Van Horn, Oisín Mac Aodha, Yang Song, Yin Cui, Chen Sun, Alex Shepard, Hartwig Adam, Pietro Perona, and Serge Belongie. The iNaturalist species classification and detection dataset. In *CVPR*, pages 8769–8778, 2018.
- [79] Pascal Vincent, Hugo Larochelle, Yoshua Bengio, and Pierre-Antoine Manzagol. Extracting and composing robust features with denoising autoencoders. In *ICML*, pages 1096–1103, 2008.
- [80] Ross Wightman. PyTorch image models, 2019.
- [81] Jianxiong Xiao, James Hays, Krista A. Ehinger, Aude Oliva, and Antonio Torralba. SUN Database: Large-scale scene recognition from abbey to zoo. In *CVPR*, pages 3485–3492, 2010.
- [82] Kai Yuanqing Xiao, Logan Engstrom, Andrew Ilyas, and Aleksander Madry. Noise or signal: The role of image backgrounds in object recognition. In *ICLR*, 2020.
- [83] Zhisheng Xiao, Karsten Kreis, and Arash Vahdat. Tackling the generative learning trilemma with denoising diffusion GANs. In *ICLR*, 2021.
- [84] Qizhe Xie, Minh-Thang Luong, Eduard Hovy, and Quoc V. Le. Self-training with noisy student improves ImageNet classification. In *CVPR*, pages 10687–10698, 2020.
- [85] Hu Xu, Saining Xie, Xiaoqing Ellen Tan, Po-Yao Huang, Russell Howes, Vasu Sharma, Shang-Wen Li, Gargi Ghosh, Luke Zettlemoyer, and Christoph Feichtenhofer. Demystifying CLIP data. In *ICLR*, 2024.
- [86] Liheng Zhang, Guo-Jun Qi, Liqiang Wang, and Jiebo Luo. AET vs. AED: Unsupervised representation learning by auto-encoding transformations rather than data. In *CVPR*, pages 2547–2555, 2019.
- [87] Richard Zhang, Phillip Isola, and Alexei A Efros. Colorful image colorization. In *ECCV*, pages 649–666, 2016.
- [88] Bolei Zhou, Agata Lapedriza, Aditya Khosla, Aude Oliva, and Antonio Torralba. Places: A 10 million image database for scene recognition. *TPAMI*, pages 1452–1464, 2017.
- [89] Yongchao Zhou, Hshmat Sahak, and Jimmy Ba. Training on thin air: Improve image classification with generated data. *arXiv:2305.15316 [cs.CV]*, 2023.