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Biologically Inspired Mechanisms for Adversarial Robustness

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Abstract

A convolutional neural network strongly robust to adversarial perturbations at reasonable computational and performance cost has not yet been demonstrated. The primate visual ventral stream seems to be robust to small perturbations in visual stimuli but the underlying mechanisms that give rise to this robust perception are not understood. In this work, we investigate the role of two biologically plausible mechanisms in adversarial robustness. We demonstrate that the non-uniform sampling performed by the primate retina and the presence of multiple receptive fields with a range of receptive field sizes at each eccentricity improve the robustness of neural networks to small adversarial perturbations. We verify that these two mechanisms do not suffer from gradient obfuscation and study their contribution to adversarial robustness through ablation studies.



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Biologically Inspired Mechanisms for Adversarial Robustness

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Abstract

A convolutional neural network strongly robust to adversarial perturbations at reasonable computational and performance cost has not yet been demonstrated. The primate visual ventral stream seems to be robust to small perturbations in visual stimuli but the underlying mechanisms that give rise to this robust perception are not understood. In this work, we investigate the role of two biologically plausible mechanisms in adversarial robustness. We demonstrate that the non-uniform sampling performed by the primate retina and the presence of multiple receptive fields with a range of receptive field sizes at each eccentricity improve the robustness of neural networks to small adversarial perturbations. We verify that these two mechanisms do not suffer from gradient obfuscation and study their contribution to adversarial robustness through ablation studies.

1 Introduction

While modern convolutional neural networks (CNNs) have demonstrated remarkable performance in visual recognition, they still lag severely behind human vision on several tasks. Notably, despite intense effort in recent years, these models remain vulnerable to adversarial perturbations [1], even on standard datasets (e.g. ImageNet). In contrast, human vision appears to be particularly robust to small perturbations in visual stimuli.

Simultaneously, an increasing body of computational and experimental work demonstrates the suitability of these artificial neural networks as models of the primate brain's ventral visual stream [2, 3, 4, 5]. This suggests an opportunity to investigate if aspects of biological vision, that are not yet incorporated into current computer vision models, improve adversarial robustness. If the approach is successful, it will improve the robustness of engineered models and provide strong support for artificial neural networks being good models of primate vision. If the proposed approach does not find any way to modify the existing models to reach human-level robustness, it could demonstrate that the broad family of feedforward deep networks should be rejected as models of primate vision.

Engineering significance Robust real-world adversarial examples that fool models across a wide range of views, angles and lighting have been demonstrated [6]. CNNs are increasingly being considered for use in safety critical applications (e.g. autonomous vehicles), thus the dramatic sensitivity of state-of-the-art models to tiny perturbations in otherwise benign inputs has clear security

implications. Proposed methods for improving adversarial robustness have generally approached the problem from either a prevention or detection perspective. Some of the proposed mechanisms include defensive distillation [7], feature squeezing [8], defensive randomization [9], adversarial training [10], among many others. Faithfully evaluating adversarial robustness has proven to be non-trivial [11, 12, 13], with many proposed methods eventually being shown to be ineffective at making models robust [14, 11, 15, 16]. Adversarial training remains the most promising at increasing the robustness of models. However adversarial training comes with several downsides, ranging from significantly increased computational cost, to preferential robustness against adversarial attacks that the model was trained on [15], to decreased standard accuracy [17] and ineffectiveness at improving robustness on examples in the low density regions of the training data distribution [18]. Mechanisms that help bring the models closer to human-level robustness and alleviate this tension between performance and security would have broad implications for the application of these networks.

The learning of feature representations that are particularly well suited to visual recognition tasks is a key characteristic of CNNs that has led to their widespread use. However, the features learned by current models that perform well in standard datasets can vary significantly from features that are meaningful to humans [19]. Recent studies have demonstrated that the quality of these learnt representations are improved in adversarially robust models. In particular, many aspects of feature visualization and manipulation were better aligned with our notion of visual perception in robust models [20, 21]. This suggests that adversarial robustness holds intrinsic value, beyond security implications and potentially even at the cost of standard accuracy, as a prior for helping models learn representations that are more human meaningful and interpretable.

Biological significance Recent studies have argued that artificial neural networks are suitable models of biological vision due to the similarity between internal representations in CNNs and in the primate brain [2, 4, 3]. In this paper, we explore two biological mechanisms that are not captured in current deep learning models of vision.

The uneven distribution of cones in the primate retina results in non-uniform spatial sampling of visual stimuli. The density of sampling is highest at a fixation point on an image and decreases with distance from the fixation point. In contrast, standard CNNs accept images sampled in a uniform square grid. Previous studies have demonstrated that incorporating the non-uniform sampling performed by the primate retina into standard networks improves predictivity of neural sites in the primate V4 cortical area, allows for better neural population control via controller images [3] and helps in generating adversarial examples that impact the accuracy of time-limited humans [22]. The first mechanism that we investigate incorporates information across multiple retinal fixation points.

The receptive field size along the primate visual stream increases with eccentricity [23, 24, 25]. From a sampling perspective, this translates to several scale-space image fragments centered on a fixation point in an image. Previous studies have argued for and demonstrated the computational role of pooling over the scale-space fragments in invariant visual recognition [26]. This second “multiple scales” mechanism allows for translation, scale and clutter invariance to be incorporated into neural networks [27, 28, 29], with much lower sample complexity than standard data augmentation methods. We investigate incorporating information across multiple “cortical fixations”.

Contributions We demonstrate that two mechanisms inherent to primate vision (the “proposed mechanisms”) consistently improve the adversarial robustness of neural networks to small adversarial perturbations across a range of PGD variants, hyperparameters and adversarial criteria (by about 0% to 30% for $\epsilon \leq 0.02$). One of the mechanisms (retinal fixations) improves robustness at almost no cost to standard performance (+1.62% on ImageNet). Through ablation studies, we also identified the key features of each mechanism that contribute to robustness. Our results suggest that biologically inspired mechanisms are promising candidates for improving robustness of standard neural networks. It also probes more broadly and provides support for the hypothesis that artificial neural networks are good models of biological vision.

2 Methods

Datasets The experiments were spread across 4 datasets. CIFAR10 is a small, standard dataset [30] and was used to benchmark results against other published results on adversarial robustness. The proposed mechanisms excel with images of much higher resolution. The majority of the

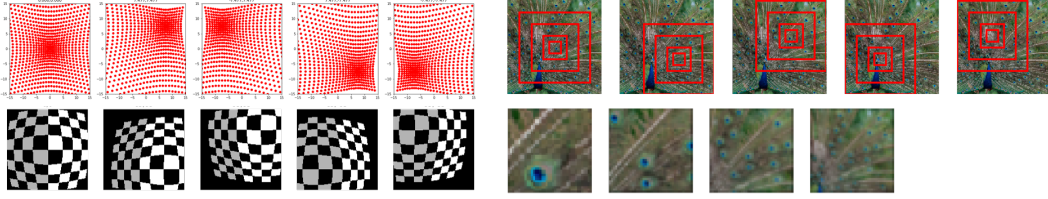


Figure 1: Left Top: Distributions of sampling points for 5 different retinal fixations (center, top right, top left, bottom right, bottom left). Red dots represent pixels that would be sampled from the original standard image to form the retina sampled image. Left Bottom: Effect of retina sampling on an image of a flat checkerboard. Images presented were re-sampled at 5 different fixation points (same as above). Right Top: Shown in red, the centering of scale-space fragments on 5 different cortical fixations on the image (center, bottom right, top right, bottom left, top left). Scale-space fragments for ImageNet images were of the sizes 40x40, 80x80, 160x160, 240x240. Right Bottom: The resulting 4 scale-space fragments from 1 fixation point. For a single fixation point, the 4 scale-space fragments result from crops of varying sizes but are all Gaussian downsampled to the size of the smallest (40x40).

experiments in this work were thus carried out on ImageNet10 and some experiments were repeated on ImageNet100 and ImageNet to study the scalability of the proposed mechanisms.

The ImageNet dataset [31] offers high resolution images split into 1000 classes that span a range of breadth (e.g. airliner, strawberry, etc) and depth (e.g. mud turtle, leatherback turtle, etc). 10 classes were hand picked to construct the ImageNet10 dataset. The classes were chosen to be visually distinct and of natural objects (e.g. pandas, snakes, etc.). To construct the ImageNet100 dataset, 100 classes were randomly chosen. Images in the ImageNet dataset are of varying dimensions. To standardize, all images in the ImageNet10, ImageNet100 and ImageNet datasets were formed only from the central 320x320 regions of the original images. For the full ImageNet dataset, in the interest of keeping the compute time for experiments reasonable, models were trained on the full training set but robustness evaluations were carried out on a test set downsampled to 5 images per class (totaling 5000 images for the 1000 classes).

Biologically inspired mechanisms The first mechanism is the non-uniform spatial sampling of visual stimuli by the photoreceptors. In the primate retina, the density of cones is maximum at the center of the fovea and decreases with eccentricity. The maximum density corresponds to a sampling distance of about 27 seconds of arc between adjacent cones, which corresponds almost exactly to the Shannon sampling limit imposed by the diffraction limited optics with a cutoff around 60 cycles/degree. The implementation of the retinal sampling was taken from [3], where it was tuned to mimic the exponentially decreasing density of cones with eccentricity. We adapted their implementation to work with arbitrary fixation points on an image (Top Left and Bottom Left in Figure 1, Model C in Figure 2).

The size of receptive fields also varies with eccentricity, presumably to avoid aliasing [23, 24, 25]. The second mechanism is that V1 neurons show a range of scales at each eccentricity [26]. The main computational reason for this non-uniform sampling and the existence of a set of spatial scales is to enable processing of images with translation invariance – small but growing with larger receptive fields – and a large range of scale invariance. We assume here the estimate by [32] with 5 “frequency channels” having in the fovea receptive field with a diameter of $2s = 1'20", 3.1', 6.2', 11.7', 21'$, covering a range of roughly 1 to 20. Following from previous studies [26, 27, 28], we implemented the estimates for the set of scale-space fragments in V1 (i.e. the frequency channels estimated by [32]) by taking multiple crops that are progressively larger by about a factor of 2 and Gaussian downsampling all the crops to the dimensions of the smallest crop (Top Right and Bottom Right in Figure 1, Model D in Figure 2).

Models Models for the CIFAR10 and ImageNet datasets were based off the standard CIFAR ResNet-20 and ImageNet ResNet-18 architectures [33].

We used a standard model and a “coarse fixations” model as baselines (Model A and Model B in Figure 2). The coarse fixations model approximates crudely the effect of fixations by applying a standard network to different image regions. This is effectively the same as standard 10-crop testing in [33] without image flipping.

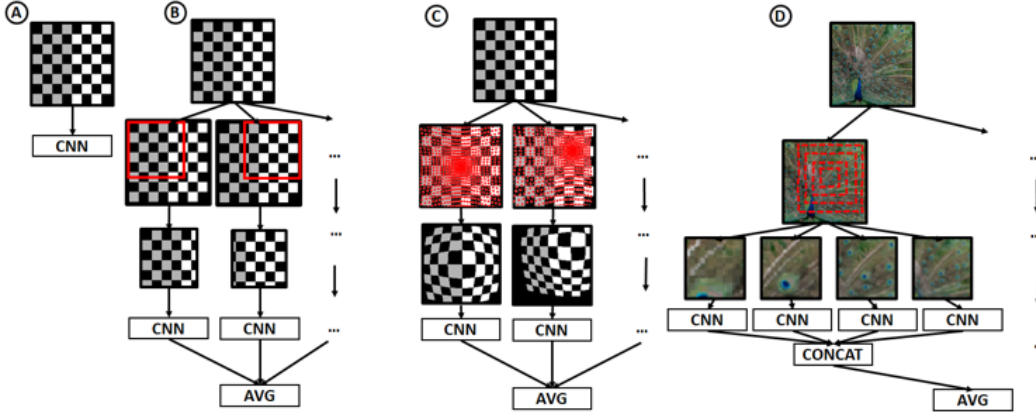


Figure 2: Model A (baseline): standard CNN. Model B (baseline): “coarse fixations”. Model C (effect): “retinal fixations”. Model D (effect): “cortical fixations”. Red marks on images in second row indicate approximate action of mechanisms centered on a fixation point. 2 fixation points visualized for Models B and C, 1 fixation point visualized for model D.

The “retinal fixations” model applies a standard network to an image that is non-uniformly sampled as previously described (Model C in Figure 2). In the “cortical fixations” model, the standard ResNet architecture is split over multiple branches that process the scales at each eccentricity independently. The number of filters for each branch were chosen such that the total compute cost of a forward pass of all the branches costs about the same as a standard ResNet. The striding in early layers of the ResNet architecture was adjusted to account for the small dimensions of each scale-space fragment. We used an auxiliary loss during training to encourage information across all the scales to contribute to the model prediction (Model D in Figure 2).

During evaluation time, information was incorporated across fixations by averaging the model logits from 5 fixation points for each mechanism (top left, top right, bottom left, bottom right, middle).

Training The models for coarse, retinal and cortical fixations depend on a fixation point on the image to center the mechanism on. During training, a fixation point is randomly sampled from the valid set of fixations for the mechanism. This is in contrast to behavior at evaluation time, when information across fixations is incorporated by averaging model logits over 5 pre-determined fixation points for each mechanism. Image augmentation was standardized across all models and datasets (random crops and random left/right flips). No color augmentation was used.

Models for CIFAR10 and ImageNet10 were both trained with an ADAM optimizer with $\beta_1 = 0.9$, $\beta_2 = 0.999$ and an initial learning rate of 0.001. CIFAR10 Models were trained for 200 epochs with a batch size of 180 and a fixed learning schedule (decay from initial by 0.1, 0.01, 0.001, 0.0005 at epoch 80, 120, 160, 180). Models for ImageNet10 were trained for 400 epochs with a batch size of 64 and a fixed learning schedule (decay from initial by 0.1, 0.01, 0.001, 0.0005 at epoch 160, 240, 320, 360). Models for ImageNet100 and Imagenet used an SGD optimizer with weight decay of 0.0001, momentum 0.9, initial learning rate of 0.1, and a batch size 256. Models for ImageNet100 were trained for 130 epochs with a fixed learning schedule (decay from initial by 0.1, 0.01, 0.001, 0.0005 at epoch 30, 70, 90, 120). Models for ImageNet were trained for 90 epochs with a fixed learning schedule (decay from initial by 0.1, 0.01, 0.001 at epoch 30, 60, 80).

Adversarial robustness We followed previously proposed guidelines [11, 12, 13] when evaluating robustness. The adversarial attacks used were as implemented in the Python package Foolbox [34].

Projected Gradient Descent (PGD) [35] was motivated by previous works as a universal first order adversary that provides a suitable security guarantee against first-order attacks [10, 36]. In this work, the adversarial robustness of the proposed mechanisms was investigated primarily with PGD. PGD (L_∞ variant) prescribes the generation of adversarial examples with the following iterative scheme:

$$x_{adv,i} = \text{CLIP}_{x,\epsilon}(x_{i-1} + \lambda \text{SIGN}(\nabla_x L(\dots))), \quad x_{adv,0} = x_{original},$$

where i is the count of iterations, CLIP is an operation that clips x back to the permissible set, λ is the step size and $\nabla_x L(\dots)$ is the gradient of the relevant loss function for the attack. The gradient was always fully propagated through the proposed mechanisms.

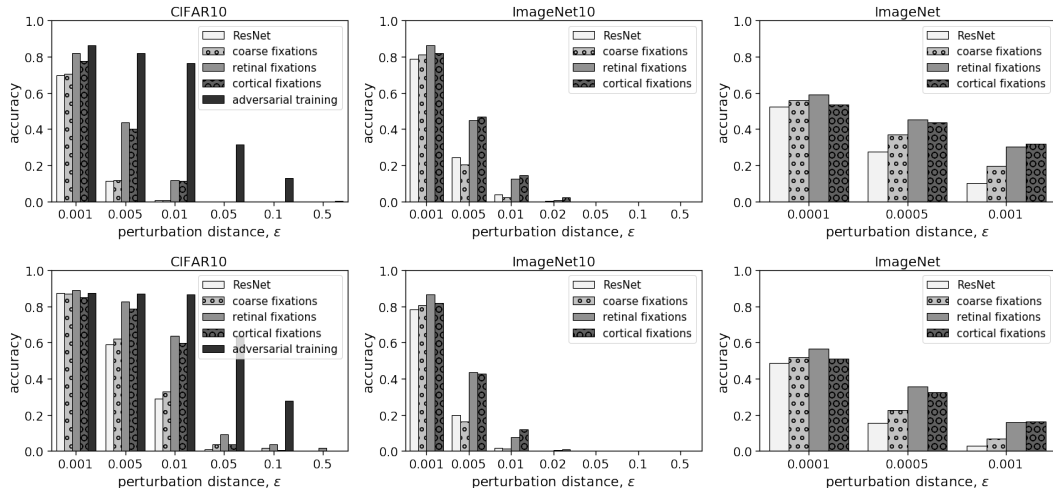


Figure 3: Robustness of the models on various datasets with increasing PGD perturbation budget. Top Row: robustness to 5-step L_∞ PGD standard adversarial examples. Bottom Left: robustness to strongly misclassified adversarial examples, Bottom Middle: robustness to 20-step PGD, Bottom Right: robustness to L_2 PGD.

When setting a maximum perturbation size ϵ with PGD, we need to choose a distance metric. Various L_p norms of the distance from the adversarial image to the original image are usually employed, $|x_{adv} - x_{original}|_p$, where typically $p = 2$ or $p = \infty$ [14]. The usual distance metrics are not necessarily well aligned with human perceived similarity. There is ongoing work in that area that would be interesting to consider in the future [37]. We mostly used L_∞ PGD and L_2 PGD in our experiments, but also checked robustness to L_1 PGD and the fast gradient sign method (FGSM) [34].

We evaluated the robustness of the models by studying how the accuracy varied as ϵ , the maximum perturbation size, was increased. We calculate the accuracy as $1 - (\text{num. naturally misclassified} + \text{num. adversarial examples})$. Whether an image is naturally misclassified was always determined by whether the true class was the most likely class predicted by the model, regardless of the adversarial criteria. Adversarial attacks were then only run against images that were not naturally misclassified. In most of the experiments, we set the step size λ to $\epsilon/3$ and ran 5 iterations. This allows PGD to reach the edge of the permissible set and explore the boundary while keeping compute time for the experiments reasonable. We also conducted some experiments with 20 iterations and step sizes λ of $\epsilon/3$ and $\epsilon/12$, and tried setting λ dynamically with an ADAM optimizer.

3 Results

We compared the test classification error to study standard performance. Here, we are referring to the performance of the models on the unperturbed natural test sets as the standard performance. The coarse fixations model generally outperformed the standard ResNet models, which is in line with previous studies [33]. The coarse fixations model underperformed on CIFAR10 likely due to the small size of images. The retinal fixations model performed about as well as the best baseline model (worse

Table 1: Standard TOP-1 performance of baselines and proposed models on various datasets.

MODEL	CIFAR10	IMAGENET10	IMAGENET100	IMAGENET
STANDARD RESNET	88.13%	89.4%	76.80%	59.46%
COARSE FIXATIONS	87.70%	91.2%	78.42%	61.28%
RETINAL FIXATIONS	88.88%	90.2%	78.22%	62.90%
CORTICAL FIXATIONS	85.16%	88.6%	73.62%	56.32%

by only 0.2% on ImageNet100 and better by 1.62% on ImageNet) but the cortical fixations model decreased standard performance (underperforms by 4.96% on ImageNet). The relative performance of the models was fairly consistent across datasets. The performance penalties for the cortical fixations

model were likely still less than for adversarial training. For example, L_∞ PGD adversarial training on CIFAR10 decreases standard performance by about 7.9% [10].

3.1 Adversarial robustness

The adversarial robustness of the proposed mechanisms was evaluated by studying the change in accuracy of the models with increasing perturbation budget. The experiments span a range of PGD variants, hyperparameters and adversarial criteria (Figures 3, 4).

The biologically inspired mechanisms consistently improved adversarial robustness to small perturbations across almost all experiments on all datasets (see Figure 4). The extent of improvement varied depending on the attack variants, hyperparameters and the dataset used. The retinal fixations and cortical fixations models improved robustness to about the same extent, with the best model varying across experiments. At larger perturbations, the mechanisms did not significantly impact robustness.

For small perturbations on ImageNet10, we observed a greater improvement in accuracy for the proposed models from the best baseline when using PGD as opposed to FGSM. This suggests that the mechanisms are effective at improving robustness, with the retinal and cortical fixations models performing proportionately better against stronger attacks that more thoroughly probe the robustness. The improvement in accuracy was relatively unchanged when increasing the number of iterations of PGD from 5 to 20 with step size λ of 0.1 or 0.025. In general, the proposed models showed greater improvement in accuracy under L_∞ PGD versus L_2 PGD, with the least improvement with L_1 PGD. Further studies could be conducted on variations in improvement with attack variants and hyperparameters to better understand the contribution of the mechanisms to adversarial robustness.

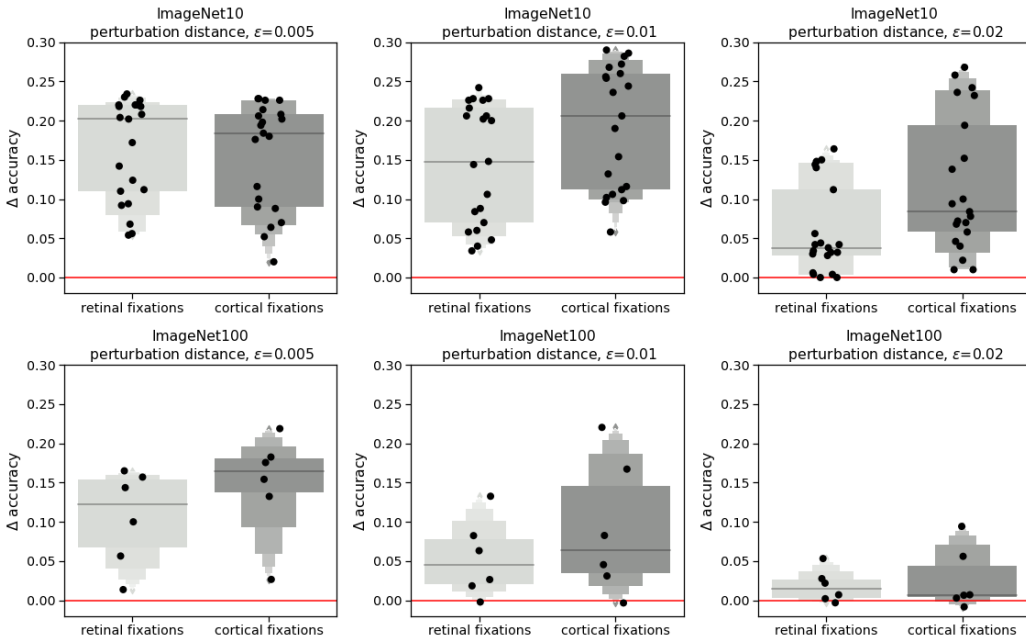


Figure 4: Improvement in accuracy of proposed models from the best baseline at small ϵ . Each dot represents a different attack configuration. Top row: ImageNet10. Bottom row: ImageNet100.

Confident misclassifications On ImageNet10, the robustness to standard misclassifications (true class not the most likely predicted class) was compared to the robustness to confident misclassifications (true class not in top 3 for untargeted attacks and adversarial class predicted with probability $>80\%$ for targeted attacks). Generally, the proposed mechanisms were more robust to confident mistakes than standard mistakes for untargeted attacks. The robustness to confident and standard mistakes for targeted attacks was about the same.

In a targeted setting, the loss used for PGD pushes towards a confident misclassification (objective is to increase probability of adversarial class) whereas in an untargeted setting, the loss does not explicitly push towards confident misclassifications (objective is to minimize true class, this can be

accomplished either by increase probability of only 1 or any number of other classes). This suggests that the proposed models improve robustness to confident misclassifications as confident mistakes were less likely to occur unless they were explicitly optimized for.

Adversarial Training On CIFAR10, the robustness of the models was benchmarked against an adversarially trained model available online from a previous study [10]. The model uses a variant of the standard ResNet architecture, w32-10 ResNet. We benchmarked the robustness of the models with L_∞ PGD, which is also the attack that was used for adversarial training (Figure 3).

The robustness of the retinal fixations and cortical fixations models was consistently better than the baselines but worse than adversarial training. The accuracy of the models that were not adversarially trained dips to approximately 0% for perturbations of size $\epsilon = 0.05$ and higher. The proposed models made far fewer confident misclassifications than the baselines, with the robustness of the proposed models to confident misclassification at $\epsilon = 0.005$ approaching adversarial training.

3.2 Ablation experiments

We performed experiments with a series of ablated models to study the contribution of various aspects of the proposed mechanisms to robustness. The experiments were conducted on ImageNet10 and span a range of PGD variants, hyperparameters and adversarial criteria (Figure 5). All ablated models employed a mechanism centered on fixations. As before, we incorporated information across fixations at evaluation time by averaging the model logits from 5 pre-determined fixation points in the image.

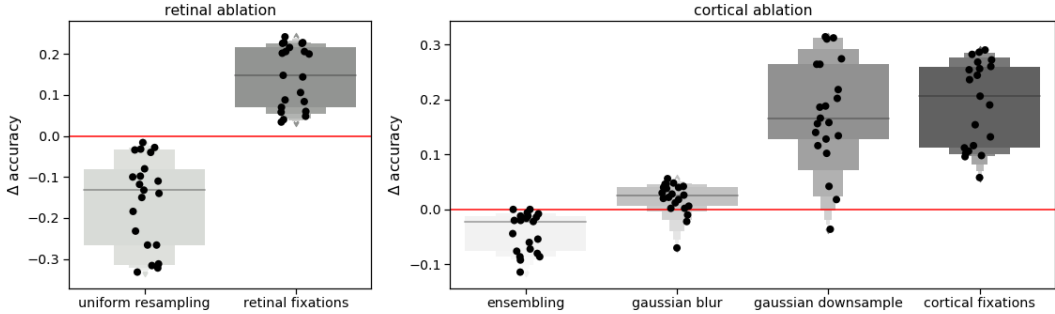


Figure 5: Improvement in accuracy of ablated models over the best baseline model under L_∞ PGD with $\epsilon = 0.01$. Each dot represents a different attack configuration/criteria.

Retinal ablation Non-uniform retinal sampling effectively sub-samples and up-samples the image. The pixels that get sub-sampled and up-sampled are chosen based on their distance to a point of fixation on the image. There are several factors that could potentially account for the improved robustness of the retinal fixations model, such as the sub-sampling or the sub-sampling combined with up-sampling or the non-uniformity of the sampling.

The retinal fixations model consistently outperformed the coarse fixations model in robustness tests. This indicates that simply sub-sampling, or applying a network on different image regions, does not improve robustness. We studied an ablated model that performs uniform sub-sampling (exactly as the coarse fixations model) followed by up-sampling. This ablated model (“uniform resampling” in Figure 5) consistently underperformed compared to the best baseline model. This indicates that uniformly sub-sampling and up-sampling an image does not improve (actually worsens) robustness.

This leaves the non-uniformity of the sampling as the main contributing factor to improving robustness. We speculate that the non-uniform sampling appropriately conditions the model to learn larger scale features during the training process and that these features are more robust to adversarial perturbations. This could be investigated further by studying the extent of robust versus non-robust features learnt by the model as in [19].

Cortical ablation The cortical fixations model breaks an image into multiple scale-space fragments centered on a given fixation point. These fragments are constructed with a uniform square crop of increasing size followed by a Gaussian downsample of all fragments to the dimensions of the smallest fragment. The fragments are then fed through separate branches of a network and the linear classifier at the end of the network uses information from all branches. Potential factors contributing to the improved robustness include Gaussian blurs on sub-samples of the image, Gaussian downsampling

on sub-samples of the image, classifying with a fixed computational budget distributed over separate branches of a network that combine their output, or a combination of the factors.

Classifying with a branched network (“ensembling” ablated model in Figure 5) worsened or at best did not change the robustness of the models. The “Gaussian blur” ablated model performs the sub-sampling exactly as the coarse fixations model, but applies a Gaussian blur on the images. This ablated model was more robust than the baselines but only to a small extent. It has been noticed previously that denoising operations (e.g. Gaussian blur) contribute to adversarial robustness [38, 39].

The “Gaussian downsample” ablated model is effectively the branch of the cortical fixations model that corresponds to the largest receptive field size. It performs sub-sampling similar to the coarse fixations model and applies a Gaussian downsample. This ablated model was more robust than the baselines but less robust than the cortical fixations model. This suggests that increasing reliance on large scale features in an image for classification partially contributed to the improved robustness of the cortical fixations models.

This leaves the ensembling across different scale-space fragments as the remaining contributing factor to the robustness of the cortical fixations model. It is possible that the fragments are sufficiently de-correlated to make ensembling effective, unlike in the case of the “ensembling” ablated model. We tried several versions of the cortical fixations model that incorporated information across the different scale-space fragments in various ways. Some methods (e.g. pooling across branches) outperformed the current cortical fixations model in several experiments. This suggests that issues remain with properly incorporating features across the scale-space fragments in the cortical fixations model.

Gradient obfuscation A common pitfall when evaluating adversarial robustness is gradient obfuscation [11]. By masking the gradient, models can appear to be robust under white-box attacks (e.g. PGD) which use the gradient to construct an adversarial example. We verified that the proposed mechanisms did not suffer from gradient obfuscation through previously suggested experiments [12].

0% Accuracy on unbounded attacks Unbounded iterative PGD should always be able to bring the accuracy of models down to 0. We achieved 0% accuracy in our models at $\epsilon = 0.5$ under L_∞ PGD and L_2 PGD on ImageNet100.

White-box attacks outperform black-box attacks The gradient propagated through the models should be more useful for constructing adversarial examples than a coarse approximation of the gradient. Adversarial examples were constructed by estimating the gradient of the retinal fixations model and cortical fixations model with a standard ResNet model (transfer attack). The examples generated with the transfer attack (black-box attack) heavily underperformed compared to PGD (white-box attack). In further experiments, PGD (white-box attack) also outperformed boundary-attack [40] and backward pass differentiable approximation [11].

Iterative attacks outperform single-step attacks Following the direction of gradient descent should generally be useful for generating stronger adversarial examples. The accuracy of our models was strictly greater or equal under FGSM, effectively a one-step PGD attack, than under PGD.

Expectation over random transformations The coarse, retinal and cortical fixations models can be used as stochastic models. The transformation performed by the mechanisms at training time was random. However, at evaluation time, the transformations were pre-determined and fixed. Thus, there was no need for taking expectations over the transformation in almost all of our experiments. We conducted a single set of experiments with random transformations at evaluation time. For that experiment, we took an expectation of the gradient from 5 random samples of the transformation.

4 Conclusion

In this work, we showed that two key features of primate vision – foveation due to non-uniform distribution of cones in the retina and multiscale filtering because of receptive fields of different sizes in V1 at each eccentricity – consistently improve the robustness of neural networks to small adversarial perturbations. These mechanisms have negligible computational effect and one of them (non-uniform sampling) improves robustness at almost no cost in recognition performance.

However, these mechanisms did not improve robustness to large perturbations. Preliminary inspection of the adversarial examples leads us to speculate that the inability of human perception to notice that the adversarial images are different from the normal ones breaks roughly around or above the

transition in our experiments from “small” to “large” perturbation. In that case, our results suggest that the two mechanisms we identified may partially explain the robustness of primate vision to “small” perturbations, while an additional, separate mechanism – akin to an anomaly detector – may detect the presence of “large” perturbations.

In summary, our results lend support to the hypothesis that artificial neural networks are suitable as a core model of object recognition in primates. They also suggest that implementing further biologically inspired mechanisms is a promising direction for increasing adversarial robustness without sacrificing standard performance.

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Broader impact

In terms of ethical aspects and future societal consequences, achieving adversarially robust models is of critical importance to deployment of autonomous technologies we can trust. Among some of the positive outcomes we could count autonomous vehicles immune to misleading by malicious agents, better trust in medical imaging applications and any other discipline to which AI can be applied and which requires safety guarantees. This naturally also comes with negative impacts, from reducing jobs available to humans, to potentially making surveillance technologies much more difficult to avoid, allowing authoritarian regimes a much tighter control over their citizens, as well as enabling progress in autonomous weapon systems. Additionally, every defense against adversarial attacks that has been so far proposed has eventually been found to be vulnerable. If such vulnerabilities are found in increasingly more accurate models of primate vision, this could suggest the possibility of existence of dynamically changing adversarial attacks that would fool humans, leading to potentially new camouflage technologies.

References

- [1] Christian Szegedy, Wojciech Zaremba, Ilya Sutskever, Joan Bruna, Dumitru Erhan, Ian Goodfellow, and Rob Fergus. 'intriguing properties of neural networks'. *International Conference on Learning Representations*, 2014.
- [2] Martin Schrimpf, Jonas Kubilius, Ha Hong, Najib J. Majaj, Rishi Rajalingham, Elias B. Issa, Kohitij Kar, Pouya Bashivan, Jonathan Prescott-Roy, Kailyn Schmidt, Daniel L. K. Yamins, and James J. DiCarlo. Brain-score: Which artificial neural network for object recognition is most brain-like? *bioRxiv preprint*, 2018.
- [3] Pouya Bashivan, Kohitij Kar, and James J. DiCarlo. Neural population control via deep image synthesis. *Science*, 364, 2019.
- [4] Daniel L K Yamins and James J DiCarlo. Using goal-driven deep learning models to understand sensory cortex. *Nature Neuroscience*, 2016.
- [5] Alexander Berardino, Johannes Ballé, Valero Laparra, and Eero P. Simoncelli. Eigen-distortions of hierarchical representations, 2017.
- [6] Anish Athalye, Logan Engstrom, Andrew Ilyas, and Kevin Kwok. Synthesizing robust adversarial examples. *International Conference on Machine Learning*, 2018.
- [7] Nicolas Papernot, Patrick McDaniel, Xi Wu, Somesh Jha, and Ananthram Swami. Distillation as a defense to adversarial perturbations against deep neural networks. *IEEE Symposium on Security and Privacy*, 2016.
- [8] Weilin Xu, David Evans, and Yanjun Qi. Feature squeezing: Detecting adversarial examples in deep neural networks. *Network and Distributed Systems Security Symposium*, 2018.
- [9] Cihang Xie, Jianyu Wang, Zhishuai Zhang, Zhou Ren, and Alan Yuille. Mitigating adversarial effects through randomization. *International Conference on Learning Representations*, 2018.
- [10] Aleksander Madry, Aleksandar Makelov, Ludwig Schmidt, Dimitris Tsipras, and Adrian Vladu. Towards deep learning models resistant to adversarial attacks. *International Conference on Learning Representations*, 2018.
- [11] Anish Athalye, Nicholas Carlini, and David Wagner. Obfuscated gradients give a false sense of security: Circumventing defenses to adversarial examples. *International Conference on Machine Learning*, 2018.
- [12] Nicholas Carlini, Anish Athalye, Nicolas Papernot, Wieland Brendel, Jonas Rauber, Dimitris Tsipras, Ian Goodfellow, Aleksander Madry, and Alexey Kurakin. On evaluating adversarial robustness. *arXiv preprint*, 2019.
- [13] Jonathan Uesato, Brendan O'Donoghue, Aaron van den Oord, and Pushmeet Kohli. Adversarial risk and the dangers of evaluating against weak attacks. *International Conference on Machine Learning*, 2018.
- [14] Nicholas Carlini and David Wagner. Towards evaluating the robustness of neural networks. *arXiv preprint*, 2018.
- [15] Lukas Schott, Jonas Rauber, Matthias Bethge, and Wieland Brendel. Towards the first adversarially robust neural network model on mnist. *International Conference on Learning Representations*, 2019.
- [16] Warren He, James Wei, Xinyun Chen, Nicholas Carlini, and Dawn Song. Adversarial example defenses: Ensembles of weak defenses are not strong. *arXiv preprint*, 2017.
- [17] Dimitris Tsipras, Shibani Santurkar, Logan Engstrom, Alexander Turner, and Aleksander Madry. 'robustness may be at odds with accuracy'. *International Conference on Learning Representations*, 2019.
- [18] Huan Zhang, Hongge Chen, Zhao Song, Duane Boning, Inderjit S. Dhillon, and Cho-Jui Hsieh. 'the limitations of adversarial training and the blind-spot attack'. *International Conference on Learning Representations*, 2019.
- [19] Andrew Ilyas, Shibani Santurkar, Dimitris Tsipras, Logan Engstrom, Brandon Tran, and Aleksander Madry. Adversarial examples are not bugs, they are features. *Advances in Neural Information Processing Systems*, 2019.

- [20] Shibani Santurkar, Andrew Ilyas, Dimitris Tsipras, Logan Engstrom, Brandon Tran, and Aleksander Madry. Image synthesis with a single (robust) classifier. *Advances in Neural Information Processing Systems*, pages 1260–1271, 2019.
- [21] Logan Engstrom, Andrew Ilyas, Shibani Santurkar, Dimitris Tsipras, Brandon Tran, and Aleksander Madry. Adversarial robustness as a prior for learned representations. *arXiv preprint*, 2019.
- [22] Gamaleldin F. Elsayed, Shreya Shankar, Brian Cheung, Nicolas Papernot, Alex Kurakin, Ian Goodfellow, and Jascha Sohl-Dickstein. Adversarial examples that fool both computer vision and time-limited humans. *Advances in Neural Information Processing Systems*, 2018.
- [23] J. Freeman and Eero Simoncelli. Metamers of the ventral stream. *Nature Neuroscience*, 14:1195–1201, 2011.
- [24] R Gattass, C G Gross, and J H Sandell. Visual topography of v2 in the macaque. *The Journal of Comparative Neurology*, 1981.
- [25] R Gattass, AP Sousa, and CG Gross. Visuotopic organization and extent of v3 and v4 of the macaque. *Journal of Neuroscience*, 1988.
- [26] Tomaso Poggio, Jim Mutch, and Leyla Isik. Computational role of eccentricity dependent cortical magnification. *CBMM Memo*, 2014.
- [27] Francis X. Chen, Gemma Roig, Leyla Isik, Xavier Boix, and Tomaso Poggio. Eccentricity dependent deep neural networks: Modeling invariance in human vision. *Association for the Advancement of Artificial Intelligence*, 2017.
- [28] Anna Volokitin, Gemma Roig, and Tomaso Poggio. Do deep neural networks suffer from crowding? *Advances in Neural Information Processing Systems*, 2017.
- [29] Yena Han, Gemma Roig, Gad Geiger, and Tomaso Poggio. Scale and translation-invariance for novel objects in human vision. *Scientific Reports*, 10, 12 2020.
- [30] A Krizhevsky. Learning multiple layers of features from tiny images. *Technical Report*, 2009.
- [31] O. Russakovsky, J. Deng, H. Su, J. Krause, S. Satheesh, S. Ma, Z. Huang, A. Karpathy, A. Khosla, Bernstein M., A.C. Berg, and Fei-Fei L. Large scale visual recognition challenge. *ImageNet*, *arXiv:1409.0575*, 2014.
- [32] E. Hildreth D. Marr, T. Poggio. Smallest channel in early human vision. *Journal of the Optical Society of America*, 1980.
- [33] Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Deep residual learning for image recognition. *Conference on Computer Vision and Pattern Recognition*, 2016.
- [34] Jonas Rauber, Wieland Brendel, and Matthias Bethge. Foolbox: A python toolbox to benchmark the robustness of machine learning models. *arXiv preprint arXiv:1707.04131*, 2017.
- [35] Alexey Kurakin, Ian J. Goodfellow, and Samy Bengio. Adversarial examples in the physical world. *International Conference on Learning Representations*, 2017.
- [36] Nicholas Carlini, Guy Katz, Clark Barrett, and David L. Dill. Provably minimally-distorted adversarial examples. *arXiv preprint*, 2018.
- [37] Zhengyu Zhao, Zhuoran Liu, and Martha Larson. Towards large yet imperceptible adversarial image perturbations with perceptual color distance. *arXiv preprint*, 2019.
- [38] Cihang Xie, Yuxin Wu, Laurens van der Maaten, Alan Yuille, and Kaiming He. Feature denoising for improving adversarial robustness. *Conference on Computer Vision and Pattern Recognition*, 2019.
- [39] Xin Li and Fuxin Li. Adversarial examples detection in deep networks with convolutional filter statistics. *International Conference on Computer Vision*, 2017.
- [40] Wieland Brendel, Jonas Rauber, and Matthias Bethge. Decision-based adversarial attacks: Reliable attacks against black-box machine learning models. *International Conference on Learning Representations*, 2018.

Appendix

5 Datasets

5.1 Preprocessing

All images x were centered on the 0 to 1 scale by $x/255$.

Images in ImageNet10 and ImageNet100 were formed from the central 320x320 regions of images from ImageNet. If the image dimensions for either height or width (or both) were less than 320, we upsampled the image with a bilinear filter with a constant aspect ratio so that both dimensions were at least 320x320.

We conducted a set of preliminary experiments on ImageNet10 with training images (not test images) trimmed to bounding boxes. Results from these preliminary experiments were not reported in the paper but we report the results here in the supplementary materials. The standard bounding boxes were used as provided with the ImageNet dataset. If images had 0 bounding boxes, they were discarded for this dataset. If images had 1 bounding box, they were trimmed to the bounding box before the standard central 320x320 crop described above was performed. If images had more than 1 bounding box, we only kept the first bounding box.

5.2 ImageNet10

Classes comprising the dataset are listed below:

1. Snake: n01742172 boa constrictor
2. Dog: n02099712, Labrador retriever
3. Cat: n02123045, tabby
4. Frog: n01644373, tree frog
5. Turtle: n01665541, leatherback turtle
6. Bird: n01855672 goose
7. Bear: n02510455 giant panda
8. Fish: n01484850 great white shark
9. Crab: n01981276 king crab
10. Insect: n02206856 bee

5.3 ImageNet100

Classes comprising the dataset are listed below:

['n01644900', 'n02096051', 'n04366367', 'n03544143', 'n02105412', 'n01914609', 'n02105162', 'n02132136', 'n03026506', 'n03063599', 'n02815834', 'n07802026', 'n01968897', 'n03788365', 'n04443257', 'n12998815', 'n02454379', 'n03991062', 'n04332243', 'n04254680', 'n02097298', 'n07590611', 'n03680355', 'n02165105', 'n01491361', 'n04120489', 'n03742115', 'n07880968', 'n02808304', 'n03888257', 'n03095699', 'n01494475', 'n03673027', 'n02488702', 'n01871265', 'n02104365', 'n02281787', 'n04118538', 'n01828970', 'n02837789', 'n03127747', 'n04005630', 'n02115913', 'n01514859', 'n03452741', 'n02107908', 'n01847000', 'n04200800', 'n04153751', 'n04389033', 'n02487347', 'n02769748', 'n01843383', 'n02219486', 'n02009912', 'n03676483', 'n02797295', 'n04417672', 'n04591157', 'n04229816', 'n02058221', 'n03814906', 'n02097130', 'n02939185', 'n03710637', 'n02116738', 'n04418357', 'n03775071', 'n04328186', 'n02090721', 'n02667093', 'n03929855', 'n02089078', 'n02389026', 'n03388183', 'n07613480', 'n02749479', 'n02174001', 'n07932039', 'n02112018', 'n02398521', 'n04069434', 'n03838899', 'n02233338', 'n03207743', 'n02791270', 'n02114855', 'n04204238', 'n02342885', 'n02110063', 'n01518878', 'n02099712', 'n01704323', 'n02168699', 'n04238763', 'n03494278', 'n03980874', 'n02097209', 'n01616318', 'n03131574']

6 Biologically Inspired Mechanisms

6.1 Retinal Sampling

Implementation for retinal sampling was adapted from [3]. Please consult their paper for full details on the sampling procedure and chosen parameters. In their work, they defined a function g , that mapped points from the re-sampled image (r') to the original image (r). Their code was open-sourced at <https://github.com/dicarloolab/retinawarp>. As part of the transform, the pixel coordinates in the image grid (x, y) were mapped to polar (r, θ). To work with arbitrary fixation points, we simply re-centered this transform at a fixation point instead of at the Cartesian origin. We present here a visualization of the distribution of the sampling points (Figure 1: Top Left) and some examples of retina sampled images at 5 different fixation points (Figure 1: Bottom Left).

6.2 Cortical Sampling

Biological measurements [24, 25] have demonstrated that in primates, the receptive field size varies with eccentricity. With the slope of the relationship between receptive field size and eccentricity also becoming steeper further down the ventral stream (Figure 6). Following from previous studies [26, 27, 28], we approximate this by centering multiple scale-space fragments on a point of fixation on the image, with the larger scales corresponding to larger receptive field sizes. We employed 4 scales of dimensions 40x40, 80x80, 160x160 and 240x240 that were all gaussian downsampled to 40x40 for ImageNet. For CIFAR10, we only employed 2 scales (15x15 and 30x30 that were both gaussian downsampled to 15x15) because of the significantly lower resolution of images in the dataset (32x32 in CIFAR10 vs 320x320 for ImageNet). We present here a visualization of the centering of the scale-space fragments at various fixation points in an image (Figure 1: Top Right) and some of the resulting scales (Figure 1: Bottom Right).

When making a prediction for a given fixation point, models incorporating cortical sampling have to incorporate information across the different scales. Each scale is fed to a separate CNN. These separate CNNs do not end with a dense layer. We concatenate the final latent vector from each branch and this concatenated representation was then passed through a single dense layer for classification. During training time, we used an auxiliary loss to ensure that each branch was also predictive of the label on its own. We also provide results from some preliminary experiments with alternate concatenation mechanisms (e.g. max, average pooling across scales, etc.) in the supplementary results section below.

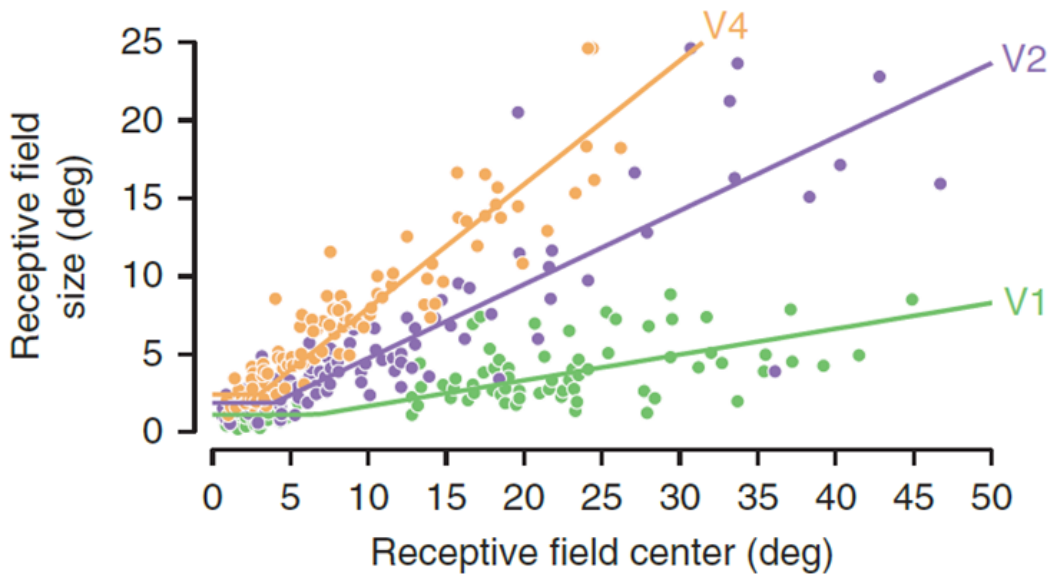


Figure 6: Biological measurements in V1, V2 and V4 support a model in which the maximum scale depends on eccentricity. Adapted from (author?) 23 (original monkey data from [24, 25]).

7 Models

As described in the paper, we employed two baseline models ('ResNet' and 'coarse fixations') and two effect models ('retinal fixations' and 'cortical fixations'). At evaluation time, the 'coarse fixations', 'retinal fixations' and 'cortical fixations' models each center their mechanisms on 5 pre-defined fixation points (top left, top right, bottom left, bottom right, center) and combine information across fixations by averaging models logits across the fixation points.

The 'ResNet' baseline model directly feeds the full image through a standard ResNet architecture (32x32 for CIFAR10 or 320x320 for ImageNet). The 'coarse fixations' model applies a standard ResNet architecture to 5 different regions of the image (5 224x224 regions from the 320x320 image for ImageNet, centered on (0,0),(48,48),(48,-48),(-48,48),(-48,-48) or 5x24x24 from 32x32 for CIFAR10, centered on (0,0),(4,4),(4,-4), (-4,4), (-4,-4)). This acts as a very coarse approximation of foveation. At training time, the model randomly trains on a single region from all valid regions, not just the 5 to be used at evaluation time (i.e. centered on (rand(-48 to 48),rand(-48 to 48)) for ImageNet and centered on (rand(-4 to 4),rand(-4 to 4)) for CIFAR10).

The 'retinal fixations' model applies the retinal sampling at 5 different fixation points (re-samples the image, keeping dimensions the same). At evaluation time, the mechanism is centered on the points (0,0),(80,80),(80,-80),(-80,80),(-80,-80) for ImageNet and on the points (0,0),(8,8),(8,-8),(-8,8),(-8,-8) for CIFAR. At training time, the model randomly trains on a single fixation from all possible fixations (centered on (rand(-80 to 80),rand(-80 to 80)) for ImageNet and centered on (rand(-8 to 8),rand(-8 to 8)) for CIFAR10).

The 'cortical fixations' model applies the cortical sampling at 5 different fixation points (re-samples the ImageNet images from 320x320 to 5x40x40 and CIFAR10 images from 32x32 to 2x15x15). At evaluation time, the mechanism is centered on the points (0,0),(40,40),(40,-40),(-40,40),(-40,-40) for ImageNet and (0,0),(1,1),(1,-1),(-1,1),(-1,-1) for CIFAR10. At training time, the model randomly trains on a single fixation from all possible fixations (centered on (rand(-40 to 40),rand(-40 to 40)) for ImageNet and centered on (rand(-1 to 1),rand(-1 to 1)) for CIFAR10).

8 Adversarial Robustness

8.1 Determinism In TensorFlow

We performed all experiments, training, etc. on TensorFlow 2.0.0. On this version, TensorFlow implements a reduced form of GPU-deterministic op functionality. We fix this to ensure deterministic operations with a patch from NVIDIA (see <https://github.com/NVIDIA/tensorflow-determinism>). This patch was applied only when evaluating adversarial robustness. We verified that the results from 3 experiments (coarse fixations, retinal fixations, cortical fixations models for 5 iterations of L_∞ PGD with a targeted loss ($y_{adv} = y_{true} + 1$) with $\epsilon=0.01$ and step size of $\epsilon / 3$) were consistent with and without this patch. See "check determinism" notebook in the checks folder in source code for additional details.

8.2 Accuracy Calculation

To calculate the accuracy under an adversarial attack, we employed the following procedure. We first evaluated the model on the natural images in the test splits for the datasets. This gives us a number of natural images that are correctly classified and a number that are misclassified (always determined by the true-class not being the top-1 class predicted by model, num_misclassified). We then ran the adversarial attack on the correctly classified natural images, generating some number of adversarial examples that meet the desired adversarial criteria (num_adversarial). We then calculated the accuracy under attack as $1 - ((\text{num_misclassified} + \text{num_adversarial}) / (\text{total_num_images}))$.

9 Results

9.1 CIFAR10 Benchmark

We benchmarked our evaluation pipeline against the pipeline used in (author?) 10 (see Table 2). We perform these benchmarks on the CIFAR10 test set of 10000 images. Across our experiments, our

Table 2: Comparison of accuracy under PGD attacks between our pipeline and the pipeline used in (author?) 10. Top Table: 5-step L_∞ PGD, step size of $\epsilon/3$. Bottom Table: 20-step L_∞ PGD step size, step size of $2/255$.

ϵ	BENCHMARK ACCURACY	OUR ACCURACY
0.001	86.15%	86.149%
0.005	82.06%	82.06%
0.01	76.60%	76.60%
0.05	31.26%	31.26%
0.1	12.95%	12.949%
0.5	0.12%	0.1199%

ϵ	BENCHMARK ACCURACY	OUR ACCURACY
8/255	45.72%	45.73%

pipelines were exactly consistent (except in the one case of 20-step PGD where our results differed by 1 image on the full test set). The benchmark pipeline from (author?) 10 was open-sourced at https://github.com/MadryLab/cifar10_challenge.

9.2 All Experiment Hyperparameters

We provide an almost complete list of hyperparameters used for the experiments presented in the paper (Table 3). Please refer to the full evaluation data provided with the source code for an exhaustive list of all relevant hyperparameters. For ImageNet10 for example, not presented in the table, we also ran 1 experiment with 5 randomly chosen fixation points and 1 experiment where the images were initialized with random noise in an ϵ_{init} ball. Both these experiments were run with L_∞ PGD for 5 steps with `ATTACK_STEP_SIZE = 0.1` and `CRITERION_TAG = MISCLASSIFY_3`.

For each set of hyperparameters, the value for maximum perturbation size ϵ was scanned across [0.001, 0.005, 0.01, 0.05, 0.1, 0.5] for CIFAR10 and [0.001, 0.005, 0.01, 0.02, 0.05, 0.1, 0.5] for ImageNet.

9.3 Robustness To FGSM, PGD, PGD ADAM

We compared the robustness for the FGSM, PGD ADAM, PGD adversarial attacks using the L_∞ distance metric, 5 attack iterations (1 for FGSM), step size of $\epsilon/3$ ($5\epsilon/3$ for FGSM), adversarial criteria of true class not in top-3 predicted classes by model at $\epsilon = [0.005, 0.01, 0.02]$. Retinal fixations and cortical fixations models showed biggest improvements in robustness from the best baseline for PGD, and the least with FGSM (see Figure 7).

9.4 Robustness To PGD 5 Steps, PGD 20 Steps

We compared the robustness for L_∞ PGD at 5 and 20 iterations. We ran the attacks with a step size of $\epsilon/3$, with the adversarial criteria of true class not top-1 predicted class by model at $\epsilon = [0.005, 0.01, 0.02]$. Improvement in robustness of retinal fixations and cortical fixations models from the best baseline was approximately the same for 5 and 20 iterations (see Figure 8).

9.5 Robustness To PGD Step Size $\epsilon/3, \epsilon/12$

We compared the robustness for L_∞ PGD at step sizes of $\epsilon/3$ (`ATTACK_STEP_SIZE = 0.1`) and $\epsilon/12$ (`ATTACK_STEP_SIZE = 0.025`). We ran the attacks for 20 iterations, with the adversarial criteria of true class not top-1 predicted class by model at $\epsilon = [0.005, 0.01, 0.02]$. Improvement in robustness of retinal and cortical fixations models from the best baseline was approximately the same for the 2 step sizes (see Figure 9).

Table 3: Attack hyperparameters used for evaluating the robustness of the models in most of the experiments presented in the paper. Please see full evaluation data provided with the source code for an exhaustive list. ATTACK_ALGO refers to the algorithm used for generating the adversarial example, ATTACK_DISTANCE_METRIC refers to the form of L_p norm used to measure distances and the L_p variant of the attack algorithm, ATTACK_ITERATIONS refers to the number of steps of the iterative algorithms, ATTACK_STEP_SIZE refers to a constant used internally to calculate the actual step size (actual step size: $(\epsilon / 0.3) * \text{ATTACK_STEP_SIZE}$), CRITERION_TAG refers to the loss and criteria used for the attack (TARGETED_X: targeted attack ($\text{adv_class} = \text{true_class} + 1$, classified as adv_class with probability at least X if $X \neq 50$, classified as adv_class as top1 predicted class if $X = 50$), MISCLASSIFY_X: untargeted attack (true class not in top-X classes predicted by model)). Top Table: For experiments on CIFAR10, Middle Table: IMAGENET10, Bottom Table: IMAGENET100.

ATTACK_ALGO	ATTACK_DISTANCE_METRIC	ATTACK_ITERATIONS	ATTACK_STEP_SIZE	CRITERION_TAG
PGD	LINF	5	0.100	MISCLASSIFY_1
PGD	LINF	5	0.100	MISCLASSIFY_3

ATTACK_ALGO	ATTACK_DISTANCE_METRIC	ATTACK_ITERATIONS	ATTACK_STEP_SIZE	CRITERION_TAG
PGD	L2	5	0.100	TARGETED_50
PGD	LINF	20	0.025	TARGETED_50
PGD	LINF	20	0.100	TARGETED_50
PGD	LINF	5	0.100	TARGETED_50
PGD	L2	5	0.100	MISCLASSIFY_1
PGD	LINF	20	0.025	MISCLASSIFY_1
PGD	LINF	20	0.100	MISCLASSIFY_1
PGD	LINF	5	0.100	MISCLASSIFY_1
FGSM	LINF	1	-1.000	MISCLASSIFY_3
PGD	L1	5	0.100	MISCLASSIFY_3
PGD	L2	5	0.100	TARGETED_80
PGD	L2	5	0.100	MISCLASSIFY_3
PGD	LINF	20	0.025	TARGETED_80
PGD	LINF	20	0.025	MISCLASSIFY_3
PGD	LINF	20	0.100	TARGETED_80
PGD	LINF	20	0.100	MISCLASSIFY_3
PGD	LINF	5	0.100	TARGETED_80
PGD	LINF	5	0.100	MISCLASSIFY_3
PGD_ADAM	LINF	5	0.100	MISCLASSIFY_3

ATTACK_ALGO	ATTACK_DISTANCE_METRIC	ATTACK_ITERATIONS	ATTACK_STEP_SIZE	CRITERION_TAG
PGD	L2	5	0.100	MISCLASSIFY_1
PGD	LINF	5	0.100	MISCLASSIFY_1
PGD	L2	5	0.100	MISCLASSIFY_3
PGD	LINF	5	0.100	MISCLASSIFY_3
PGD	L2	5	0.100	MISCLASSIFY_10
PGD	LINF	5	0.100	MISCLASSIFY_10

9.6 Robustness Under L_∞, L_2, L_1 Metrics

We compared the robustness for L_∞, L_2 and L_1 PGD run for 5 iterations with a step size of $\epsilon / 3$ and the adversarial criteria of true class not in the top-3 predicted classes by model at $\epsilon = [0.005, 0.01, 0.02]$. Improvement in robustness of retinal and cortical fixations models was greater for L_∞ and least for L_1 (see Figure 10).

9.7 Robustness To Confident Mistakes

We compared the robustness for L_∞ PGD run for 5 iterations with a step size of $\epsilon / 3$ and the adversarial criteria of untargeted misclassified out of top-1 or top-3 predicted classes by model (misclassify_1, misclassify_3) and targeted misclassification ($y_{\text{adv}} = y_{\text{true}} + 1$) with adversarial

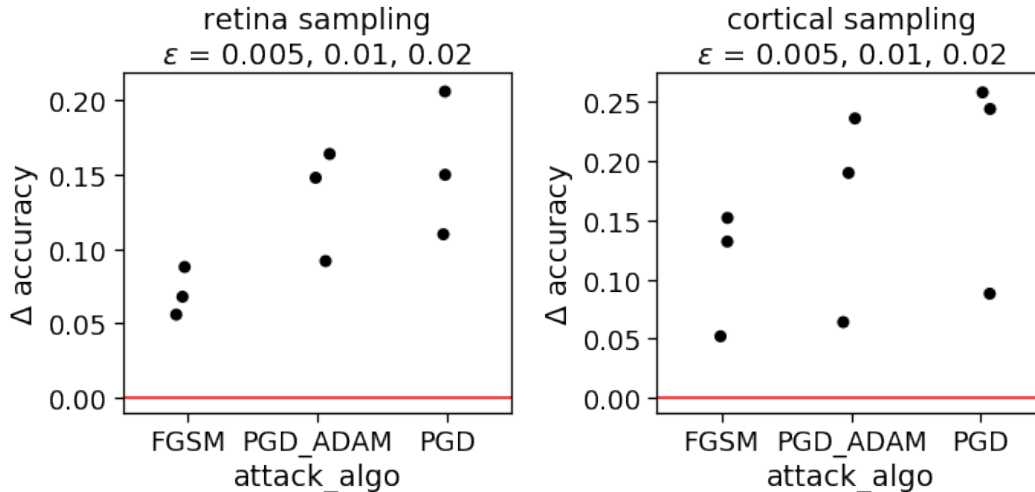


Figure 7: Improvements in robustness for retinal fixations and cortical fixations models from the best baseline under various adversarial attacks at small perturbations on ImageNet10.

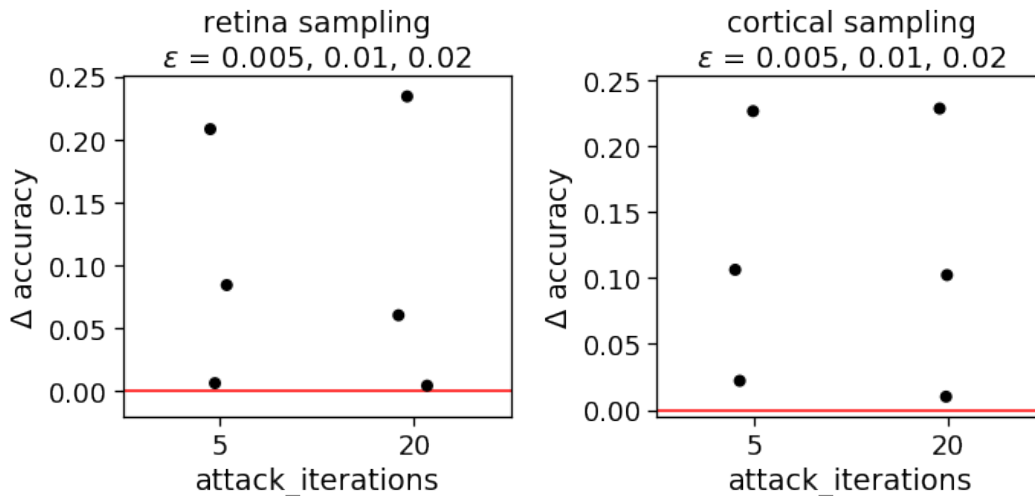


Figure 8: Improvements in robustness for retinal fixations and cortical fixations models from the best baseline at varying PGD attack iterations at small perturbations on ImageNet10.

class in top-1 or predicted with at least 80% probability (targeted_50, targeted_80). Improvement in robustness of retinal and cortical fixations models was greater for misclassify_3 compared to misclassify_1. Improvement in robustness of retinal and cortical fixations models was approximately the same for targeted_50 and targeted_80 (see Figure 11).

9.8 Quality of Adversarial Perturbations

We explored how semantically meaningful (“quality”) large adversarial perturbations were for cortical fixations and retinal fixations models (see Figure 12). The large adversarial perturbations for the models were not anymore meaningful than for the coarse fixations model.

9.9 Visibility of Adversarial Perturbations

We explored the L_∞ distance at which the adversarial perturbations become visible to the naked eye when the adversarial example and the original image are presented side by side. We present

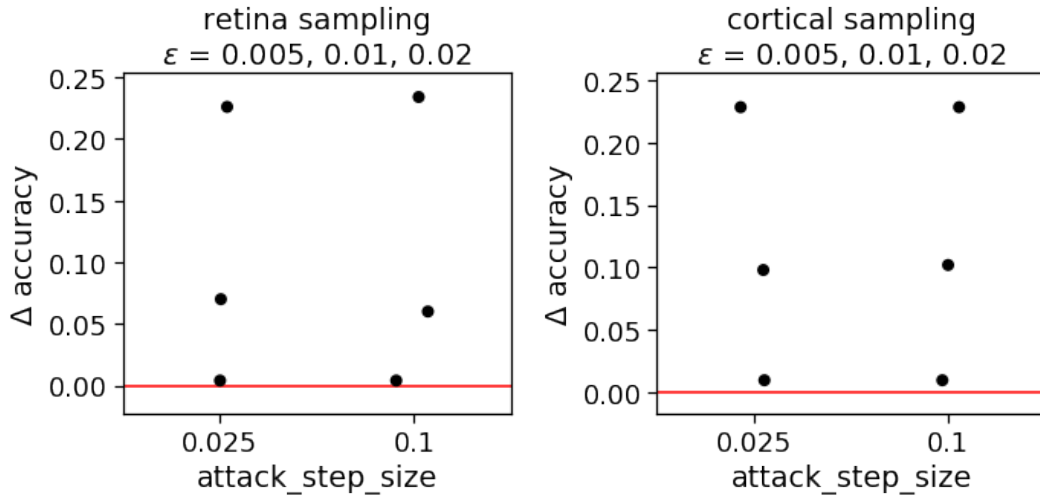


Figure 9: Improvements in robustness for retinal fixations and cortical fixations models from the best baseline at varying PGD attack steps at small perturbations on ImageNet10. ATTACK_STEP_SIZE = 0.1, 0.025 corresponds to a PGD step size of $\epsilon/3$ and $\epsilon/12$.

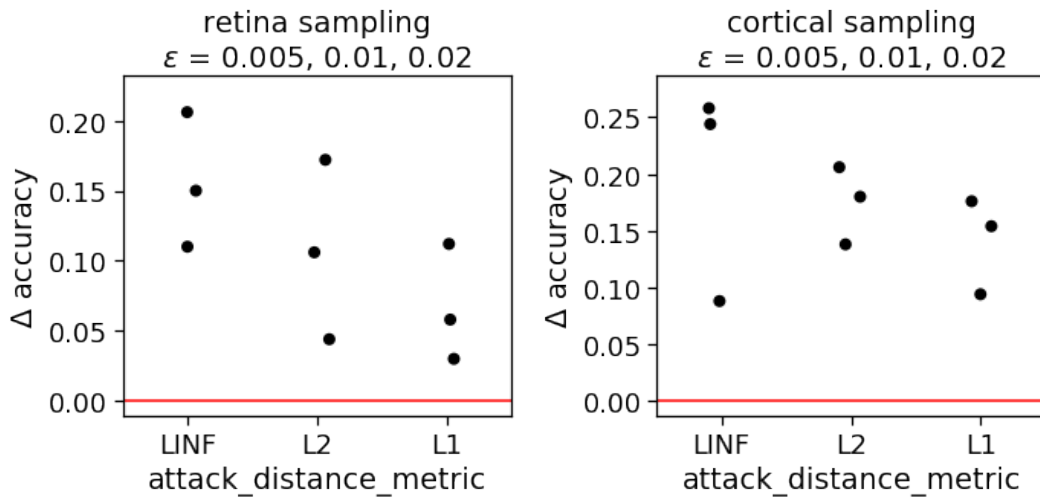


Figure 10: Improvements in robustness for retinal and cortical fixations models from the best baseline using various distance metrics at small perturbations on ImageNet10.

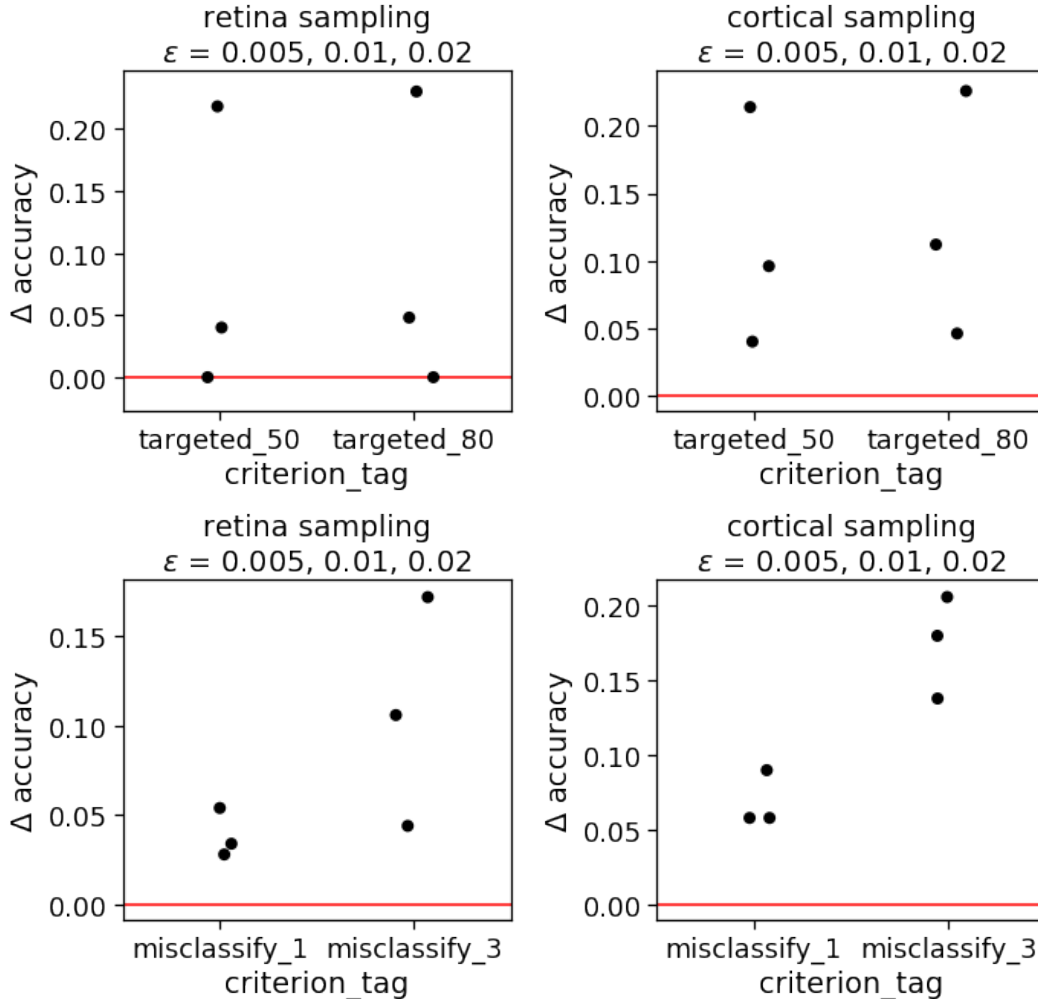


Figure 11: Improvements in robustness for retinal and cortical fixations models from the best baseline for various adversarial criteria at small perturbations on ImageNet10.

the visualized scan for an image of a shark here (see Figure 12). At preliminary inspection, the adversarial perturbations seem to become visible around $\epsilon \approx 0.2$ or 0.5 .

9.10 Training With Only Bounding Boxes

We tried training the cortical fixations model on just the training images bounding boxes. We trimmed images in the training set of ImageNet10 (only training images, test images were left as is) to just their first bounding box and trained a cortical fixations model without the standard auxiliary loss during training. We compared this to a cortical fixations model trained on the usual training images without the standard auxiliary loss during training (see Figure 13).

Since only some of the images in the training set come with a bounding box annotation and since we only kept the first bounding box annotation in images, the model trained on the bounding boxes trained on far fewer samples. The model trained only on the bounding boxes did not show improved robustness compared to the model trained on the standard images.

9.11 Alternate Cortical Sampling Implementations

We carried out some experiments with alternate methods of incorporating information across the scales (that result from a single fixation point) for the cortical sampling (see Figure 14). We experimented

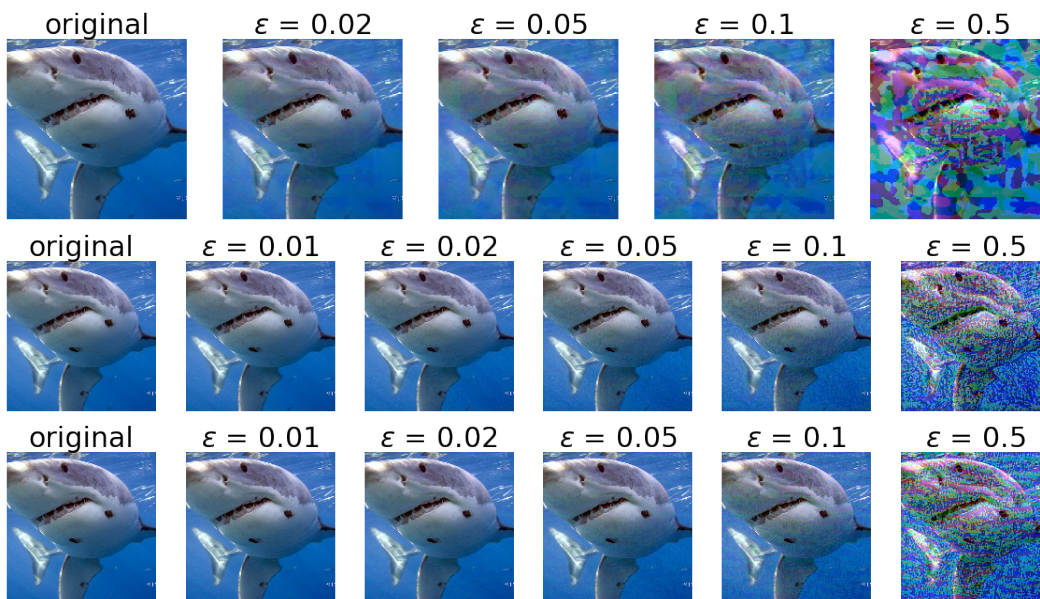


Figure 12: Original image and adversarial examples at various L_∞ distances ϵ . Adversarial examples were generated for the cortical fixations model (top row), retinal fixations model (middle row), coarse fixations model (bottom row) using 5-step PGD with step size $\epsilon/3$.

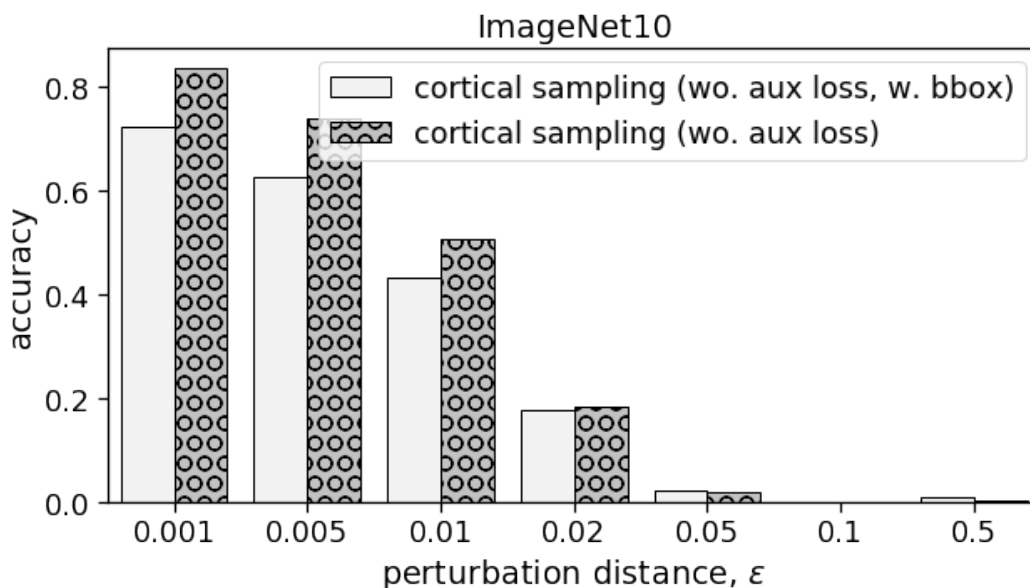


Figure 13: Robustness of cortical fixations models trained on only the bounding boxes of training images ('w. bbox') and on the standard training images. Both models were trained without the standard auxiliary loss during training. Both models were evaluated on ImageNet10 to targeted ($y_{adv} = y_{true} + 1$) L_∞ PGD attacks run for 5 iterations with step size $\epsilon/3$.

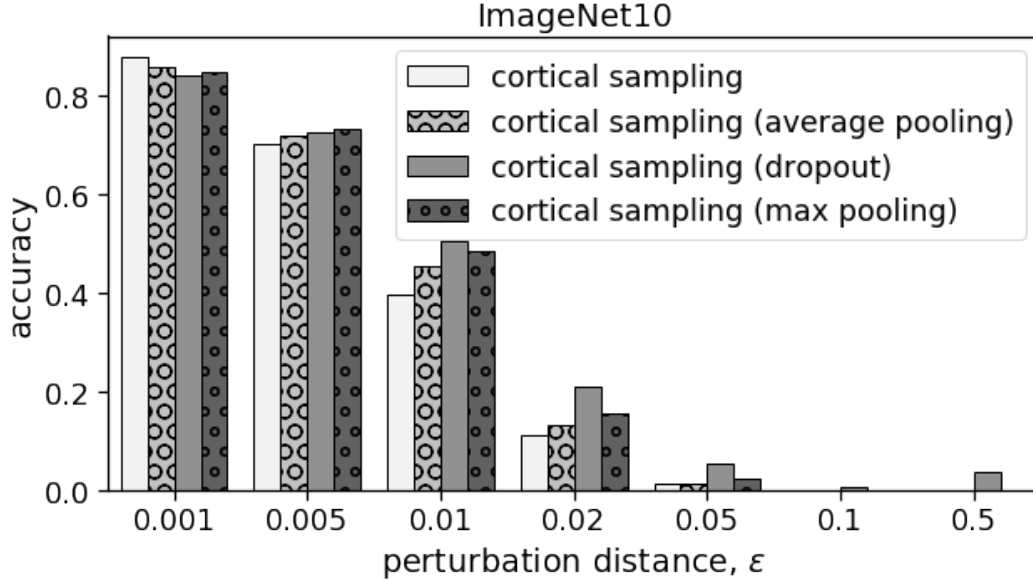


Figure 14: Robustness of alternate cortical fixations models as compared to the cortical fixations model as used in the rest of the paper on ImageNet10 to targeted ($y_{adv} = y_{true} + 1$) L_∞ PGD attacks run for 5 iterations with step size $\epsilon/3$.

with max and average pooling across the scales and employing a large dropout during training on the concatenated representation.

For the cortical fixations models as used in the rest of the paper, we simply concatenated the representation from each scale to form the complete representation for each fixation. For the pooling alternatives, we pool the representations across the scales. For the large dropout alternative, we randomly drop 75% of the elements in the final concatenated representation during training time. These alternate methods of incorporating information across the scales all performed better than the cortical sampling as used in the rest of the paper. This suggests that there are more robustness improvements to be gained from the cortical sampling models.

9.12 Combining Retinal And Cortical Sampling

We attempted to combine the two proposed mechanisms, by first performing the retinal sampling on the image, then the cortical sampling. We envisioned this to be similar to how when presented with a visual stimulus, the re-sampling by the photoreceptors would occur before any further processing in the visual stream. Naively combining the two mechanisms in this manner resulted in an improvement in robustness from the baselines but the combined mechanisms model was only as robust as or less robust than either of the proposed mechanisms (see Figure 15).

9.13 L2 CarliniWagner Attack

We also conducted some preliminary experiments comparing the robustness of the models to the L2 variant of the CarliniWagner attack [14] (see Table 4). We ran the attack for 100 iterations with the initial constant set to 0.01 for the ImageNet10 models. The preliminary results are consistent with our reported results with PGD (proposed mechanisms outperform the baselines).

10 Gradient Obfuscation

10.1 Iterative Attacks Outperform Single-Step Attacks

To check that gradient obfuscation was not an issue with the models, we verified that PGD was always more successful or as successful as FGSM when generating adversarial examples (see Table 5). We

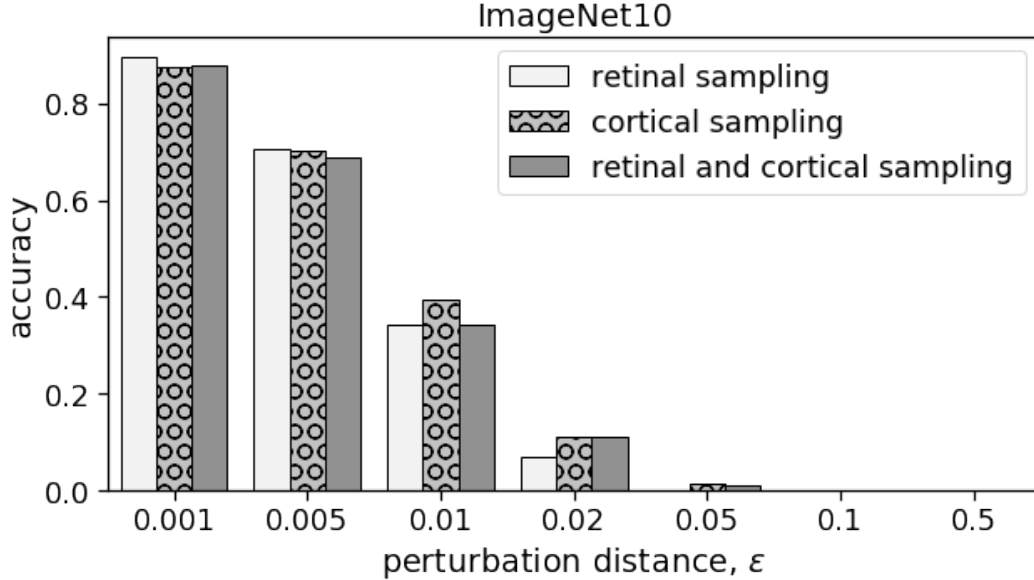


Figure 15: Robustness of the retinal fixations models as compared to the cortical fixations model and the combined (retinal and cortical) fixations model on ImageNet10 to targeted ($y_{adv} = y_{true} + 1$) L_∞ PGD attacks run for 5 iterations with step size $\epsilon/3$.

Table 4: Accuracy of the models under L_2 CarliniWagner attack with the initial constant set to 0.01 on ImageNet10. Retinal and cortical fixations models outperformed the baselines (standard ResNet, coarse fixations).

MECHANISM	ACCURACY
VANILLA RESNET	0.692
COARSE FIXATIONS	0.71
RETINAL FIXATIONS	0.81
CORTICAL FIXATIONS	0.758

verified this with L_∞ PGD run for 5 iterations against the equivalent FGSM, with the adversarial criteria that the true class is not in the top-3 classes predicted by the model.

We saw that PGD consistently outperformed or at the very least performed as well as FGSM, this suggests that following the direction of gradient descent is useful for constructing adversarial examples and that gradient obfuscation is likely not an issue with the models.

10.2 White-Box Attacks Outperform Black-Box

If gradient obfuscation is not an issue with the models, white-box attacks (attacks that directly use the model gradients) should always outperform black-box attacks.

10.2.1 Transfer Attack

We performed a transfer attack from the standard ResNet model to the retinal fixations and cortical fixations models (see Table 6). We compared the accuracy of the models under this transfer attack and accuracy under standard PGD. We perform L_∞ PGD for 5 steps, with a step size of $\epsilon/3$, maximum adversarial perturbation $\epsilon = 0.005$ or $\epsilon = 0.5$. We perform targeted attacks with desired adversarial class ($y + 1 \pmod n$, $n = 10$) and desired predicted probability of at least 0.8.

For each perturbation limit, we first run PGD on the images in the ImageNet10 test split that were correctly predicted by the standard ResNet model. We then evaluate the retinal fixations and cortical fixations models on these adversarial examples generated for the standard ResNet model (transfer

Table 5: Comparison of accuracy under PGD and equivalent FGSM attack. Top Table: Retinal Fixations Model. Bottom Table: Cortical Fixations Model. PGD consistently performs as well as or outperforms FGSM.

ϵ	ACCURACY (FGSM)	ACCURACY (PGD)
0.500	0.054	0.000
0.100	0.240	0.000
0.050	0.378	0.014
0.020	0.540	0.236
0.010	0.698	0.600
0.005	0.850	0.840
0.001	0.900	0.900

ϵ	ACCURACY (FGSM)	ACCURACY (PGD)
0.500	0.108	0.010
0.100	0.326	0.036
0.050	0.440	0.098
0.020	0.636	0.344
0.010	0.742	0.638
0.005	0.834	0.818
0.001	0.886	0.886

Table 6: Accuracy of the retinal fixations and cortical fixations models was lower under a standard PGD attack performed directly on the models compared to a transfer attack from a standard ResNet model.

MECHANISM	ATTACK METHOD	ACCURACY
RETINAL	PGD ($\epsilon = 0.005$)	0.560694
RETINAL	TRANSFER ($\epsilon = 0.005$)	0.933333
CORTICAL	PGD ($\epsilon = 0.005$)	0.549133
CORTICAL	TRANSFER ($\epsilon = 0.005$)	0.887179
RETINAL	PGD ($\epsilon = 0.5$)	0.000000
RETINAL	TRANSFER ($\epsilon = 0.5$)	0.181208
CORTICAL	PGD ($\epsilon = 0.5$)	0.000000
CORTICAL	TRANSFER ($\epsilon = 0.5$)	0.261745

attack). For the comparison to an equivalent white-box attack, we then run PGD on the retinal fixations and cortical fixations models for the images in ImageNet10 test split that were correctly predicted by both the standard ResNet model and the retinal or cortical fixations model.

The transfer attacks consistently underperformed at generating adversarial examples compared to a direct white-box PGD attack. This suggests that gradient obfuscation is not an issue with the models.

10.2.2 Boundary Attack

We compared the adversarial examples generated with boundary attack (black-box decision-based attack, (author?) 40) with PGD (white-box gradient-based attack) (see Table 7).

Both attacks were run in a targeted setting on models trained on ImageNet10. We ran it on a single image of a panda (ILSVRC2012_val_00042615.JPEG) to be misclassified as a shark. We initialized the boundary attack with an image of a shark (ILSVRC2012_val_00029481.JPEG). We only ran the comparison for a single image because boundary attack takes a while to run. We ran boundary attack for 1000 iterations and PGD for 5 iterations, comparing the size of adversarial perturbations.

Generated adversarial perturbations were always smaller (better) with 5 steps of PGD compared to 1000 steps of boundary attack. This again suggests that gradient obfuscation is not an issue with the models. The size of adversarial perturbations for the retinal and cortical fixations models generated with boundary attack was also larger than for the coarse fixations or standard ResNet model.

Table 7: Size of adversarial perturbations generated with 5 steps of PGD was always less than with 1000 steps of boundary attack. Here, we refer to the standard ResNet model as 'vanilla', coarse fixations as 'coarse', retinal fixations as 'retinal', cortical fixations as 'cortical'.

MECHANISM	ATTACK METHOD	DISTANCE
CORTICAL	PGD	8.2E-06
CORTICAL	BOUNDARY ATTACK	2.5E-03
RETINAL	PGD	1.0E-05
RETINAL	BOUNDARY ATTACK	1.4E-03
COARSE	BOUNDARY ATTACK	1.1E-03
VANILLA	BOUNDARY ATTACK	6.45E-04

Table 8: Ability to find an adversarial example with standard PGD was always superior to the BPDA PGD. Top, Bottom Tables: Ability to find adversarial examples using various hyperparameters with two different pictures as the original image.

MECHANISM	ATTACK METHOD (STEPS, ϵ)	ADV FOUND
CORTICAL	PGD (5,0.005)	Y
CORTICAL	PGD BPDA (60,0.005)	N
CORTICAL	PGD BPDA (5,0.5)	Y
RETINAL	PGD (5,0.005)	Y
RETINAL	PGD BPDA (120,0.005)	N
RETINAL	PGD BPDA (5,0.5)	Y

MECHANISM	ATTACK METHOD (STEPS, ϵ)	ADV FOUND
CORTICAL	PGD (5,0.01)	Y
CORTICAL	PGD BPDA (300,0.01)	N
CORTICAL	PGD BPDA (5,0.5)	Y
RETINAL	PGD (10,0.005)	Y
RETINAL	PGD BPDA (300,0.005)	N
RETINAL	PGD BPDA (10,0.5)	Y

The probability assigned to the mispredicted class for examples generated with 5 steps PGD was also much greater than for 1000 steps of boundary attack ($\approx 100\%$ for PGD vs $\approx 50\%$ for boundary attack). This is however an unfair comparison since PGD explicitly optimizes for the probability of the mispredicted class while boundary attack does not, but we mention it here for completeness.

10.2.3 Backward Pass Differentiable Approximation

We also attempted to generate adversarial examples using the backward pass differentiable approach (BDPA) [11] (see Table 8). If gradient obfuscation is not an issue with the models, this surrogate gradient approach should not outperform directly using the full model gradient with PGD.

For the retinal fixations model, we approximated the retina transform $g(x)$ as $g(x) \approx x$ for the gradient (backward pass). The cortical fixations model performs several transforms $h(i(j(x)))$ for each scale fragment. We approximated $i(x)$ as $i(x) \approx x$ for the gradient (backward pass). We did not approximate the gradients for the subsample and cropping operation further. We performed L_∞ PGD on one image of a panda (top in Table 8) and one image of a frog (bottom in Table 8).

Standard PGD, taking the gradient through the full model, was always superior to PGD BPDA at finding an adversarial example. This suggests that gradient obfuscation is not an issue with the models.

We also verified that PGD BDPA was able to find adversarial examples when we allow very large perturbations.

11 Image Sources

The original pictures of the peacock (e.g. see Figure 1: Bottom Right in main paper) and checkerboard (e.g. see Figure 1: Bottom Left in main paper) used to visualize the effect of the biologically inspired mechanisms were obtained from online sources. The image of a peacock was taken from Flickr (see www.flickr.com/photos/kkoshy/32401990166). The author, Koshy Koshy (see <https://www.flickr.com/photos/kkoshy/>), explicitly authorized the image for reuse and modification under the Attribution 2.0 Generic (CC BY 2.0) license (<https://creativecommons.org/licenses/by/2.0/>). The image of a checkerboard was taken from Wikimedia Commons (see https://en.m.wikipedia.org/wiki/File:Checkerboard_reflection.svg). The author, M. W. Toews (see <https://commons.wikimedia.org/wiki/User:Mwtoews>), explicitly authorized the image for reuse and modification under the Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) license (<https://creativecommons.org/licenses/by-sa/4.0/deed.en>).