CRITICAL LEARNING PERIODS IN DEEP NETWORKS

Anonymous authors
Paper under double-blind review

ABSTRACT

Similar to humans and animals, deep artificial neural networks exhibit critical periods during which a temporary stimulus deficit can impair the development of a skill. The extent of the impairment depends on the onset and length of the deficit window, as in animal models, and on the size of the neural network. Deficits that do not affect low-level statistics, such as vertical flipping of the images, have no lasting effect on performance and can be overcome with further training. To better understand this phenomenon, we use the Fisher Information of the weights to measure the effective connectivity between layers of a network during training. Counterintuitively, information raises rapidly in the early phases of training, and then decreases, preventing redistribution of information resources in a phenomenon we refer to as a loss of "Information Plasticity". Our analysis suggests that the first few epochs are critical for the creation of strong connections that are optimal relative to the input data distribution. Once such strong connections are created, they do not appear to change during additional training. These findings suggest that the initial learning transient, under-scrutinized compared to asymptotic behavior, plays a key role in determining the outcome of the training process. Our findings, combined with recent theoretical results in the literature, also suggest that forgetting (decrease of information in the weights) is critical to achieving invariance and disentanglement in representation learning. Finally, critical periods are not restricted to biological systems, but can emerge naturally in learning systems, whether biological or artificial, due to fundamental constrains arising from learning dynamics and information processing.

1 INTRODUCTION

Critical periods are time windows of early post-natal development during which sensory deficits can lead to permanent skill impairment (Kandel et al., 2013). Researchers have documented critical periods affecting a range of species and systems, from visual acuity in kittens (Wiesel & Hubel, 1963b; Wiesel, 1982) to song learning in birds (Konishi, 1985). Uncorrected eye defects (*e.g.*, strabismus, cataracts) during the critical period for visual development lead to amblyopia in one in fifty adults.

The cause of critical periods is ascribed to biochemical processes (Hensch, 2004). In this paper, however, we show that deep neural networks (DNNs), while completely devoid of biochemistry, respond to sensory deficits in ways similar to those observed in humans and animal models. This surprising result suggests that critical periods may actually arise from information processing, rather than biochemical, phenomena.

We propose using the information in the weights, measured by an efficient approximation of the Fisher Information, to study critical period phenomena in DNNs. We show that, counterintuitively, the information in the weights does not increase monotonically during training. Instead, a rapid growth in information ("memorization phase") is followed by a *reduction of information* ("reorganization" or "forgetting" phase), even as classification performance keeps increasing. This behavior is consistent across different tasks and network architectures. Critical periods correspond to the memorization phase.

Our findings, described in Section 2, indicate that the early transient is critical in determining the final solution of the optimization associated with training an artificial neural network. In particular, the effects of sensory deficits during a critical period cannot be overcome, no matter how much

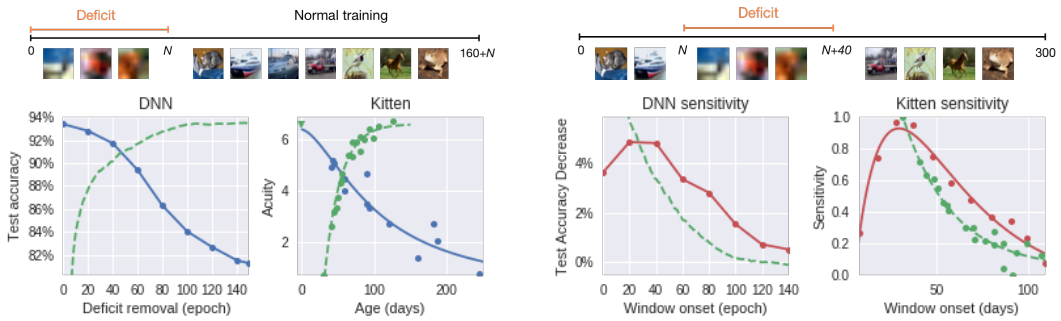

Figure 1: **DNNs exhibit critical periods. (A)** Final accuracy achieved by a CNN trained with a cataract-like deficit as a function of the training epoch N at which the deficit is removed (solid line). Performance is permanently impaired if the deficit is not corrected early enough, regardless of how much additional training is performed. As in animal models, critical periods coincide with the early learning phase during which, in the absence of deficits, test accuracy would rapidly increase (dashed). **(B)** For comparison, we report acuity for kittens monocularly deprived since birth and tested at the time of eye-opening (solid), and normal visual acuity development (in kittens) as a function of their age (dashed) (Giffin & Mitchell, 1978; Mitchell, 1988). **Sensitivity during learning: (C)** Final test accuracy of a DNN as a function of the onset of a short 40-epoch deficit. The decrease in the final performance can be used to measure the sensitivity to deficits. The most sensitive epochs corresponds to the early rapid learning phase, before the test error (dashed line) begins to plateau. Afterwards, the network is largely unaffected by the temporary deficit. **(D)** This can be compared with changes in the degree of functional disconnection (normalized numbers of V1 monocular cells disconnected from the contralateral eye) as a function of the kittens' age at the onset of a 10-12-day deficit window (Olson & Freeman, 1980). Dashed lines are as in A and B respectively, up to a re-scaling of the y-axis.

additional training is performed. Yet most theoretical studies have focused on the network behavior after convergence (Representation Learning) or on the asymptotic properties of the optimization scheme used for training (SGD).

To study this early phase, in Section 3, we use the Fisher Information to quantify the *effective connectivity* of a network during training, and introduce the notion of *Information Plasticity* in learning. Information Plasticity is maximal during the memorization phase, and decreases in the reorganization phase. We show that sensitivity to critical periods correlates highly with effective connectivity.

In Section 4 we discuss our contribution in relation to previous work. When considered in conjunction with recent results on representation learning (Achille & Soatto, 2018), our findings indicate that forgetting (reducing information in the weights) is critical to achieving invariance to nuisance variability as well as independence of the components of the representation, but bears the price of a reduced adaptability later in the training. We also hypothesize that the loss of physical connectivity in biology (neural plasticity) could be a consequence, rather than a cause, of the loss of information plasticity, which depends on how the information is distributed throughout a network during the early stages of learning. These results also shed light on the common practice of pre-training a model on a task and then fine-tune it for another, one of the most rudimentary forms of transfer learning. Our experiments show that, rather than helpful, pre-training can be detrimental, even if the tasks are similar (*e.g.*, same labels, slightly blurred images).

2 Experiments

A notable example of critical period-inducing deficit, commonly affecting humans, is amblyopia (reduced visual acuity in one eye) caused by cataracts during infancy or childhood (Vaegan & Taylor, 1979; von Noorden, 1981). Even after surgical correction of the cataracts, the ability of the patients to regain normal acuity in the affected eye depends both on the duration of the deficit and on its age of onset, with earlier and longer deficits causing more severe effects. In this section, we aim to

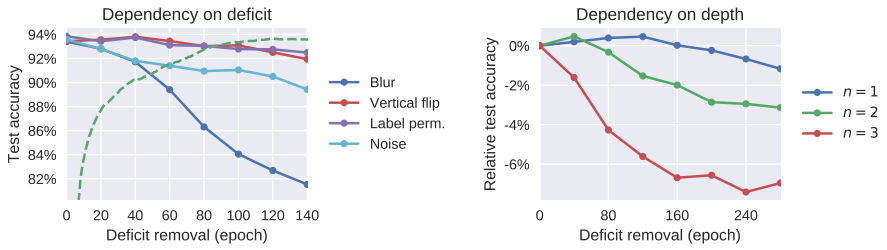

Figure 2: **(Left) High-level perturbations do not induce a critical period.** When the deficit only affects high-level features (vertical flip of the image) or the last layer of the CNN (label permutation), the network does not exhibit critical periods (test accuracy remains largely flat). On the other hand, a sensory deprivation-like deficit (image is replaced by random noise) does cause a deficit, but the effect is less drastic than in the case of image blur. **(Right) Dependence of the critical period profile on the network's depth.** Adding more convolutional layers increases the effect of the deficit during its critical period (shown here is the decrease in test accuracy due to deficits with respect to the test accuracy reached without deficit).

study the effects of similar deficits in DNNs. To do so, we train a standard All-CNN architecture based on Springenberg et al. (2014) (see Appendix A) to classify objects in small 32×32 images from the CIFAR-10 dataset (Krizhevsky & Hinton, 2009). We train with SGD using an exponential annealing schedule for the learning rate. To simulate the effect of cataracts, for the first t_0 epochs the images in the dataset are downsampled to 8×8 and then upsampled back to 32×32 using bilinear interpolation, in practice blurring the image and destroying small-scale details.[1] After that, the training continues for 160 more epochs, giving the network time to converge and ensuring it is exposed to the same number of uncorrupted images as in the control ($t_0 = 0$) experiment.

DNNs exhibit critical periods: In Figure 1, we plot the final performance of a network affected by the deficit as a function of the epoch t_0 at which the deficit is corrected. We can readily observe the existence of a critical period: if the blur is not removed within the first 40-60 epochs, the final performance is severely decreased when compared to the baseline (up to a threefold increase in error). The decrease in performance follows trends commonly observed in animals, and may be compared, for example, to the loss of visual acuity observed in kittens monocularly deprived from birth as a function of the length of the deficit (Mitchell, 1988).[2]

We can measure more accurately the sensitivity to a blur deficit during learning by introducing the deficit in a short constant window (40 epochs), starting at different epochs, and then measure the decrease in the DNN's final performance compared to the baseline (Figure 1). Doing this, we can observe that the sensitivity to the deficit peaks in the central part of the early rapid learning phase (at around 30 epochs), while introducing the deficit later produces little or no effect. A similar experiment performed on kittens, using a window of 10-12 days during which the animals are monocularly deprived, shows again a remarkable similarity between the profiles of the sensitivity curves (Olson & Freeman, 1980).

High-level deficits are not associated with a critical period: A natural question is whether any change in the input data distribution will have a corresponding critical period for learning. This is not the case for neuronal networks, which remain plastic enough to adapt to high-level changes in sensory processing (Daw, 2014). For example, it is well-reported that even adult humans can rapidly adapt to certain drastic changes, such as the inversion of the visual field (Stratton, 1896; Kohler, 1964). In Figure 2, we observe that DNNs are also largely unaffected by high-level deficits – such as vertical flipping of the image, or random permutation of the output labels: After deficit correction, the network quickly recovers its baseline performance. This hints at a finer interplay between the structure of the data distribution and the optimization algorithm which results in the existence of a critical period.

[1] We employed this method, instead of a simpler Gaussian blur, since it has a very similar effect and makes the quantification of information loss clearer.

[2] See Appendix C for details on how to compare different models and deficits.

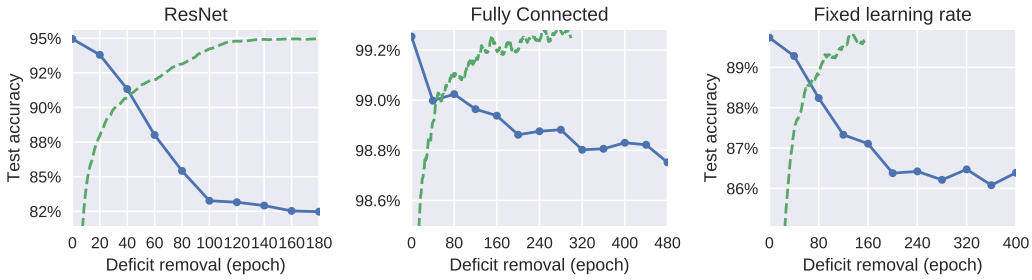

Figure 3: **Critical periods in different DNN architectures and optimization schemes. (Left)** Effect of an image blur deficit in a ResNet architecture trained on CIFAR-10 with learning rate annealing and **(Center)** in a deep fully-connected network trained on MNIST with a fixed learning rate. Different architectures, using different optimization methods and trained on different datasets, still exhibit qualitatively similar critical period behavior. **(Right)** Same experiment as in Figure 1, but using a fixed learning rate instead of an annealing scheme. Although the time scale of the critical period is longer, the trends are similar, supporting the notion that critical periods cannot be explained solely in terms of the loss landscape of the optimization.

Sensory deprivation: We now apply to the network a more drastic deficit, where each image is replaced by white noise. Figure 2 shows hows this extreme deficit exhibits a remarkably less severe effect than the one obtained by only blurring images: Training the network with white noise does not provide any information on the natural images, and results in milder effects than those caused by a deficit (*e.g.*, image blur), which instead conveys *some* information, but leads the network to (incorrectly) learn that no fine structure is present in the images. A similar effect has been observed in animals, where a period of early sensory deprivation (dark-rearing) can lengthen the critical period and thus cause less severe effects than those documented in light-reared animals (Mower, 1991). We refer the reader to Appendix C for a more detailed comparison between sensory deprivation and training on white noise.

Architecture, depth, and learning rate annealing: Figure 3 shows that a fully-connected networks trained on the MNIST digit classification dataset also shows a critical period for the image blur deficit. Therefore, the convolutional structure is not necessary, nor is the use of natural images. Similarly, a ResNet-18 trained on CIFAR-10 also has a critical period, which is also remarkably sharper than the one found in a standard convolutional network (Figure 1). This is especially interesting, since ResNets allow for easier backpropagation of gradients to the lower layers, thus suggesting that the critical period is not caused by vanishing gradients. However, Figure 2 (Right) shows that the presence of a critical period does indeed depend critically on the depth of the network. In Figure 3, we confirm that a critical period exists even when the network is trained with a constant learning rate, and therefore cannot be explained by an annealed learning rate in later epochs.

3 Fisher Information Analysis

We have established empirically that, in animals and DNNs alike, the initial phases of training are critical to the outcome of the training process. In animals, this strongly relates to changes of the brain architecture in the areas associated with the deficit (Daw, 2014). This is inevitably different in artificial networks, since their connectivity is formally fixed at all times during training. However, not all the connections are equally useful to the network: Consider a network encoding the approximate posterior distribution $p_w(y|x)$, parameterized by the weights w, of the task variable y given an input image x. The dependency of the final output from a specific connection can be estimated by perturbing the corresponding weight and looking at the magnitude of the change in the final distribution. Specifically, given a perturbation $w' = w + \delta w$ of the weights, the discrepancy between the $p_w(y|x)$ and the perturbed network output $p_{w'}(y|x)$ can be measured by their Kullback-Leibler divergence, which, to second-order approximation, is given by:

$$\mathbb{E}_x \, \mathrm{KL}(\, p_{w'}(y|x) \,\|\, p_w(y|x) \,) = \delta w \cdot F \delta w + o(\delta w^2),$$

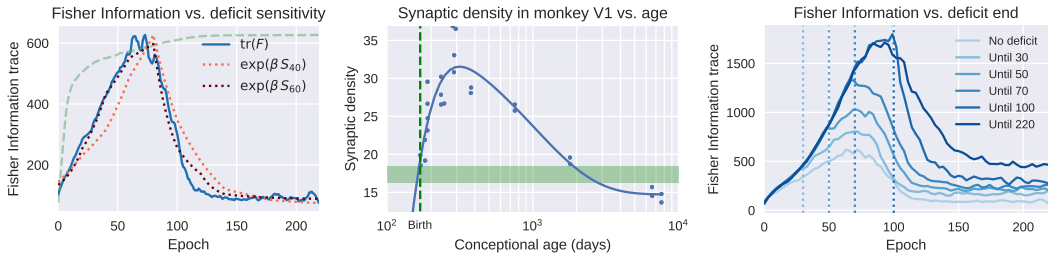

Figure 4: **Critical periods in DNNs are traced back to changes in the Fisher Information. (Left)** Trace of the Fisher Information of the network weights as a function of the training epoch (blue line), showing two distinct phases of training: First, information sharply increases, but once test performance starts to plateau (green line), the information in the weights decreases during a "consolidation" phase. Eventually less information is stored, yet test accuracy improves slightly (green line). The weights' Fisher Information correlates strongly with the networks sensitivity to critical periods, computed as in Figure 1 using both a window size of 40 and 60, and fitted here to the Fisher Information using a simple exponential fit. **(Center)** Recalling the connection between FIM ad connectivity, we may compare it to synaptic density during development in the visual cortex of macaques (Rakic et al., 1986). Here too, a rapid increase in connectivity is followed by elimination of synapses (pruning) continuing throughout life. **(Right)** Effects of critical period-inducing deficit (image blur) on the Fisher Information: The impaired network uses more information to solve the task, compared to training in the absence of a deficit, since it is forced to memorize the labels case by case.

where the expectation over x is computed using the empirical data distribution $\hat{Q}(x)$ given by the dataset, and

$$F := \mathbb{E}_{x\sim\hat{Q}(x)}\mathbb{E}_{y\sim p_w(y|x)}[\nabla_w \log p_w(y|x)\nabla_w \log p_w(y|x)^T]$$

is the Fisher Information Matrix (FIM). The FIM can thus be considered a local metric measuring how much the perturbation of a single weight (or a combination of weights) affects the output of the the network (Amari & Nagaoka, 2007). In particular, weights with low Fisher Information can be changed or pruned with little effect on the network's performance. This suggests that the Fisher Information can be used as a measure of the effective connectivity of a DNN, or, more generally, of the "synaptic" strength of a connection (Kirkpatrick et al., 2017). Finally, the FIM is also a semi-definite approximation of the Hessian of the loss function (Martens, 2014) and hence of the curvature of the loss landscape at a particular point w during training, which provides an elegant connection between the FIM and the optimization procedure (Amari & Nagaoka, 2007), which we will also employ later.

Unfortunately, the full FIM is too large to compute. Rather, we use its trace to measure the global or layer-wise connection strength, which we can compute efficiently using (Appendix A):

$$\mathrm{tr}(F) = \mathbb{E}_{x\sim\hat{Q}(x)}\mathbb{E}_{y\sim p_w(y|x)}[\|\nabla_w \log p_w(y|x)\|^2].$$

In order to capture the behavior of the off-diagonal terms, we also tried computing the log-determinant of the full matrix using the Kronecker-Factorized approximation of Martens & Grosse (2015), but we observed the same qualitative trend as the trace. Since the FIM is a local measure, it is very sensitive to the irregularities of the loss landscape. Therefore, in this section we mainly use ResNets, which have a relatively smooth landscape (Li et al., 2017). For other architectures we use instead a more robust estimator of the FIM based on the injection of noise in the weights (Achille & Soatto, 2018), also described in Appendix A.

Two phases of learning: As its name suggests, the FIM can be thought as a measure of the quantity of information that the model contains about the training data (Fisher, 1925). Based on this, one would expect the overall strength of the connections to increase monotonically as we acquire information from experience. However, this is not the case: While in an initial phase, the network acquires information about the data, which results in a large increase in the strength of the connections, once the performance in the task begins to plateau, the network starts reducing the overall strength of its connections. However, this does not correspond to a decrease in performance, rather,

performance keeps slowly improving. This can be seen as a "forgetting, or "compression" phase, during which redundant connections are eliminated and non-relevant variability in the data is discarded. It is commonly believed that forgetting is a critical part of learning; Figure 4 shows this phenomenon clearly and quantitatively for DNNs.

Strikingly, this change in the connection strength is closely related to the sensitivity to critical-period-inducing deficits such as image blur, computed using the "sliding window" method as in Figure 1. In Figure 4 we see that the sensitivity closely follows the trend of the FIM. This is remarkable since the FIM is a local quantity computed at a single point during the training of a network in the absence of deficit, while the sensitivity during a critical period is computed, using the the test data, at the end of the impaired network training. A similar phenomenon is also observed in the development of neuronal networks (Figure 4, Center). Figure 4 (Right) further emphasizes the effect of deficits on the FIM: in the presence of a deficit, the FIM grows and remains substantially higher even after the deficit is removed. This may be attributed to the fact that, when the data are so corrupted that classification is impossible, the network is forced to memorize the labels, therefore increasing the quantity of information needed to perform the same task.

Layer-wise effects of deficits: A layer-wise analysis of the FIM sheds further light on how the deficit affects the network. When the network (in this case All-CNN, which has a clearer division among layers than ResNet) is trained without deficits, the most important connections are in the intermediate layers (Figure 5, Left), which can process the input CIFAR-10 image at the most informative intermediate scale. However, if the network is initially trained on blurred data (Figure 5, top right), the strength of the connections is dominated by the top layer (Layer 6). This is to be expected, since the low-level and mid-level structures of the images are destroyed, making the lower layers ineffective. However, if the deficit is removed early in the training (Figure 5, top center), the network manages to "reorganize', reducing the information contained in the last layer, and, at the same time, increasing the information in the intermediate layers. We refer to these phenomena as changes in "Information Plasticity'. If, however, the data change occurs after the consolidation phase, the network is unable to change its effective connectivity: The connection strength of each layer remains substantially constant. The network has lost its Information Plasticity and is past its critical period.

Critical period as bottleneck crossing: The analysis of the FIM also sheds light on the geometry of the loss function and the learning dynamics. Since the FIM can be interpreted as the local curvature of the residual landscape, Fig. 4 shows that learning entails crossing bottlenecks: The initial phase enters regions of high curvature (high Fisher Information), and once consolidation begins, the curvature decreases, allowing crossing the bottleneck to enter the valley below. If the statistics change after crossing the bottleneck, the network is trapped. In this interpretation, the early phases of convergence are critical in leading the network towards the "right" final valley. The end of critical periods comes after the network has crossed all bottlenecks (hence learned the features) and entered a wide valley (region of the weight space with low curvature, or low Fisher Information).

4 Discussion and Related Work

Critical periods have thus far been considered an exclusively biological phenomenon. At the same time, the analysis of DNNs has focused on asymptotic properties and neglected the initial transient behavior. To the best of our knowledge, we are the first to show that artificial neural networks exhibit critical period phenomena, and to highlight the critical role of the transient in determining the asymptotic performance of the network. Inspired by the role of synaptic connectivity in modulating critical periods, we introduce the use of Fisher Information to study this initial phase. We show that the initial sensitivity to deficits closely follows changes in the FIM, both global, as the network first rapidly increases and then decreases the amount of stored information, and layer-wise, as the network "reorganizes" its effective connectivity in order to optimally process information.

Our work naturally relates to the extensive literature on critical periods in biology. Despite artificial networks being a mere cartoon approximation of neuronal networks, they exhibit behaviors that are qualitatively similar to the critical periods observed in human and animal models. Our information analysis shows that the initial rapid memorization phase is followed by a loss of Information Plasticity which, counterintuitively, further improves the performance. On the other hand, when combined

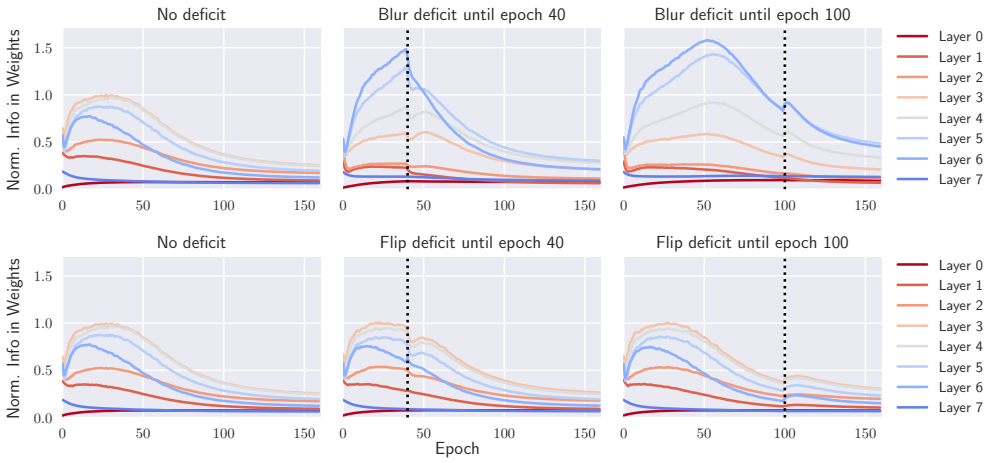

Figure 5: Normalized quantity of information contained in the weights of each layer as a function of the training epoch. **(Top Left)** In the absence of deficits, the network relies mostly on the middle layers (3-4-5) to solve the task. **(Top Right)** In the presence of an image blur deficit until epoch 100, more resources are allocated to the higher layers (6-7) rather than to the middle layers. The blur deficit destroys low- and mid-level features processed by those layers, leaving only the global features of the image, which are processed by the higher layers. Even if the deficit is removed, the middle layers remain underdeveloped. **(Top Center)** When the deficit is removed at an earlier epoch, the layers can partially reconfigure (notice, *e.g.*, the fast loss of information of layer 6), resulting in less severe long-term consequences. We refer to the redistribution of information and the relative changes in effective connectivity, as Information Plasticity. **(Bottom row)** Same plots, but using a vertical flip deficit, which does not induce a critical period. As expected, the quantity of information in the layers is not affected.

with the analysis of Achille & Soatto (2018) this suggests that a "forgetting" phase may be desirable, or even necessary, in order to learn robust, nuisance-invariant representations.

It must be noted that the existence of two phases during training has also been observed by Shwartz-Ziv & Tishby (2017) who, however, focus on the compression of the *activations* of the network, rather than the effective connectivity of the *weights*. There are fundamental differences in the two analyses. In particular, compression of the weights can imply compression of the activations (Achille & Soatto, 2018), while the converse is generally not true. Once training is completed, the weights are fixed, and compressing the activations has no effect on the weights.

One advantage of focusing on the information of the weights rather than on the activations, or behavior of the network, is to have a readout of the "effective connectivity" during critical periods, which can be compared to similar readouts in animals. In fact, "behavioral" readouts upon deficit removal, both in artificial and neuronal networks, can potentially be confounded by deficit-coping changes at different levels of the visual pathways (Daw, 2014; Knudsen, 2004). On the other hand, deficits in deprived animals are mirrored by abnormalities in the circuitry of the visual pathways, which we characterize in DNNs using the FIM to study its "effective connectivity", *i.e.*, the connections that are actually employed by the network to solve the task. Sensitivity to critical periods and the trace of the Fisher Information peak at the same epochs, in accord with the evidence that skill development and critical periods in neuronal networks are modulated by changes (generally experience-dependent) in synaptic plasticity (Knudsen, 2004; Hensch, 2004). Our layer-wise analysis of the Fisher Information (Figure 5) also shows that visual deficits reinforce higher layers to the detriment of intermediate layers, leaving low-level layers virtually untouched. If the deficit is removed after the critical period ends, the network is not able to reverse these effects. Although the two systems are radically different, a similar response can be found in the visual pathways of animal models: Lower levels (*e.g.*, retina, lateral geniculate nucleus) and higher-level visual areas (*e.g.*, V2 and post-V2) show little remodeling upon deprivation, while most changes happen in different layers of V1 (Wiesel & Hubel, 1963a; Hendrickson et al., 1987).

An insightful interpretation of critical periods in animal models was proposed by Knudsen (2004): The initial connections of neuronal networks are unstable and easily modified (highly plastic), but as more "samples" are observed, they change and reach a more stable configuration which is difficult to modify. Learning can, however, still happen within the newly created connectivity pattern. This is largely compatible with our findings: Sensitivity to critical-period-inducing deficits peaks when connections are remodeled (Figure 4, Left), and different connectivity profiles are observed in networks trained with and without a deficit (Figure 5). Moreover, high-level deficits such as image-flipping and label permutation, which do not require restructuring of the network's connections in order to be corrected, do not exhibit a critical period.

Applying a deficit at the beginning of the training may be compared to the common practice of pre-training, which is generally found to improve the performance of the network. Erhan et al. (2010) study the somewhat related, but now seldom used, practice of layer-wise unsupervised pre-training, and suggest that it may act as a regularizer by moving the weights of the network towards an area of the loss landscape closer to the attractors for good solutions, and that early examples have a stronger effect in steering the network towards particular solutions. Here, we have shown that pre-training on blurred data can have the opposite effect; *i.e.*, it can severely decrease the final performance of the network. However, in our case, interpreting the deficits effect as moving the network close to a bad attractor is difficult to reconcile with the smooth transition observed in the critical periods, since the network would either converge to this attractor, and thus have low accuracy, or escape completely.

Instead, we reconcile our experiments with the geometry of the loss function by introducing a different explanation based on the interpretation of the FIM as an approximation of the local curvature. Figure 4 suggests that SGD encounters two different phases during the network training: At first, the network moves towards high-curvature regions of the loss landscape, while in the second phase the curvature decreases and the network eventually converges to a flat minimum (as also observed in Keskar et al. (2017)). We can interpret these as the network crossing narrow bottlenecks during its training in order to learn useful features, before eventually entering a flat region of the loss surface once learning is completed and ending up trapped there. When combining this assumption with our deficit sensitivity analysis, we can hypothesize that the critical period occurs precisely upon crossing of this bottleneck. It is also worth noticing how there is evidence that convergence to flat minima (minima with low curvature) in a DNN correlates with a good generalization performance (Hochreiter & Schmidhuber, 1997; Li et al., 2017; Chaudhari et al., 2016; Keskar et al., 2017). Indeed, using this interpretation, Figure 4 (Right) tells us that networks more affected by the deficit converge to sharper minima. However, we have also found that the performance of the network is already mostly determined during the early "sensitive" phase. The final sharpness at convergence may therefore be an epiphenomenon, rather than the cause of good generalization.

5 Conclusion

Our goal in this paper is not so much to investigate the human (or animal) brain through artificial networks, as to understand fundamental information processing phenomena, both in their biological or artificial implementations. It is also not our goal to suggest that, since they both exhibit critical periods, DNNs are necessarily a valid model of neurobiological information processing, although recent work has emphasized this aspect. We engage in an "Artificial Neuroscience" exercise in part to address a technological need to develop "explainable" artificial intelligence systems whose behavior can be understood and predicted. While traditionally well-understood mathematical models were used by neuroscientists to study biological phenomena, information processing in modern artificial networks is often just as poorly understood as in biology, so we chose to exploit well-known biological phenomena as probes to study information processing in artificial networks.

Conversely, it would also be interesting to explore ways to test whether biological networks prune connections as a consequences of a loss of Information Plasticity, rather than as a cause. The mechanisms underlying network reconfiguration during learning and development might be an evolutionary outcome obtained under the pressure of fundamental information processing phenomena.

Acknowledgements

(witheld for review)

REFERENCES

A. Achille and S. Soatto. Emergence of Invariance and Disentangling in Deep Representations. *Journal of Machine Learning Research*, 2018.

Shun-ichi Amari and Hiroshi Nagaoka. *Methods of information geometry*, volume 191. American Mathematical Soc., 2007.

M S Banks, R N Aslin, and R D Letson. Sensitive period for the development of human binocular vision. *Science*, 190(4215):675–7, nov 1975. ISSN 0036-8075. doi: 10.1126/science.1188363.

Pratik Chaudhari, Anna Choromanska, Stefano Soatto, and Yann LeCun. Entropy-sgd: Biasing gradient descent into wide valleys. *arXiv preprint arXiv:1611.01838*, 2016.

Nigel W. Daw. *Visual Development*. Springer, New York, NY, 3rd edition, 2014. doi: 10.1007/978-1-4614-9059-3. URL https://doi.org/10.1007/978-1-4614-9059-3.

Dumitru Erhan, Yoshua Bengio, Aaron Courville, Pierre-Antoine Manzagol, Pascal Vincent, and Samy Bengio. Why does unsupervised pre-training help deep learning? *Journal of Machine Learning Research*, 11(Feb):625–660, 2010.

Ronald Aylmer Fisher. Theory of statistical estimation. In *Mathematical Proceedings of the Cambridge Philosophical Society*, volume 22, pp. 700–725. Cambridge University Press, 1925.

F Giffin and D E Mitchell. The rate of recovery of vision after early monocular deprivation in kittens. *The Journal of physiology*, 274(1978):511–37, jan 1978. doi: 10.1113/jphysiol.1978.sp012164.

Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Deep residual learning for image recognition. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pp. 770–778, 2016.

A E Hendrickson, J A Movshon, H M Eggers, M S Gizzi, R G Boothe, and Lynne Kiorpes. Effects of early unilateral blur on the macaque's visual system. II. Anatomical observations. *The Journal of neuroscience*, 7(5):1327–39, may 1987. ISSN 0270-6474.

Takao K. Hensch. Critical period regulation. *Annual review of neuroscience*, 27(1):549–79, 2004. ISSN 0147-006X. doi: 10.1146/annurev.neuro.27.070203.144327.

Sepp Hochreiter and Jürgen Schmidhuber. Flat minima. *Neural Computation*, 9(1):1–42, 1997.

E. R. Kandel, J. H. Schwartz, T. M. Jessell, S. A. Siegelbaum, and A. J. Hudspeth. *Principles of Neural Science*. McGraw-Hill, New York, NY, 5th edition, 2013.

Nitish Shirish Keskar, Dheevatsa Mudigere, Jorge Nocedal, Mikhail Smelyanskiy, and Ping Tak Peter Tang. On large-batch training for deep learning: Generalization gap and sharp minima. 2017.

Diederik P. Kingma, Tim Salimans, and Max Welling. Variational dropout and the local reparameterization trick. In *Proceedings of the 28th International Conference on Neural Information Processing Systems*, NIPS'15, pp. 2575–2583, 2015.

James Kirkpatrick, Razvan Pascanu, Neil Rabinowitz, Joel Veness, Guillaume Desjardins, Andrei A. Rusu, Kieran Milan, John Quan, Tiago Ramalho, Agnieszka Grabska-Barwinska, Demis Hassabis, Claudia Clopath, Dharshan Kumaran, and Raia Hadsell. Overcoming catastrophic forgetting in neural networks. *Proceedings of the National Academy of Sciences*, 114(13):3521–3526, 2017. ISSN 0027-8424. doi: 10.1073/pnas.1611835114.

Eric I Knudsen. Sensitive periods in the development of the brain and behavior. *Journal of cognitive neuroscience*, 16(8):1412–25, oct 2004. ISSN 0898-929X. doi: 10.1162/0898929042304796. URL http://www.ncbi.nlm.nih.gov/pubmed/15509387.

I. Kohler. *The formation and transformation of the perceptual world*. Psychological Issues Monographs. International Universities Press, New York, NY, 1964.

M Konishi. Birdsong: from behavior to neuron. *Annual review of neuroscience*, 8(1):125–70, 1985. ISSN 0147-006X. doi: 10.1146/annurev.ne.08.030185.001013.

Alex Krizhevsky and Geoffrey Hinton. Learning multiple layers of features from tiny images. Technical report, University of Toronto, 2009.

Hao Li, Zheng Xu, Gavin Taylor, and Tom Goldstein. Visualizing the loss landscape of neural nets. *arXiv preprint arXiv:1712.09913*, 2017.

James Martens. New insights and perspectives on the natural gradient method. *arXiv preprint arXiv:1412.1193*, 2014.

James Martens and Roger Grosse. Optimizing neural networks with kronecker-factored approximate curvature. In *International conference on machine learning*, pp. 2408–2417, 2015.

D E Mitchell. The extent of visual recovery from early monocular or binocular visual deprivation in kittens. *The Journal of physiology*, 395:639–60, jan 1988. doi: 10.1113/jphysiol.1988.sp016939.

G D Mower. The effect of dark rearing on the time course of the critical period in cat visual cortex. *Brain research. Developmental Brain Research*, 58(2):151–8, feb 1991.

C R Olson and R D Freeman. Profile of the sensitive period for monocular deprivation in kittens. *Experimental Brain Research*, 39(1):17–21, 1980.

Pasko Rakic, J P Bourgeois, Maryellen F Eckenhoff, Nada Zecevic, and P S Goldman-Rakic. Concurrent overproduction of synapses in diverse regions of the primate cerebral cortex. *Science*, 232 (4747):232–5, apr 1986. ISSN 0036-8075.

Ravid Shwartz-Ziv and Naftali Tishby. Opening the black box of deep neural networks via information. *arXiv preprint arXiv:1703.00810*, 2017.

Jost Tobias Springenberg, Alexey Dosovitskiy, Thomas Brox, and Martin Riedmiller. Striving for simplicity: The all convolutional net. *arXiv preprint arXiv:1412.6806*, 2014.

George M Stratton. Some preliminary experiments on vision without inversion of the retinal image. *Psychological Review*, 3(6):611–617, 1896. ISSN 0033-295X. doi: 10.1037/h0072918.

Vaegan and D Taylor. Critical period for deprivation amblyopia in children. *Transactions of the ophthalmological societies of the United Kingdom*, 99(3):432–9, 1979. ISSN 0078-5334. URL `http://www.ncbi.nlm.nih.gov/pubmed/298827`.

Gunter K. von Noorden. New clinical aspects of stimulus deprivation amblyopia. *American journal of ophthalmology*, 92(3):416–21, sep 1981. ISSN 0002-9394. doi: 10.1016/0002-9394(81)90534-1.

T N Wiesel and D H Hubel. Single-Cell responses in striate cortex of kittens deprived of vision in one eye. *Journal of neurophysiology*, 26:1003–17, nov 1963a. ISSN 0022-3077. URL `http://www.ncbi.nlm.nih.gov/pubmed/14084161`.

Torsten N. Wiesel. Postnatal development of the visual cortex and the influence of environment. *Nature*, 299(5884):583–91, oct 1982. ISSN 0028-0836. doi: 10.1038/299583a0. URL `http://www.ncbi.nlm.nih.gov/pubmed/6811951`.

Torsten N. Wiesel and David H. Hubel. Effects of visual deprivation on morphology and physiology of cells in the cat's lateral geniculate body. *Journal of Neurophysiology*, 26(6):978–993, 1963b. ISSN 0022-3077. URL `http://jn.physiology.org/content/26/6/978`.

A DETAILS OF THE EXPERIMENTS

A.1 ARCHITECTURES AND TRAINING

In all of the experiments, unless otherwise stated, we use the following All-CNN architecture, adapted from Springenberg et al. (2014):

```
conv 96 - conv 96 - conv 192 s2 - conv 192 - conv 192 - conv 192
  s2 - conv 192 - conv1 192 - conv1 10 - avg. pooling - softmax
```

where each `conv` block consists of a 3×3 convolution, batch normalization and ReLU activations. `conv1` denotes a 1×1 convolution. The network is trained with SGD, with a batch size of 128, learning rate starting from 0.05 and decaying smoothly by a factor of .97 at each epoch. We also use weight decay with coefficient 0.001. In the experiments with a fixed learning rate, we fix the learning rate to 0.001, which we find to allow convergence without excessive overfitting. For the ResNet experiments, we use the ResNet-18 architecture from He et al. (2016) with initial learning rate 0.1, learning rate decay .97 per epoch, and weight decay 0.0005.

When experimenting with varying network depths, we use the following architecture:

$$\texttt{conv } 96 \texttt{ - [conv } 96 \cdot 2^{i-1} \texttt{ - conv } 96 \cdot 2^{i} \texttt{ s2]}_{i=1}^{n} \texttt{ - conv } 96 \cdot 2^{n} \texttt{ - conv1 } 96 \cdot 2^{n} \texttt{ - conv1 } 10$$

In order to avoid interferences between the annealing scheme and the architecture, in these experiments we fix the learning rate to 0.001.

The Fully Connected network used for the MNIST experiments has hidden layers of size $[2500, 2000, 1500, 1000, 500]$. All hidden layers use batch normalization followed by ReLU activations. We fix the learning rate to 0.005. Weight decay is not used. We use data augmentation with random translations up to 4 pixels and random horizontal flipping. For MNIST, we pad the images with zeros to bring them to size 32×32.

A.2 APPROXIMATIONS OF THE FISHER INFORMATION MATRIX

To compute the trace of the Fisher Information Matrix, we use the following expression derived directly from the definition:

$$\begin{aligned}\mathrm{tr}(F) &= \mathbb{E}_{x\sim\hat{Q}(x)}\mathbb{E}_{y\sim p_w(y|x)}[\mathrm{tr}(\nabla_w \log p_w(y|x)\nabla_w \log p_w(y|x)^T)] \\ &= \mathbb{E}_{x\sim\hat{Q}(x)}\mathbb{E}_{y\sim p_w(y|x)}[\|\nabla_w \log p_w(y|x)\|^2],\end{aligned}$$

where the input image x is sampled from the dataset, while the label y is sampled from the output posterior. Expectations are approximated by Monte-Carlo sampling. Notice, however, that this expression depends only on the local gradients of the loss with respect to the weights at a point $w = w_0$, so it can be noisy when the loss landscape is highly irregular. This is not a problem for ResNets Li et al. (2017), but for other architectures we use instead a different technique, proposed in Achille & Soatto (2018). More in detail, let $L(w)$ be the standard cross-entropy loss. Given the current weights w_0 of the network, we find the diagonal matrix Σ that minimizes:

$$L' = \mathbb{E}_{w\sim N(w_0,\Sigma)}[L(w)] - \beta \log|\Sigma|,$$

where β is a parameter that controls the smoothness of the approximation. Notice that L' can be minimized efficiently using the method in Kingma et al. (2015). To see how this relates to the Fisher Information Matrix, assume that $L(w)$ can be approximated locally in w_0 as $L(w) = L_0 + a \cdot w + w \cdot Hw$. We can then rewrite L' as

$$L' = L_0 + \mathrm{tr}(\Sigma H) - \beta \log|\Sigma|.$$

Taking the derivative with respect to Σ, and setting it to zero, we obtain $\Sigma_{ii} = \beta / H_{ii}$. We can then use Σ to estimate the trace of the Hessian, and hence of the Fisher information.

A.3 CURVE FITTING

Fitting of sensitivity curves and synaptic density profiles from the literature was performed using:

$$f(t) = \mathrm{e}^{-(t-d)/\tau_1} - k\mathrm{e}^{-(t-d)/\tau_2}$$

as the fitting equation, where t is the age at the time of sampling and τ_1, τ_2, k and d are unconstrained parameters (Banks et al., 1975).

The exponential fit of the sensitivity to the Fisher Information trace uses the expression

$$F(t) = a \exp(cS_k(t)) + b,$$

where a, b and c are unconstrained parameters, $F(t)$ is the Fisher Information trace at epoch t of the training of a network without deficits and S_k is the sensitivity computed using a window of size k. That is, $S_k(t)$ is the increase in the final test error over a baseline when the network is trained in the presence of a deficit between epochs t and $t + k$.

B ADDITIONAL PLOTS

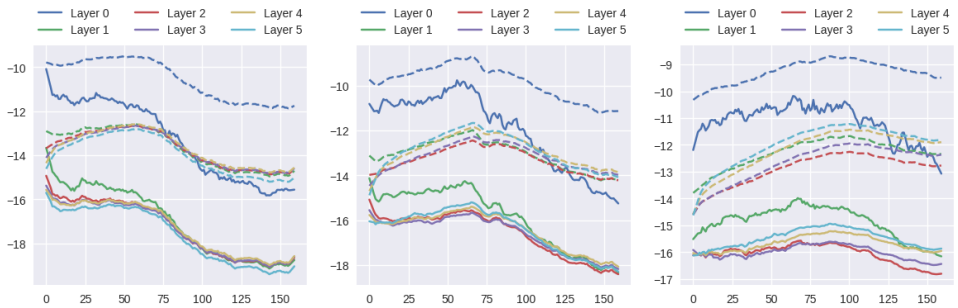

Figure 6: Log of the norm of the gradient means (solid line) and standard deviation (dashed line) during training when: **(Left)** No deficit is present, **(Center)** A blur deficit is present until epoch 70, and **(Right)** a deficit is present until the last epoch. Notice that the presence of a deficit does not decrease the magnitude of the gradients propagated to the first layers during the last epochs, rather it seems to increase it, suggesting that vanishing gradients are not the cause of the critical period for the blurring deficit.

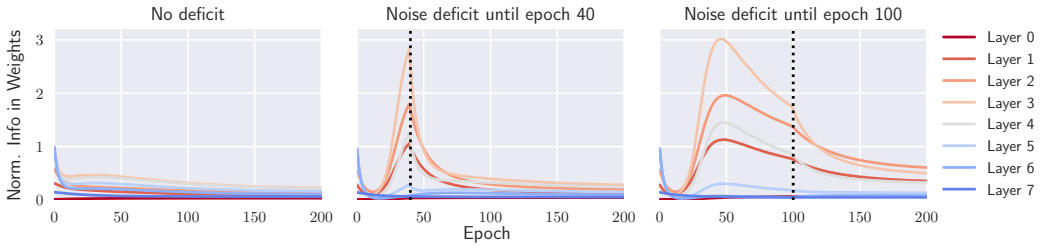

Figure 7: Same plot as in Figure 5, but for a noise deficit. Unlike with blur, much more resources are allocated to the lower-layers rather than higher-layers. This may explain why it is easier for the network to reconfigure to solve the task after the deficit is removed.

C EXPERIMENTAL DESIGN AND COMPARISON WITH ANIMAL MODELS

Critical periods are task- and deficit-specific. The specific task we address is visual acuity, but the performance is necessarily measured through different mechanisms in animals and Artificial Neural Networks. In animals, visual acuity is traditionally measured by testing the ability to discriminate

between black-and-white contrast gratings (with varying spatial frequency) and a uniform gray field. The outcome of such tests generally correlates well with the ability of the animal to use the eye to solve other visual tasks relying on acuity. Convolutional Neural Networks, on the other hand, have a very different sensory processing mechanism (based on heavily quantized data), which may trivialize such a test. Rather, we directly measure the performance of the network on an high-level task, specifically image classification, for which CNNs are optimized.

We chose to simulate cataracts in our DNN experiments, a deficit which allows us to explore its complex interactions with the structure of the data and the architecture of the network. Unfortunately, while the overall trends of cataract-induced critical periods have been studied and understood in animal models, there is not enough data to confidently regress sensibility curves comparable to those obtained in DNNs. For this reason, in Figure 1 we compare the performance loss in a DNN trained in the presence of a cataract-like deficit with the results obtained from monocularly deprived kittens, which exhibit similar trends and are one of the most common experimental paradigms in the visual neurosciences.

Simulating complete visual deprivation in a neural network is not as simple as feeding a constant stimulus: a network presented with a constant blank input will rapidly become trivial and thus unable to train on new data. This is to be expected, since a blank input is a perfectly predictable stimulus and thus the network can quickly learn the (trivial) solution to the task. We instead wanted to model an uninformative stimulus, akin to noise. Moreover, even when the eyes are sutured or maintained in the darkness, there will be background excitation of photoreceptors that is best modeled as noise. To account for this, we simulate sensory deprivation by replacing the input images with a dataset composed of (uninformative) random Gaussian noise. This way the network is trained on solving the highly non-trivial task of memorizing the association between the finitely-many noise patterns and their corresponding labels.