摘要

生物视觉系统的鲁棒性是指其在复杂环境中识别物体并做出准确反应的能力。由于对生物生存具有重要意义，鲁棒性成为视觉系统最重要的功能之一。视网膜间隙连接位于视觉系统前端，通过连接相邻神经元形成双向信息交流的网络，提升了整个视觉系统的信息处理能力，因此在提高视觉系统鲁棒性方面发挥重要作用。相比之下，尽管经典的卷积神经网络模型经常被用作高级视觉中枢的计算模型，但它们通常缺少视网膜模块，其预处理功能相对简单，导致鲁棒性较弱。因此，如何对视网膜间隙连接网络提升视觉系统鲁棒性的机理进行研究，并增强经典卷积神经网络的鲁棒性，是一个亟待探索的科学问题。由于计算神经生物学的建模方法既能保持间隙连接网络的生物合理性，又能转化为卷积神经网络的前置模块，因而是上述问题的一个潜在解决方案。本研究首先建立了视网膜间隙连接网络模型并探讨其机理，其次实现了具有视网膜间隙连接网络特性的卷积神经网络，最后通过图像降噪和对抗攻击两个视觉任务，研究了视网膜间隙连接对视觉系统鲁棒性的影响。本研究的主要贡献包括：

1. 为了研究视网膜间隙连接网络的鲁棒性，提出了包含多种动力学机制的精细视网膜光感受器网络模型及其启发的间隙连接滤波器。对该网络模型的理论分析表明，间隙连接使得该网络表现出丰富的时空滤波效应，能够进行复杂的信息平滑和整合。受此启发，本研究保留该网络的间隙连接，并简化了其他动力学机制，提出了间隙连接滤波器。实验表明，该滤波器对一定范围内参数扰动具有高鲁棒性，可以将不同噪声分布转换成相似分布，这些分布的余弦相似度稳定地保持在 0.98 以上，这种稳定地转换使得信号中的噪声在后续层级中易于处理，从而提高整个系统的鲁棒性。通过与 5 种经典滤波器对比，在 4 种类型的噪声下验证了间隙连接滤波器是一种有效的通用滤波器，峰值信噪比平均提升 63%。

2. 为了研究视网膜间隙连接网络对视觉系统盲噪声鲁棒性的作用，提出了一种包含视网膜（间隙连接滤波器）和高级视觉中枢（卷积神经网络）的新型视觉层级架构。该架构保留了生物视觉层级的特点，即不存在从高级视觉中枢到视网膜的反馈，间隙连接滤波器充当该架构的预处理单元。实验表明，在图像盲降噪任务中，间隙连接滤波器能够将降噪卷积神经网络的降噪性能平均提升约 18%；在大噪声下（14 dB），平均提升约 34%; 进一步的研究揭示了间隙连接滤波器使得模型在面对一定范围内的参数扰动时具有高鲁棒性，其平均性能波动约 4%。在带有盲噪声的图像分类任务中，间隙连接滤波器显著提高了经典卷积神经网络（ResNet50、VGG19 和 Inception V3）防御盲噪声的性能，平均提升 20%；在大噪声下（均匀噪声宽度：0.6），平均提升 30%。

3. 为了研究视网膜间隙连接网络对视觉系统对抗噪声鲁棒性的作用，提出了一种与间隙连接滤波器等价的循环神经网络, 即“浅层视网膜模块”，并利用该模块研究模型的流形及决策边界。本研究通过多种流形分析方法揭示了间隙连接滤波器可以使卷积神经网络形成独特的流形及决策边界，该形成过程受到间隙连接电导的影响，这种独特的流形及决策边界有助于提升视觉系统的对抗噪声鲁棒性。实验表明，与其他预处理及对抗训练方法相比，带有间隙连接滤波器的卷积神经网络在白盒攻击下，平均性能比其他方法提升至少 29%；在黑盒攻击下，平均性能比其他方法提升至少 25%。

综上所述，本研究通过对视网膜间隙连接网络的深入分析，分别从视网膜间隙连接网络的鲁棒性、视网膜间隙连接网络对视觉系统盲噪声鲁棒性的作用、视网膜间隙连接网络对视觉系统对抗噪声鲁棒性的作用这三个方面，揭示了视网膜间隙连接是提升视觉系统鲁棒性的一个关键机制。本研究深入挖掘了视网膜间隙连接对视觉系统鲁棒性的贡献，可以为计算机视觉模型的性能提升和仿生神经网络设计提供新的思路和方向。

关键词：视觉系统, 视网膜间隙连接, 视觉鲁棒性, 图像降噪, 对抗攻击

The robust vision driven by the mechanism of retinal gap junctions: a computational study

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ABSTRACT

The robustness of the biological visual system refers to its ability to recognize objects and make accurate responses in complex environments. Due to its importance for survival, robustness is one of the most important functions of the visual system. The gap junctions in the retina are located at the front end of the visual system and form a network of bidirectional information exchange between adjacent neurons, enhancing the information processing capacity of the entire visual system. Thus, they play an important role in improving the robustness of the visual system. In contrast, although classical convolutional neural networks are often used as computational models for higher visual centers, they usually lack a retinal module, and their preprocessing functions are relatively simple, leading to weaker robustness. Therefore, exploring the mechanisms by which the gap junction network in the retina enhances the robustness of the visual system and enhancing the robustness of classical convolutional neural networks are significant scientific questions. Since the modeling method of computational neuroscience can both maintain the biological plausibility of the gap junction network and transform it into a preprocessing module of the convolutional neural network, it is a potential solution to the above problems. In this thesis, we first established a model of the gap junction network in the retina and explored its mechanism. Secondly, we implemented a convolutional neural network with the characteristics of the gap junction network, and finally studied the impact of the gap junction on the robustness of the visual system through two visual tasks: image denoising and adversarial attack.

This thesis presents the following main contributions：

Firstly, to study the robustness of the gap junction network in the retina, a detailed retina photoreceptor network model containing multiple dynamic mechanisms and its inspired gap junction filter are proposed. The theoretical analysis of this network model shows that the gap junctions enable the network to exhibit rich spatiotemporal filtering effects and can perform complex information smoothing and integration. Inspired by this, we retain the gap junctions in the network and simplify other dynamic mechanisms, proposing a gap junction filter. Experiments show that this filter has high robustness to parameter perturbations within a certain range and can transform different noise distributions into similar distributions, and the cosine similarity of these distributions remains stable above 0.98. This stable transformation makes the noise in the signal easy to handle in subsequent layers, thereby improving the overall robustness of the system. The gap junction filter is compared with five classical filters and validated under four types of noise, with an average peak signal-to-noise ratio improvement of 63%.

Secondly, to investigate the role of the retinal gap junction network in the robustness of the visual system to visual noise, a new visual hierarchy architecture is proposed, which includes the retina (gap junction filter) and the higher visual center (convolutional neural network). This architecture retains the characteristics of the biological visual hierarchy, namely, there is no feedback from the higher visual center to the retina, and the gap junction filter serves as the pre-processing unit of this architecture. Experiments show that in the image blind denoising task, the gap junction filter can increase the denoising performance of the convolutional neural network by about 18% on average; under high noise conditions (14 dB), the increase is about 34%. Further research reveals that the gap junction filter makes the model highly robust to parameter perturbations within a certain range, with an average performance fluctuation of about 4%. In image classification tasks with blind noise, the gap junction filter significantly improves the performance of classical convolutional neural networks (ResNet50, VGG19, and Inception V3) in defending against blind noise, with an average increase of 20%; under high noise conditions (uniform noise width: 0.6), the increase is about 30%.

Thirdly, to investigate the role of the retinal gap junction network in the robustness of the visual system to adversarial noise, a new type of recurrent neural network equivalent to the gap junction filter, namely the ”shallow retinal module”, is proposed and applied to study the manifold and decision boundary of the hierarchical model. Based on the new visual hierarchy architecture and shallow retinal module, we reveal through various manifold analysis methods that the gap junction filter can enable the convolutional neural network to form unique manifolds and decision boundaries, which is influenced by the gap junction conductance, and these unique manifolds and decision boundaries help enhance the robustness of the visual system to adversarial noise. Experiments show that compared with other pre-processing and adversarial training methods, the convolutional neural network with the gap junction filter can improve the average performance by at least 29% under white-box attacks, and by at least 25% under black-box attacks.

In summary, this thesis provides an in-depth analysis of the retinal gap junction network and reveals its key role in enhancing the robustness of the visual system from three aspects: the robustness of the retinal gap junction network, the effect of the retinal gap junction network on blind noise robustness, and the effect of the retinal gap junction network on adversarial noise robustness. This thesis thoroughly explores the contribution of the retinal gap junction network to the robustness of the visual system and provides insights and new directions for improving the performance of computer vision models and designing biomimetic neural networks.

KEY WORDS: visual system, retinal gap junctions, visual robustness, image denoising, adversarial attack