An Analysis of Nature's Mechanism for Convolutions and its Impact on Machine Learning

Anthony Galczak

University of New Mexico

agalczak@unm.edu

Abstract

Convolutional neural networks are widely used in the field of Machine Learning and Data Science. CNN's derive most of their inspiration directly from biology. In the past, scientific study of the biological dendrite have shown them to be strictly input gathering devices. However, recent research shows that dendrites have more functionality than just processing presynaptic inputs. Within an image processing system, dendrites perform a critical operation for figure detection and spatial awareness. In this paper, we will show that dendrites and associated V1 cells perform a spatial blurring operation. This operation is directly analogous to the convolution that is performed in an artificial CNN. This paper seeks to better understand the biology of the visual system of the blowfly. Scientific exploration into the visual system will allow us to better understand and implement the convolution operation in artificial CNN's. The dendritic tree is the secret to this operation and will be the focus of the analysis in this paper.

1.0 Introduction

This paper seeks to better understand the origins of the convolution and how nature implements it. Image processing and analysis is critical for biological creatures and a multitude of applications in technology. Processing every detail in every frame in an image processing system is computationally infeasible. Biology has come up with a clever mechanism for our visual system to detect changes and specific features in a scene, i.e. edges and object classification. This mechanism is a convolution, or more specifically from biology, a "spatial blurring" of the frame. The convolution operation is performed in various animals' visual systems**[1]**, but the analysis for this paper will be from blowflies. The first two primary sources analyze the visual system in a computational sense. The third source observes the blowflies' brain directly.

We are upon a "Machine Learning revolution" and a lot of that success is derived from biological inspirations. One of the greatest success stories for applying biology to computational applications is the convolutional neural network**[2]**. Convolutions in the CNN are critically

important not only for natural objection detection, but also for artificial object/figure detection. CNNs are useful for simple problems like recognizing handwritten digits on mail.**[3]** CNNs also succeed at complex problems like self-driving cars**[4]** recognizing humans, road signs, and more. These applications are what drive the field of Computer Science as well as driving technology to its' limits. Gaining a better understanding of how biology implements the convolution will remind us of what we left out when we implemented convolutions artificially.

This paper will first look at approaches from three primary sources that analyze the visual system of the blowfly. An emphasis will be placed on the FD-cells' behavior. Then we will discuss the results from each paper and how they came to these results. Afterwards, there will be a discussion comparing and contrasting the methods of each paper as well as offering some additional analysis on the topic of convolutions. Lastly, the paper will close with some final comments and possible future work.

2.0 Approaches in the Literature

The first source was **Neural image processing by dendritic networks** by Hermann Cuntz, et al.**[5]** This paper uses an artificial model called NEURON to analyze different neuron types and member types of the blowfly's visual system. The neuron types are broken into two main groups, CH cells and HS cells. Centrifugal Horizontal (CH) has members vCH, dCH and the Horizontal System (HS) has members: HSS, HSE. Simulated electrodes were placed in the axons of the previously mentioned cells. Then connections, called linear conductances, were made between a dendrite found in the HS model and a dendrite in the CH model. These connections would be made based upon the shortest distance from one dendrite to another.

There was a primary simulation done in this paper with a supplementary simplified model. Both intended on analyzing the image processing capability of the blowfly. The initial simulation superimposed dendritic trees with a 10-μm spacing between them. This procedure resulted in 760 synapses giving the shortest connections between the HS and CH systems. The simplified model only used five electrical synapses with distance of 100-μm between them per the reference model made by Borst**[5]**. Additionally, they used parameters of 2.5nS conductance and 100-ohm axial resistance. MATLAB, Origin, and NMODL were used as computational

libraries to interface with the NEURON simulation system to produce their data.**[5]** Cuntz, et al. took existing models made by Borst for HSS, HSE, and vCH cells and adapted them directly to the NEURON framework. These models sought to simulate dendro-dendritic connectivity between the CH and HS cells to show spatial blurring of an input image. This paper gives an empirical result that validates convolutions occuring at the dendrite level.

The second source was **Distributed Dendritic Processing Facilitates Object Detection: A Computational Analysis on the Visual System of the Fly** by Patrick Hennig, et al.**[1]** This paper seeks to find a model to best simulate the FD-cells found in the blowfly. As opposed to the other two papers, this paper focuses on the derivative "FD1-cell". FD1-cells are the figure detection cells that are most understood and studied at the moment. Thus, there is more experimental data to base this study on. These FD1-cells are figure detection cells for objects, moving or still. The constraints of the paper's methods were given by experimental data. The data was gathered based upon the wiring of the FD-cell's input circuitry, and the responses of the FD-cell to different conditions of object movement including velocity and different backgrounds. This experimental data was given by several sources cited in the paper.**[1]**

They ran three different simulations with three different circuit architectures representing the FD-cell. It does not appear that they used a standard neuroscience library for these simulations. There is some a priori information about how FD-cells operate and their goal was to simulate this behavior the best they could. The simulation was very dependent upon the velocity of the foreground object as well as the velocity of the background. This paper is significant because the analysis was heavily dependent upon the "spatial blurring" that occurs in the dendritic trees.**[1]**

The third source was **Dendro-Dendritic Interactions between Motion-Sensitive Large-Field Neurons in the Fly** by Haag and Borst. The methods in this paper are somewhat similar in ideology to the second paper by Hennig with one major difference. The experiments here were performed on female blowflies. The motivation here is to analyze the connection between CH and HS cells and how it affects object detection. The behavior of the FD cells is in direct contrast to the sort of visual input from self motion.**[6]**

In the first step of the experiment, they anesthetized female blowflies and mounted them with wax on a small platform. They then removed a few organs that cover the lobula plate as that is the area they wanted to analyze. From there, they produced visual stimuli with an arc lamp projecting onto a 10x8cm screen. They were able to view the brain directly from behind with a microscope. Additionally, they used electrodes filled with KCl to stimulate axon cells. This was necessary to analyze the coupling between the CH and HS cells, electrically and chemically. The computational hardware shows the age of this paper as they were using a Pentium III to process the output signal of the electrodes.**[6]** This paper is significant to our analysis as it looks at the visual system and FD-cells from a biological perspective.

3.0 Results in the Literature

The first paper**[5]** by Cuntz found that three electrically connected neurons mapped appropriately to the experimental results that the paper was based upon. To be specific, image rectification occurred between the HS and CH model. This leads to an analysis of the "spatial low-pass characteristics", i.e. blurring, found in both the CH and HS cells. It was found that the blurring occurs from the electrical synergy of multiple cells rather than the geometry of the dendritic tree. The blurring is dependent upon how long the the signal takes to travel and it's attenuation. This is because the signals interspersing and convolving with each other cause blurring at the postsynaptic neuron.

As for the second paper**[1]**, Hennig, et al. generated new neural models for analyzing potential architectures of feature detection cells in blowflies. These models are based on "available physiological and anatomical data". *Direct Pooled Inhibition, Direct Distributed Inhibition,* and *Indirection Distributed Inhibition* are the three models that were simulated in this paper. In DPI, the vCH are inhibiting the FD-cells after spatial pooling occurs at the dendrite. In DDI and IDI, the vCH instead inhibits the FD-cells in a distributed way. We will discuss the results of the experiments as well as the implications of the successful models.

Their findings were that DPI did not mimic the empirical data known about FD-cells. DDI and IDI both seemed to give plausible architectures for the FD-cells as it mimicked the velocity dependence and size dependence of the FD-cell's responses. For DDI, it was found that

when the background velocity and the focused object velocity was high, the model response did not match the experimental results. While the IDI model does not have this flaw and appears to match the experimental results in more cases. The spatial blurring that occurs in the dendritic trees of inhibitory neurons contributed to the good performance of both distributed models, IDI and DDI.

In the third paper**[6]** by Haag and Borst, the primary outcome was measuring intracellular recordings between HS and CH cells. The data shows that HS and CH cells are coupled to each other in that the polarity of one cell influences the other. This coupling does not allow fast signals to travel between them, which is likely a result of the low-pass filtering of the dendrites. This low-pass filtering causes the fast signals to attenuate before reaching the complementing cell. This finding emphasizes previous research that frequency-dependent amplification is found in HS cells, but not in CH cells.

Both CH and HS cells were injected with solution to analyze the behavior of these cells together. In both experiments, it was found that the cell that was not injected would have an increase in fluorescence. This leads to the result that HS and CH cells have a dendro-dendritic coupling. This is important because a CH cell may not receive direct synaptic input, but can accumulate calcium accumulation in its dendrites. To emphasize this finding there was an additional experiment done to discriminate whether this coupling between the CH and HS cells was electrical or chemical. Chemical blocking agents, i.e. curare, mecamylamine, and alpha-bungarotoxin, were used to block the chemical effect of current injection into the HS cells. The result was that the injection of solution into HS cells was still affecting the CH cells. This means that the dendritic coupling is made feasible by an electrical coupling and not a chemical one.**[6]**

4.0 Discussion

Before discussing the details of each paper's methodologies and their results, I want to take an aside to talk about the experiment done by Haag and Borst**[6]**. I found the method for analysis on the brain of the fly to be gruesome. It involved removing the trachea, "gut", and various other parts of the fly in order to see the brain via a microscope. This likely would've

been a quarter shell of the entire body of the fly. I understand that this is necessary for the experiment as well as the fact that this was published in 2002 and they were using Pentium III's for analysis. These sort of experiments are necessary to build our simulations and models that we use today. As the other two papers used simulations; I found the fly experiment fairly interesting as well as a bit spooky.

The paper by Cuntz, et al.**[5]** was a bit hard to follow as it was heavily based on previous work by Borst and Haag on standard models for HSS, HSE and vCH cells. The direct background work there was referenced amounted to 3 papers spanning about 100 pages. However, the conclusions drawn in this paper are mostly straight-forward. The dendro-dendritic electric coupling between HS and CH cells causes a spatial blurring or a convolution between the cells. The "dendro-dendritic electric coupling" is just fancy language for the electrical intersection of the dendrites of two cells. To explain in further detail; HSE and HSS cells typically fire into the presynaptic dendrite of the vCH cell which then interacts with the FD cells. However, due to the fact that the HSE/HSS and vCH dendrites overlap, there is a blurring between the firing of HSE/HSS cells and the direct input to the vCH cells. Due to the mechanism of spatial blurring performed in the CH dendrites, dendrites become an output in addition to an input in the visual system. See Fig. 1**[7]** below for a more detailed layout of this architecture of the visual system and its' cells.

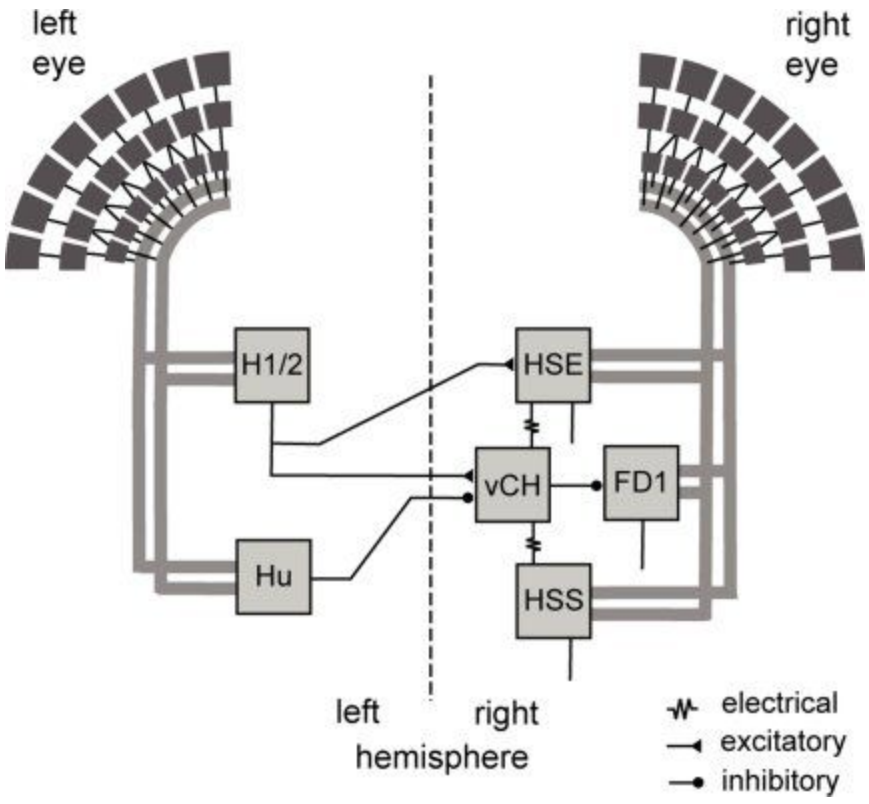

Figure 1: Visual System architecture**[7]**

The papers by Hennig**[1]** and Haag**[5]** are more similar to each other than the paper by Cuntz**[5]**. Both are looking to form a model of how flies perform object and figure detection. Their methodologies are vastly different as Hennig uses a NEURON computer simulation whereas Haag uses real blowflies and analyzes actual brain function. This really becomes relevant as in the real blowfly experiment they were unable to measure the fine dendritic branchlets in CH cells**[6]**. Not being able to measure electrical signals in the CH cells was a limitation of the paper and is of course a downfall of doing a real world experiment. The computational analysis paper had no such limitations and as such, was more detailed in its analysis of the flies' visual system**[1]**. Additionally, the computational paper is limited in the fact that it is trying to build a model based upon already gathered biological data; whereas Haag was able to directly view real-world results. If the experimental data used by Hennig was flawed in anyway then this would lead to fallacious results in their simulation.

It was found in both the Haag and Hennig papers that a critical part of biological image processing and figure detection is dendrites acting as a low-pass filter. This low-pass filter is analogous to a convolution operation that spatially blurs an incoming pre-synaptic signal. Hennig was able to attribute the best FD1-cell model to spatial blurring. Whereas the Haag paper was able to observe this behavior occurring between CH and HS cells through dye injection and microscopic observation.

Nearly all of the findings in these papers have direct analogies to artificial convolutional neural networks. All of the analysis done here has been in the V1 system (also known as the primary visual cortex) which is also very briefly described by Goodfellow**[2]**. He talks about "simple cells" and "complex cells" found in the first layer of the visual system. Thus, our CH, vCH, HSS, HSE cells are all encompassed by this simplification of simple and complex behavior.**[8]** The simple cells are simply a linear function of a receptive field whereas the complex cells are more like convolutional filters. Simple cells have a direct analogy to detector units in CNNs. It can be argued that the dendro-dendritic coupling between CH and HS cells serves in some part as a complex cell that performs the same sort of things that a convolution does (edge detection, shape detection). Additionally, complex cells serve an even further purpose as they are invariant to shifts in position and rotation. This sounds very analogous to pooling strategies used by modern CNN's like max-pooling or avg-pooling. Overall, dendrites are much more important to the computation done by visual systems than we may first think.

5.0 Summary and Conclusion

In this paper we performed a brief survey of three papers analyzing the visual system of the blowfly. The first paper by Cuntz was directly inspired by the behavior of dendrites and their role in image processing.**[5]** The second paper by Hennig analyzed the visual system of a blowfly through a computational neuroscience toolkit NEURON.**[1]** One of their primary results is that spatial blurring of the image signal in the dendrites is critical to image processing and figure detection. The third paper by Haag and Borst observed blowflies directly in order to analyze the relationship between the CH and HS cells in the V1 visual system.**[6]** An important

conclusion was that the HS and CH cells have dendro-dentritic electrical coupling which appears to be related to the spatial blurring done at the CH cell dendrite.

The paper by Cuntz was fairly difficult to read as it had a strong background in previous work done by these researchers. However, this paper was too critical to my topic to not analyze and read. I appreciated the research done by Hennig a lot as it was very detailed and clear what the intentions were at all times. However, I find it a bit worrying that the metric for success was comparing to older biological analysis of FD-cells. Small errors in this analysis could easily lead to wildly incorrect computational models being built. There wasn't a lot of detail given on whether or not they used multiple experimental sources for their data. Lastly, the paper by Haag and Borst was fascinating to read from a scientific standpoint. Their work was slightly limited by having to work with real animals, but this is the sort of research that we need to do to build better neuroscience models for the future.

After doing this research, it is apparent that the visual system of an insect as simple as the blowfly is quite complex. However, we only discussed the first computational layer on the visual system (V1) in this paper. Future work could be done in analyzing the retinal receptive field, LGN, V2, V4, and IT layers**[2]** for a greater understanding of the biological image processing system. Understanding all parts of the visual system is critical to forming better models for modern machine learning techniques and research. Even though researchers in the field have a lot of brilliant ideas for improving our algorithms; our best inspiration comes directly from biology. Direct study on how nature has implemented computational systems, such as image processing, can be a treasure trove of information for the field of Machine Learning.

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7.0 References

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[2] Goodfellow, Ian, et al. *Deep Learning*. The MIT Press, 2017.

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[7] Hennig, Patrick, et al. *Binocular Integration of Visual Information: a Model Study on Naturalistic Optic Flow Processing*. Frontiers in Neural Circuits, 4 Apr. 2011.

[8] Wikipedia contributors. "Complex cell." *Wikipedia, The Free Encyclopedia*. Wikipedia, The Free Encyclopedia, 29 Nov. 2018. Web. 5 Dec. 2018.

Appendix A: Acronyms

CH - Centrifugal Horizontal

vCH - Ventral CH cells

HS - Horizontal System

HSE - Northern, equatorial areas of the visual field (in context of HS)

HSS - Southern area of visual field (in context of HS)

FD-Cell - Figure Detection cell (May also refer to FD1-cell's in Hennig paper)

DPI - Direct Pooled Inhibition Model**[1]**

DDI - Direct Distributed Inhibition Model**[1]**

IDI - Indirect Distributed Inhibition Model**[1]**

Appendix B: Citation Direct Links

[1]https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0003092&type=printable

[3]https://pdfs.semanticscholar.org/8b11/230bb90f9f98d7a791f13df438efc8dd29cd.pdf

[4]https://arxiv.org/pdf/1604.07316.pdf

[5]http://www.pnas.org/content/pnas/100/19/11082.full.pdf

[6]https://pdfs.semanticscholar.org/ac5f/bd4add1d2a4760241dd9f6bc8b996f2990f8.pdf?_ga=2.102728067.322645880.1543183692-148083985.1543183692

[7]https://www.frontiersin.org/articles/10.3389/fncir.2011.00004/full

[8]https://en.wikipedia.org/wiki/Complex_cell