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Retina modeling by artificial neural networks

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Highlights

- Theoretical framework for retina structure and function.
- Neural network model simulates retinal cell behavior.
- Effectiveness influenced by network architecture and learning method.
- Potential applications in artificial retina development.

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Abstract

The objective of this article is to provide a theoretical framework for the structure and function of the retina. The first focus of this article is the examination of the physiological aspects of the retina. The given study proposes a model that utilizes artificial neural networks to create the model's structure. This approach is motivated by the resemblance between the behavior of the model and that of retinal cells. The neural network receives as input the intensity of light that is incident on the retina and produces as output the activity of the retinal ganglion cells. A comparison has been conducted between the data derived by the model and the biological data. This comparative analysis demonstrates that neural networks can adequately simulate the behavior of ganglion cells. However, the effectiveness of the network is contingent upon its architectural configuration, the number of hidden layers used, and the specific learning method utilized. The experimental findings demonstrate that including the output from earlier iterations as input to the neural network results in the system exhibiting memory. This approach enhances the model's efficiency and mitigates the occurrence of periodic behavior. The model, as mentioned above, has potential applications in the development of artificial retinas, serving as a hardware implementation to restore some visual capabilities in individuals with visual impairments.

1. Introduction

In recent years, there has been an increasing focus on the architecture of the visual system. The change in attention is a consequence of several variables. This phenomenon may be attributed to an increasing awareness among academics of vision's substantial role in individuals' lives. Furthermore, during the last several years, there has been a concomitant increase in the emphasis placed on the design of the visual system. The capacity to engage in eye communication plays a crucial role in interpersonal interactions and the many contexts in which they occur. This phenomenon may be attributed to the eyes' capacity to see and understand emotional expressions shown on the face, in conjunction with the accompanying nonverbal cues sent via body language. This phenomenon may be primarily attributed to the pivotal role of the visual sense in facilitating these interactions. Due to the successful implementation of this technological advancement, individuals can now engage in spoken communication with each other. This phenomenon arises due to the pivotal role of the visual sense in facilitating the execution of these interactions, hence elucidating the underlying cause. It is unsurprising that the sense of vision has received much scientific focus, particularly in biology and computer

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science. The focus on the sense of vision is attributed to its role in enabling people to perceive the surrounding environment. This outcome has been derived as a consequence of considering the factors above. Due to the significance attributed to the presence of a well-defined vision in the innovation of novel technologies, much attention has been directed to this particular matter. The rationale for this may be attributed to the considerable focus on this topic. This phenomenon may be attributed to the fact that vision is the primary sensory modality through which individuals see and comprehend their surrounding environment, thereby becoming the focal point of discussion. The rationale for this assertion is that vision is regarded as the primary sensory modality. Because of their advanced visual capabilities, humans possess the exclusive capacity to do tasks of this kind. This capacity is not seen in any other animal [1].

1- Consequently, the utilization of visual system modeling is expected to provide valuable insights and contribute to the advancement of future endeavors [2].

2- To enhance their understanding of the functioning of this system, medical practitioners should conduct a comprehensive investigation of the physiological framework underlying this system. This would facilitate their acquisition of knowledge about the operational mechanisms of this system, enabling them to enhance their comprehension of its functionality [3].

3- Examining natural systems through an engineering lens has resulted in the development of models that may be used in the design and construction of engineering equipment and the resolution of engineering challenges [4].

4- Visual system models, particularly the retina model, are used to develop artificial vision systems. For instance, the injured retina may be substituted by an artificial retina that utilizes the computational model of the retina to provide the necessary signal. In the present domain, it is pertinent to refer to the artificial network-building effort undertaken by Boston University, which has yielded notable outcomes so far [5].

This research aims to generate a replica of the retina by using artificial neural networks as the principal approach for replication. The central focus of this study is consistently maintained. This subject matter has served as the primary focus of interest throughout the investigation. The outcome of this research endeavor will include developing a model that can effectively replicate the intricate processes by which the retina performs its functions, surpassing the current limitations in accuracy. Throughout this discourse, alongside the neural network model, other alternative models will be examined, each of which will be presented in a manner that is distinguishable from the approach used for the others.

1-1 Biological foundations

Despite extensive research efforts dedicated to comprehending the cellular composition of the retina, which serves as the first stage in visual information processing, a complete grasp of its operational characteristics still needs to be discovered [6]. The retinal cellular structure has a hierarchical organization consisting of many layers, whereby each layer is composed of distinct cell types. The layers, as mentioned above, are located inside the retina. Fig. 1 depicts the accurate positioning of the retina inside the eye [7].

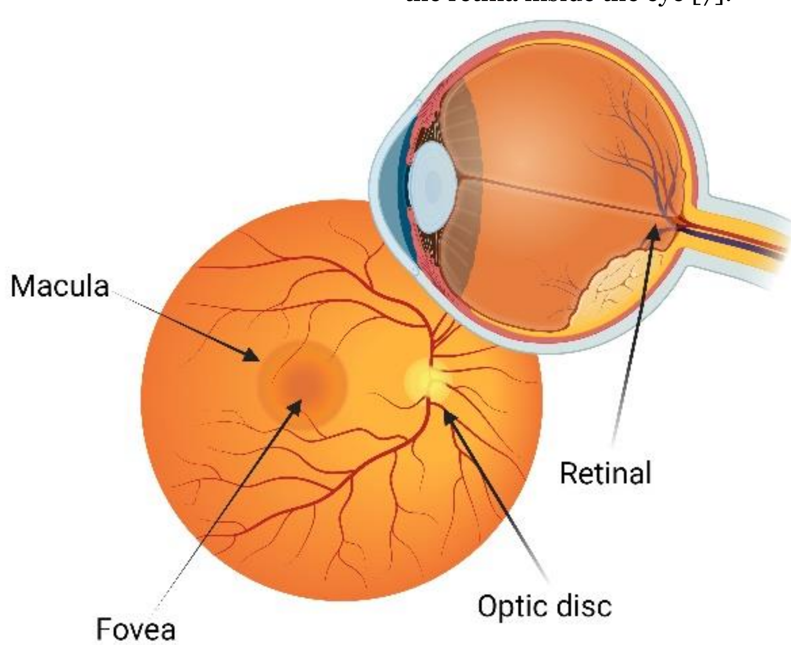


Fig. 1. Retina and its location in the eye

The process of information processing starts with the activation of light-receptive cells, whereby the conversion of light photons into electrical impulses takes place. Photoreceptor cells are interconnected with bipolar cells, which then establish connections with the subsequent layer of cells, namely ganglion cells. The ganglion cells, situated in the last layer, provide information to the brain through the modulation of impulse production frequency [8], [9]. Fig. 2, accessible at the provided location, is a very effective visual representation of the ganglion cells' reaction to the stimulation induced by alternating light. This reaction may be regarded as a physiological response elicited by the stimulus received by the ganglion cells. When stimulated by alternating light, ganglion cells elicit a response, hence inducing a corresponding reaction. This reaction may serve as an illustrative illustration of the behavioral patterns shown by ganglion cells upon stimulation. Merely clicking on this hyperlink to get the relevant response is sufficient. The phrase "intermittent input" refers to activating and deactivating the light driver at predefined intervals, also known as "intermittent input." The word "intermittent input" is used to describe the process of turning the power supply of the light driver on and off. The methodology used to execute this approach is often known as "intermittent input."

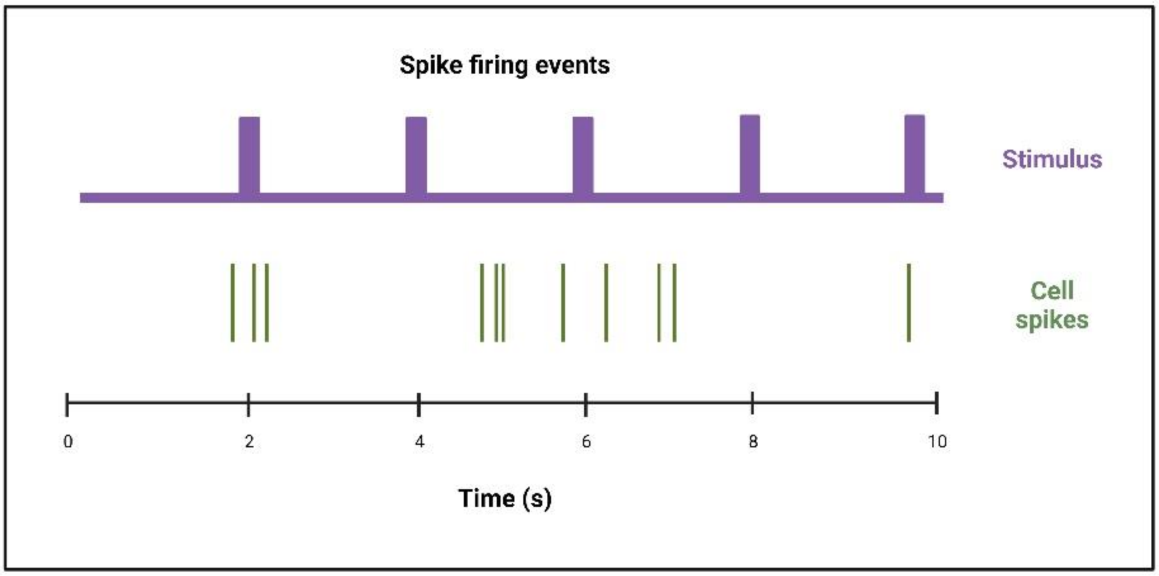


Fig. 2. An example of the response of ganglion cells to alternating light input

The ganglion cells create signals that are sent by the optic nerve to successive parts of the visual system in the brain, including the primary visual cortex [10].

The rest of this paper can be categorized as follows: In Section 2, the modeling is expressed. Retina modeling by an artificial neural network is presented in Section 3. The conclusion is also stated in Section 4.

2. Modeling

2.1. Different levels of modeling

Nevertheless, it is feasible to represent biological systems at many levels of abstraction. The level of abstraction used is contingent upon the required degree of granularity. The subsequent phase, contingent upon the feasibility of generating a model of a biological system including cellular and molecular dimensions, entails the development of a highly accurate model that meticulously depicts the constituents of the system. This phase presupposes the feasibility of constructing a model of a biological system at the cellular and molecular scales. At this juncture, we posit the assumption that constructing a model of a biological system at both the cellular and molecular levels is viable. In higher levels of academic inquiry, the modeling of neural networks generated by these cells emerges as a central focus of investigation and a significant subject of scrutiny. In more advanced stages, the human body is understood holistically, whereby it is not regarded as a mere aggregation of separate components but rather as a whole and linked system. The change in viewpoint signifies a notable advancement in our comprehension of the functioning of the human body [11], [12].

After providing a brief overview of realistic modeling and cellular neural network modeling, the subsequent focus of this talk is on artificial neural network modeling [13].

2.2. Realistic modeling

In a precise modeling scenario, the governing equations of the biological system are derived by including chemical, physical, and biological elements in the equations themselves. This procedure occurs. In order to effectively construct accurate models, it is important to possess a comprehensive understanding of the biological system [14], [15]. In the context of this particular modeling approach, the quantity of parameters involved is often substantial, necessitating the model to account for all governing rules that dictate the system's current state. The model developed by Hodgkin and Huxley, which presented the first mathematical depiction of the cellular action potential, is widely regarded as a seminal contribution to this field. This is due to the fact that the first mathematical depiction of the cellular action potential was proposed in this particular model [16].

2.3. Network modeling using cellular neural networks

The cellular neural network (CNN) was first proposed by Leon Chua in 1988 at the University of California, Berkeley, and has since gained significant recognition as a noteworthy advancement during the last twenty years. This particular domain has been regarded as an emerging avenue of investigation within the realm of neural networks. A convolutional neural network (CNN) is a computational structure that may be conceptualized as a three-dimensional array operating inside the domain of continuous signals [17].

Cells, referred to as processors with nonlinear dynamics, are strategically positioned at network locations within the array. These cells establish local connections with neighboring cells within a restricted neighborhood [18], [19]. The phenomenon of local communication is referred to as the homogeneity pattern or synaptic law, including several characteristics such as dynamism, staticity, linearity, non-linearity, instantaneousness, or latency [19].

Cells, which exhibit nonlinear dynamics, are used as processors in the context of this study. These processors are strategically positioned at the network nodes within the array and establish local connections with neighboring cells within a restricted neighborhood. The phenomenon of local communication is referred to as the homogeneity pattern or synaptic law, which encompasses several characteristics such as dynamism or stability, linearity or non-linearity, and immediacy or latency [20]. The primary distinguishing feature of the cellular neural network is its regular geometric and electrical structure, together with the localized connectivity between its processing components and its programmability. The model proposed by CNN has significant efficacy and efficiency in simulating the retina and other sensory systems, drawing inspiration from authentic biological structures [21]. The model's structure is derived from the authentic network structure of the parameters acquired via laboratory measurements. The outcomes derived from the model exhibit a high degree of resemblance to the data acquired from the retina. The suggested framework has the potential for use in hardware implementation. The hardware, as mentioned above, can be used in various artificial sensory organs, whereby its primary function is to transmit accurate biological signals to the brain [22], [23].

[24] presents an approach to bridge the gap between computational models of human vision and clinical practice in visual impairments (VI). In this study, the authors propose to connect advances in neuroscience and ML to study the impact of VI on key functional competencies and improve treatment strategies. They also review the relevant literature with the aim of promoting the full utilization of artificial neural network (ANN) models in meeting the needs of visually impaired people and operators working in the field of vision rehabilitation.

3. Retina modeling by artificial neural network

In this section, modeling by means of a neural network is used.

3.1. Define the problem

When conceptualizing the retina as an opaque system, the input to this system can be understood as the luminous intensity that is incident onto the retina. Conversely, the output of this system can be described as the level of activity shown by the ganglion cells. In the present scenario, the objective is to identify a model capable of establishing a correlation between the input of the black box and its corresponding output. Neural networks possess a remarkable capacity to address situations when the fundamental equations of a system are unknown and only the input and output of the system are available. Through training, the network may discern the underlying pattern that governs the connection between the input and the output.

The training process of neural networks involves the iterative adjustment of inter-neuronal weights to get the desired output for a given input [25].

3.2. Model components

The process of constructing a model and conducting simulations was carried out using the MATLAB program. The objective is to simulate the behavior of ganglion cells in response to a given stimulus. The desired input is the projection of a gray light onto the retina via the use of a cathode ray tube (CRT). The primary objective is to use a neural network to train on empirical data acquired from a multi-electrode recording of the ganglion cell layer, with the aim of discerning the underlying structure of the generated shock trains.

The experimental data was acquired by the placement of 60 electrodes on the chicken's retina, followed by the administration of the specified input and subsequent monitoring of ganglion cell activity. The data was collected by Erich Diedrich, a researcher affiliated with the University of Tuebingen in Germany. The data are stored in mcd format files and may be accessed and analyzed using the MC_Rack software developed by Multi Channel Systems. The program has a linkage to MATLAB, enabling the loading and use of the recorded data inside the workspace. The objective is to train a neural network through the application of a sequence of electrical impulses and diverse sensory inputs. The network has a notable capacity for adaptation, allowing it to acquire a comprehensive understanding of the impact process's properties in a very effective manner. Given the available information, the network must possess the capability to accurately forecast the likelihood of an effect at any given point in time. Based on the temporal characteristics, the impulse train generated should exhibit similarity to the impulse train generated by retinal ganglion cells.

The retinal ganglion cells generate the impulse. As previously stated, the intended input consists of a gray light that is emitted onto the retina by a cathode ray tube (CRT). In the event of a change in the input, such as its activation or deactivation, the neural network's input will manifest as a pulsating signal. The input signal may alternatively exhibit sinusoidal behavior, whereby the output light intensity varies sinusoidally over time.

3.3. *Training neural networks*

The neural network was simulated and trained via the Neural Network Toolbox inside the Matlab software environment.

A significant number of modeling studies have been conducted in order to simulate the response of retinal ganglion cells. Numerous experiments have been conducted with the aim of achieving the network configuration that yields the most precise estimation of impact frequency.

The first set of trials was conducted with the objective of identifying the most efficient and accurate learning algorithm. The experimentation also included the evaluation of activation functions. Following a sequence of trials, the network underwent training using the error backpropagation technique in order to minimize the mean square error between the learned hits and the actual hits. The calculation of the error direction for each weight was performed using the Powell-Beale complex gradient descent algorithm, specifically using the training function inside the MATLAB program. Additionally, the determination of the step size was accomplished by employing the Charalambous srchcha line search technique available in MATLAB. The determination of the adaptive learning rate was achieved via the process of interpolation. The process of cubing and dividing is performed. The pursuit of identifying the optimal network configuration constitutes the following group of underlying factors. Choosing the number of neurons and hidden layers has a direct effect on overfitting and underfitting in the model. Therefore, in order to address the problems of overfitting and underfitting in the current model, a careful investigation is done to determine the appropriate number of neurons and hidden layers. The network inputs are defined as a sequence of pulse trains having a duration of 0.096 seconds, organized into batches with a temporal resolution of one millisecond. In other words, the network takes the string of stimuli $\{I(t_1), I(t_2), \dots, I(t_N)\}$ and the value of the shock train at the time $\{t_i\}, \mathrm{t} = 1, r, \dots, \mathrm{N} - 1$ that is $\{F(t_1), F(t_2), \dots, F(t_{N-1})\}$ (1 if there is a shock and 0 if there is no shock) as input and then generates a shock. It is taught at the time of t_N that is $F(t_N)$ The output of this network is the predicted value at the time t_N The 3-layer forward network with complete connections with the desired input and output is shown in Fig. 3.

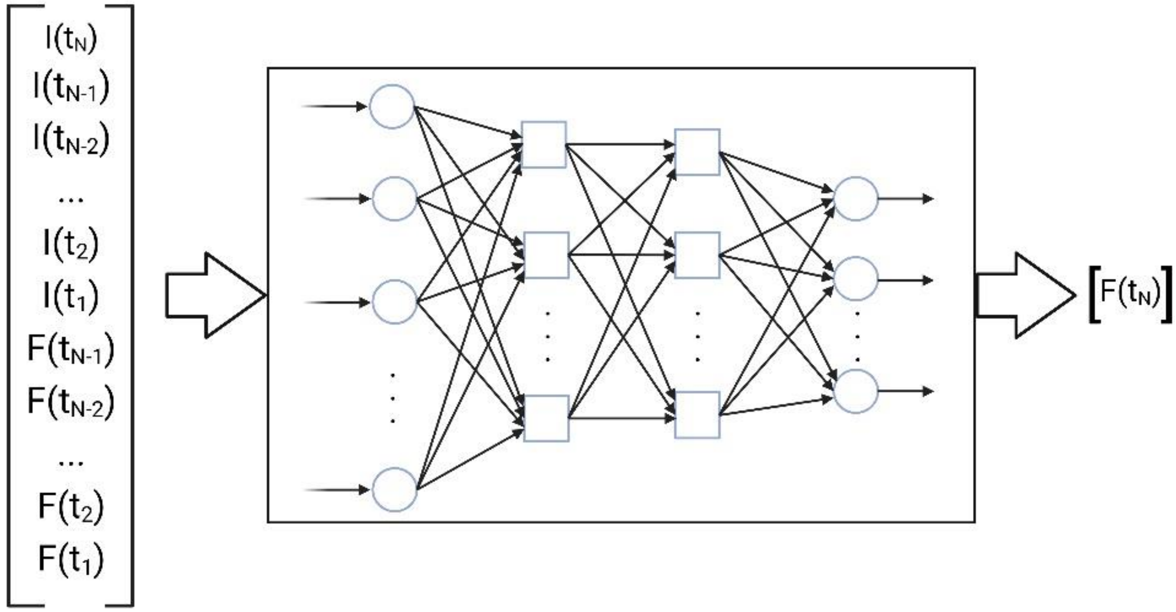
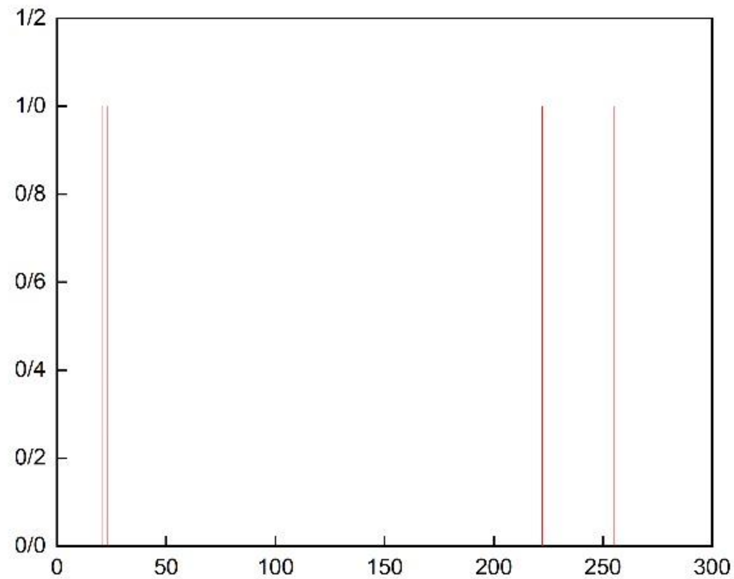


Fig. 3. Input-output structure of the neural network

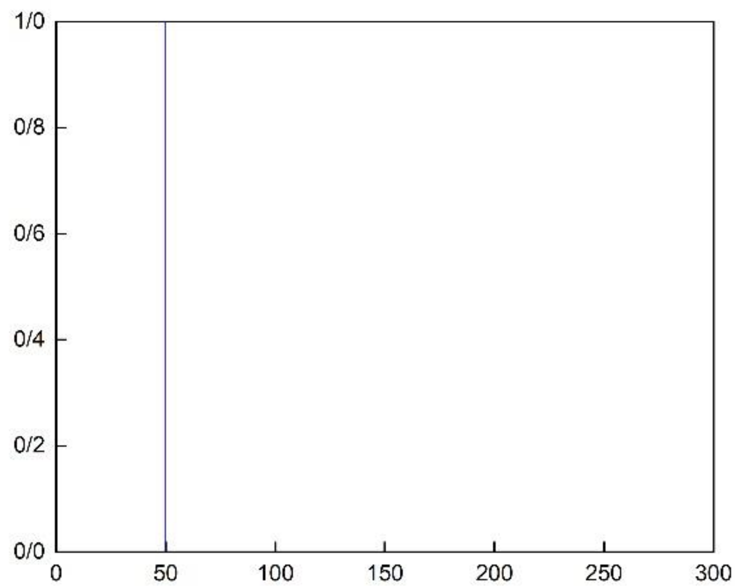
3.4. Simulation and result

To show the efficiency of the model, the actual hits of the cells are plotted along with the corresponding value estimated by the neural network model. The input is a vector with dimension N = 96, and when we add the vector of 95 hits from the previous times, its dimension will be equal to N=95+96=191 The network is trained with a different number of patterns.

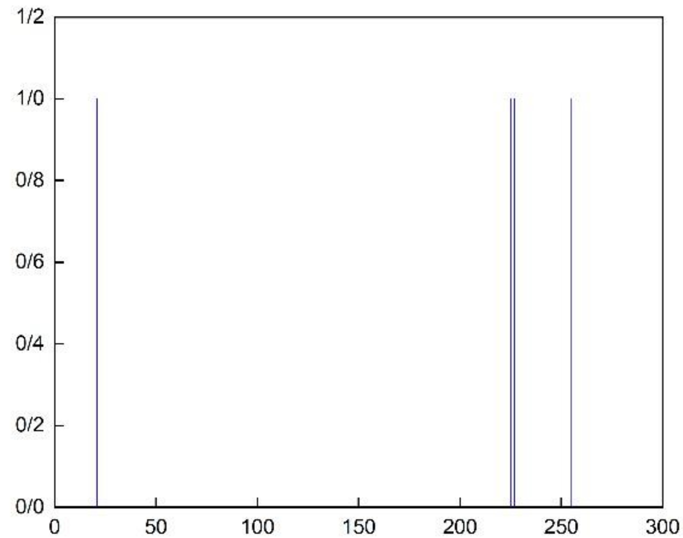
The optimal outcomes are achieved by using a set of 200 patterns and employing a neural network architecture consisting of two layers, with each hidden layer including five neurons. It is worth noting that these configurations result in a 0% error rate, as seen in Fig. 4. Fig. 5 shows the network error with 2000 patterns and structure 5-1(MSE=0).



A. Entrance



B. Cell output



C. Network output (MSE=0)

Fig. 4. Comparison of the real response of the cell with the response modeled by the neural network. The structure used in neural networks is with 5 neurons in the hidden layer.

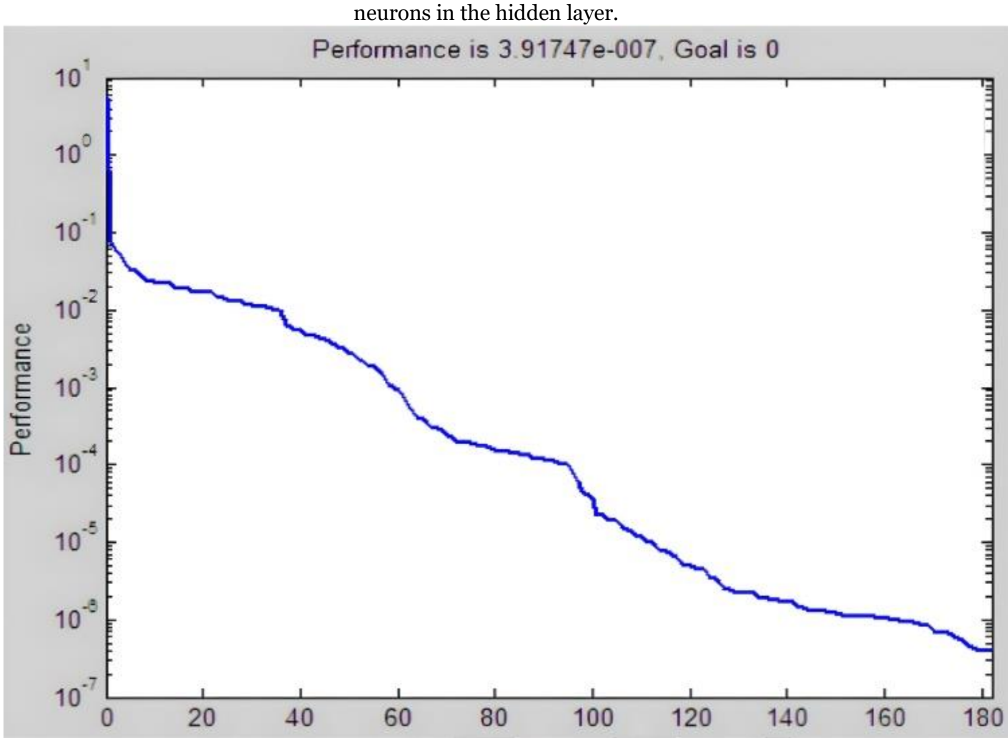
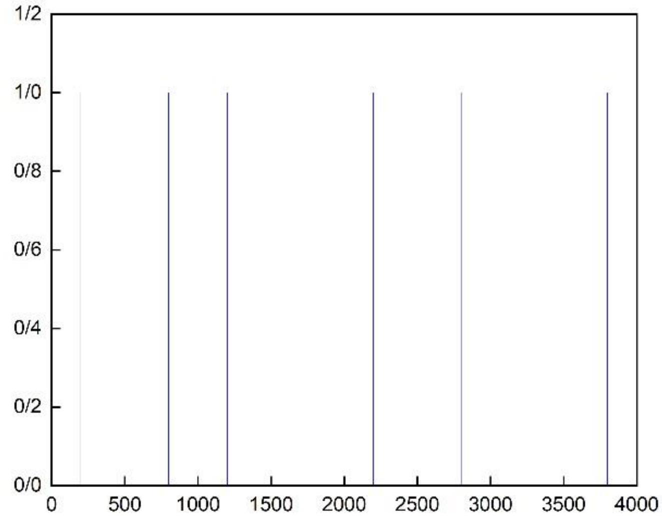
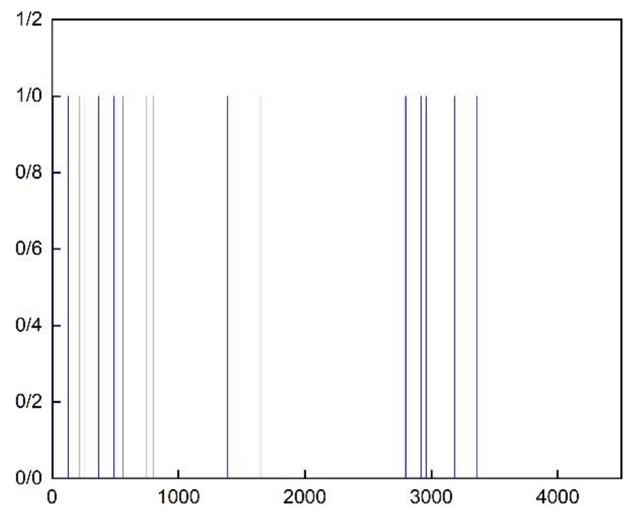


Fig. 5. Network error with 2000 patterns and structure 5-1 (MSE=0)

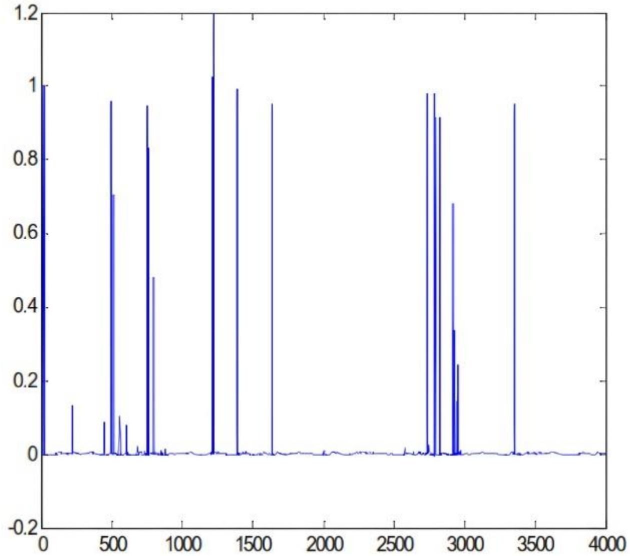
As the number of patterns is increased to 4000, there is a slight increase in inaccuracy. Nonetheless, the network continues to exhibit its ability to track the cell's response. The issue is shown in Fig. 6.



A. Entrance



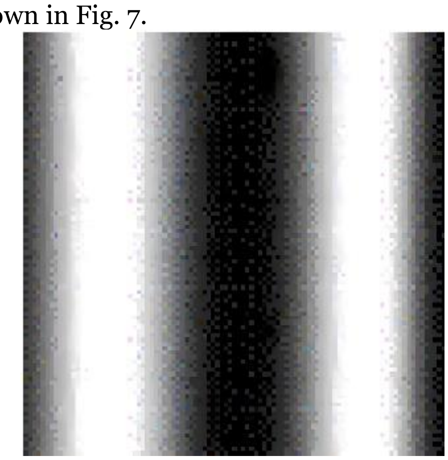
B. Cell output



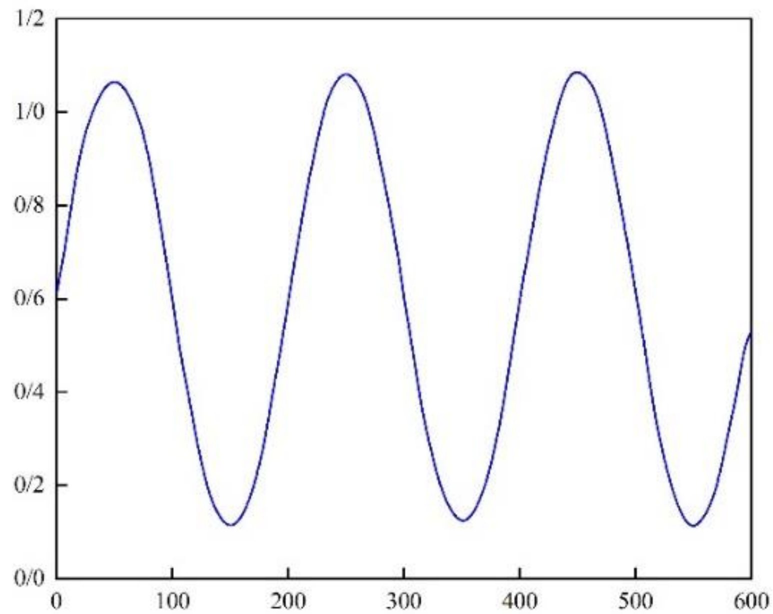
C. Network output

Fig. 6. Comparison of the real response of the cell with the response modeled by the neural network. The structure used is a neural network with 10 neurons in the first hidden layer and 5 neurons in the second hidden layer. The number of patterns has increased to 4000.

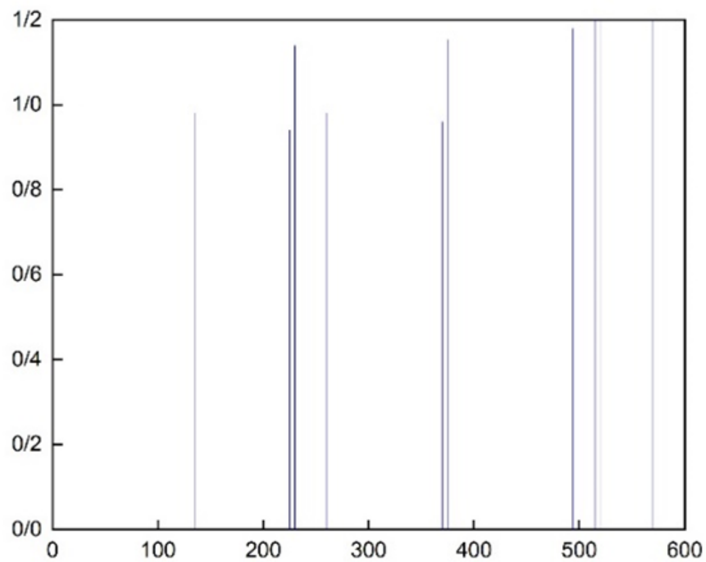
The network was subjected to a simulation using sinusoidal input and a structure of 1-5-10, with a total of 500 patterns. The simulation results are shown in Fig. 7.



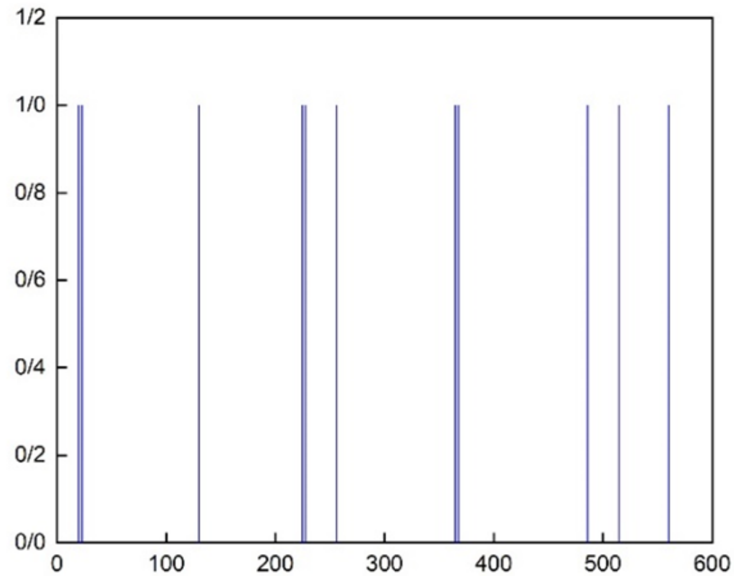
A. Laboratory input



B. Network input



C. Cell output



D. Network output

Fig. 7. Comparison of the real response of the cell with the modeled response of the neural network with sinusoidal input. The structure used is a neural network with 10 neurons in the first hidden layer and 5 neurons in the second hidden layer.

4. Conclusion

In this paper, a theoretical framework for the structure and function of the retina was presented. The first focus of this paper was to examine the physiological aspects of the retina. The presented study proposed a model that uses artificial neural networks to create the model structure. The motivation for this approach is the similarity between the behavior of the model and retinal cells. A comparison was made between the data obtained by the model and the biological data. This comparative analysis showed that neural networks can adequately simulate the behavior of ganglion cells. However, the effectiveness of the network depends on the architecture configuration, the number of hidden layers used, and the specific learning method used. Experimental findings showed that the output from the earlier iterations as input to the neural network causes the memory system to show. This approach increases the efficiency of the model and reduces the occurrence of periodic behavior. This model has potential applications in the development of artificial retinas that act as a hardware implementation to restore some visual capabilities in people with visual impairments.

For future work, we can investigate the automatic classification of retinal diseases with lightweight convolutional neural network based on transfer learning and compare its efficiency with other methods.

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