A Neural Net Based Robotic Optical Circuit that Generates 3D-visual Images:

Reverse engineering the neurophysiology of the modalities of the retinal receptors

by Alan Rosen and David B. Rosen

Abstract:
A neural net-based robotic optical circuit that generates a 3-dimensional visual sensation may be obtained by reverse engineering the neurophysiological connectivity (central connections) associated with the modalities of the retinal receptors. The optical circuit that is based on Wheatstone's stereoscope, is called the Neuronal Correlate of a Modality (NCM)-circuit. The circuit is used to generate a buillding path for a robotic controller that converts two 2-dimensional camera images into a single 3-dimensional sensation of an image that is a high fidelity representation of the objects that gave rise to the two images. In addition the NCM-circuit may be used to solve the neurobiological visual binding and recombination problem and shed light on the neurophysiological function of the LGN and striate cortex.

1. INTRODUCTION

The design of a neural net based robotic optical circuit that generates a 3D-visual image is based on three discoveries; the discovery of the Wheatstone stereoscope ([60]Wheatstone,1838), the discovery in psychophysics[1] of the relationship between physical stimuli and their subjective correlates ([58]Weber, 1846; [13]Felchner, 1860) and the discovery of a robotic sensory motor control system based on tactile modalities ([49],[50]Rosen & Rosen, 2006 a,b, [45]2007a)

The Wheatstone stereoscope converts binocular vision, consisting of two 2D-images into a 3D-image that corresponds to the 3D-objects that gave rise to the two 2D-images. Steven Pinker ([38]1997) writes "Wheatstone proved that the brain turns trigonometry into consciousness when he designed the 3D-picture stereogram."

In the field of psychophysics, the visual receptors, the retinal rods and cones, and the central connections associated with them, are sensation generating systems (when activated) that generate the sensation defined as the modality of the receptor ([16]Guyton,1991; [17]Kandel, Schwartz, Jessell, 2000; [14]Gazzaniga, Ivry, Mangun, 2002; [4]Bear, Connors, Paradiso, 2001). The sensation associate with the activation of an L, M, or S cone is that of "seeing" a pinpoint of colored light ([16]Guyton, 1991).

The sensory-motor control system ([49],[50]Rosen & Rosen, 2006 a,b, [45]2007a) is designed by reverse engineering the connectivity of the tactile receptors distributed on the skin surface of the body. Each receptor is assumed to have a "itch-type" modality-sensation correlated with it. The connectivity of the receptors and the central connections associated with them may be viewed as a neuronal circuit in the brain, defined as the biological Neuronal Correlate of a Modality (NCM). The reverse engineered NCM-circuit is the Sensation-generating Mechanism (SgM) that generates the "itch-type" sensation defined by the modality of the tactile sensor (reverse engineered by pressure transducers) ([51]Rosen & Rosen, 2006c).

2. METHOD

The design procedure for reverse engineering the central connections of the visual-NCM was defined ([49],[50]Rosen & Rosen, 2006 a,b, [45]2007a) and presented at the IEEE-IJCNN-WCCI-Vancouver conference, the ICONIP-2006 Hong Kong Conference, and IJCNN-2007-Orlando Fl ([46],[47]Rosen & Rosen, 2007b,c). The design procedure was described as follows:

A. The modalities and central connections of the visual receptors must give rise to a sensory form of "self"-location and identification data (of all body parts) in a coordinate frame defined by the visual receptors and located within the controller.

B. The coordinate frame defined by the visual receptors must be consistent with, and calibrated with the coordinate frame defined by the tactile-modalities of mechanoreceptors.

In order to proceed with the reverse engineered design of a visual NCM-circuit, it is necessary to expand the law of specific nerve energy to collective groups of receptors that are activated simultaneously. In the field of psychophysics[1], The law of specific nerve energy ([34]Muller, 1826; [18]Haines, 2002) applied to the modalities of the individual visual receptors, explains the subjective sensation of pinpoints of light, and small patches of visual colors correlated with the L, M, and S cones ([16]Guyton, 1991). However, groups and patterns of receptors must be activated simultaneously, in order to generate a visual experience of "seeing" the

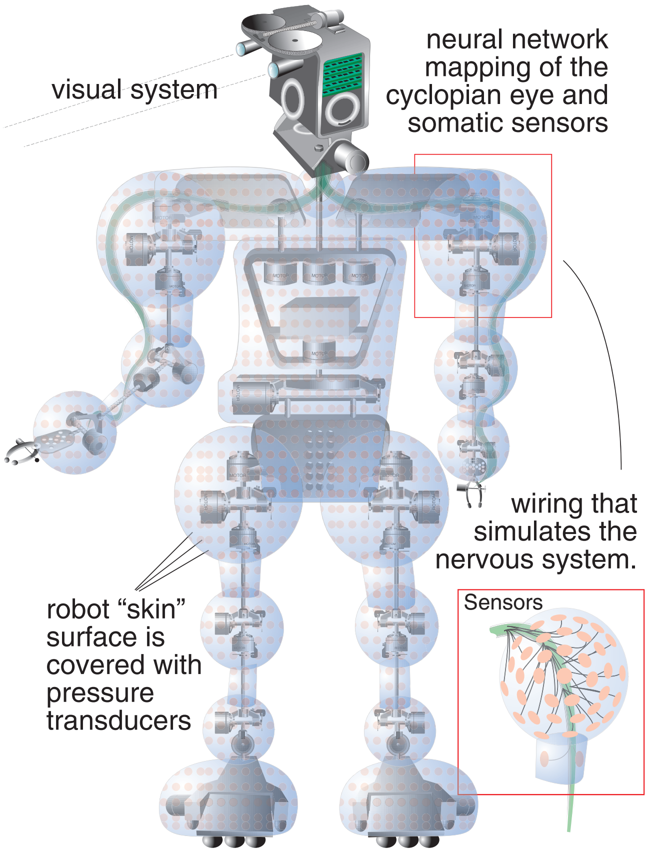

Figure 1 A reverse engineered building path for the major muscles and sensors that are used to control locomotive functions. The mechanoreceptors and nociceptors, the proprioceptors, and the vestibular sensors, are reverse engineered by pressure transducers uniformly distributed on the robotic (skin) surface, the angle measuring transducers associated with each motor, and the circular rings on the controller (head) section of the robot, respectively. The nervous system is reverse engineered by thin wires that connect all the sensors, via cable wire bundles, to the controller (see insert). The camera/eyes mounting, shown at the top of the figure, and the modalities of the CCD-array receptors are discussed in this paper. The connectivity of the system is assumed to adhere to the biological "labeled line" principle.

shape, form, and color generated by the pattern. Thus the law of specific nerve energy must be expanded to a collection of receptors that are activated simultaneously. The law of collective nerve energy consists of the sum of the activations that adhere to the law of specific nerve energy. In the following sections the subjective experience of a collective sensation is defined to be the collective modality of groups of biological receptors that are activated simultaneously[2]. Furthermore, the collective sensation is assumed to be correlated with the collective receptors, the collective afferent axons, and the central connections in the brain activated by the collective set of axons.

The biological visual Sensation-generating Mechanism (SgM) is a NCM-circuit that depends on all the collective modalities present in the retinal system. In the following sections the implementation of the Rosen and Rosen ([49],[50]2006,a,b, [45]2007a) design procedure for a visual NCM-circuit is divided into the following five sections (2.1-2.5).

2.1 Engineering Designs Of Superposed Multi-Modal CCD-Arrays

A visual NCM-robot is shown in Figure 1. The eyes are reverse engineered by 50-millimeter focal length camera lenses and the retinas of the eyes are replaced by two 35-millimeter color detecting Charge Coupled Devices (CCD)-arrays located in the film-region of the camera.

The collective sensations of the right and left camera CCD-array project onto an overlay of two neural networks shown in Figure 2, or the 6 neural networks shown in Figure 3. Each neural network is made up of electronic neurons that maintain the retinotopic organization pattern of each of the CCD-arrays. The superposition and correspondence of the two overlays into a single neural network system located within the controller is discussed in the next section and shown in Figure 2 and 3 as a "neural network mapping of the cyclopean eye."

2.1.1 Design of a single collective modality into the CCDs of a binocular neural net based cyclopean eye

In this section it is assumed that a single collective modality that reverse engineers the tri-chromatic receptors in the retinal layers, is designed into the CCD array. The design is motivated by the distribution of differing receptor modalities in the human retina ([44]Rodiek, 1998), and the existence of overlaid image planes in the Field of View (FOV) of the robot (see Figure 7). The first step for the design of a binocular robotic optical system is to project the collective modalities of the right and left CCD-camera array onto a single overlay of two superposed retinotopic collectives. Figure 2 shows the 2-CCD-arrays covered with a Bayer pattern of filters. Four photo sites, may be combined to form one color-hue receptive field. The resolution of the color image is less than that of a comparable monochrome image, obtained by taking the output of each photo-site, without combining the colors ([55]Scientific Imaging Technologies, 1994; [42]Redlake Inc., 2003).

In Figure 2, the collective modalities of the right and left camera CCD-array project onto an overlay of two neural networks. Each neural network maintains the retinotopic organization pattern of each CCD-array. Within the robotic controller, the electronic "cyclopean eye" shown in Figure 2 is made up of overlaid arrays of visual receiving neurons that form a neural

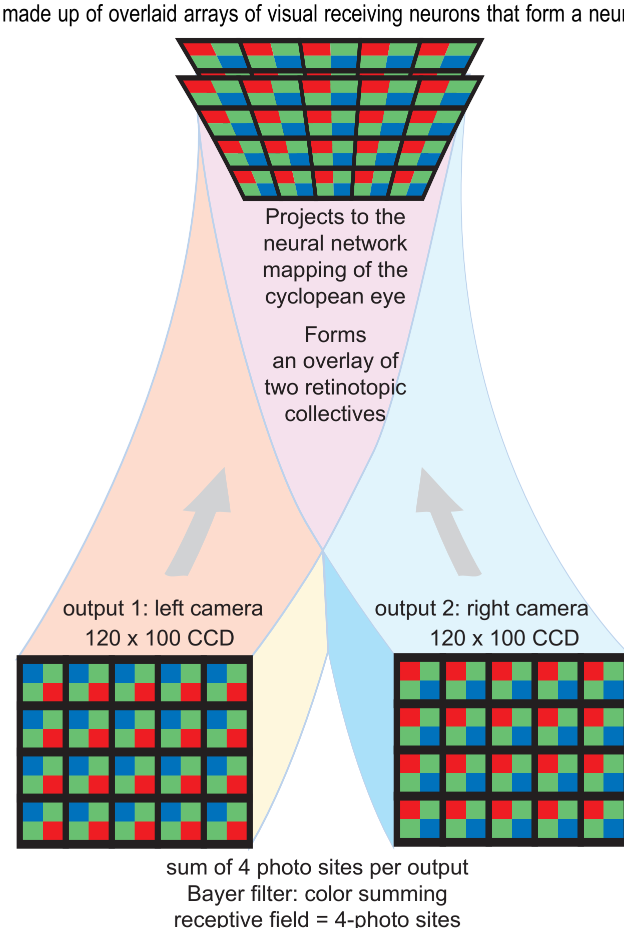

Figure 2 For binocular vision, the collective modalities of the right and left camera project onto an overlay of two superposed neural network arrays. The right and left CCD-images then form a single neural network overlay, which is called the cyclopean eye of the system.

network that is part of the input circuit to the “self” receiving neurons of the NCM-circuit.

2.1.2 A Multi-modal CCD-array: Design of multiple collective modalities in the CCD-arrays of a binocular neural net based cyclopean eye

A multi-modal CCD-array that reverse engineers the retinal layers, may be designed into the cyclopean eye. For example, three collective modalities are shown in each CCD-array illustrated in Figure 3. These modalities devolve into 3-pair of binocular layers in the cyclopean eye, as follows:

a) A tri-chromatic collective modality: The tri-chromatic modality is shown as squares, and each square is made up of 4-different color photo-sites (the same as those illustrated in Figure 2).

b) Monochromatic high-resolution low transient response photoreceptors: The transient response of the photoreceptor reaches an intensity peak during the first three frame periods, then drops to zero during the fourth frame period. The resolution is 18-times that of the tri-chromatic collective modality (18 photo-sites per tri-chromatic photo-site). When the image is steady on the CCD-array, this modality is engineered to integrate the image over 3-4 frame periods.

c) Monochromatic high-resolution high transient response photoreceptors: The transient response of the photoreceptor reaches an intensity peak and drops to zero during the first-activation frame period. The resolution is 18-times that of the tri-chromatic collective modality (18 photo-sites per tri-chromatic photo-site), and this collective modality is engineered to track image motion on a frame-by-frame basis.

The first step for the design of a multi-modal binocular robotic optical system is to project the collective modalities of the right and left CCD-camera array onto a single overlay of multiple superposed retinotopic collectives. Figure 3 shows the distribution of the 3-modality, 6-layered system originating from the CCD- receptors on the right and left camera CCD-array. Each modality forms a binocular superposition of that modality in the cyclopean eye. For the composite 3-modalities CCD-arrays, the cyclopean eye is made up of the 6-collective modality layers shown in Figure 3. Each layer of the cyclopean eye is made up of receiving neurons that maintain the retinotopic organization of the CCD-arrays.

2.1.3 The Correspondence Problem: The Marr-solution to an ill-posed problem

How does binocular vision, consisting of two 2D-surfaces, generate a 3D-image that corresponds to the 3D-objects that gave rise to that image? This problem is often referred to as the correspondence problem. This problem was first described by David Marr ([27]1962) as the correspondence between the visual image in the brain and the real external world that gave rise to that image. It is a problem of perceiving an object’s shape-depth and substance from its projection on the retinas of both eyes. This problem is part of the inverse optics problem and is often referred to as an “ill-posed” problem, since it is not amenable to a unique solution[3] (Marr & Poggio, [29]1976, [30]1979).

Steven Pinker ([38]1997) writes (relating to David Marr ([27]1962) solution to “ill posed” problems) “Vision has evolved to convert those ill posed problems into solvable ones by adding premises: assumptions about how the world we evolved in, is on the average put together.”

David Marr ([27]1962) views these assumptions as constraints that are imposed on the biological visual system in order to obtain acceptable solutions to the correspondence problem. The focusing reflex and the eye-crossing reflex help satisfy these constraints. The constraints listed by David Marr ([27]1962)[3] are viewed in this paper as visual cues that generate the perception of 3D-depth throughout the FOV (The fixation point as well as regions that are offset from the fixation point).

The problem is one of learning how to fixate and focus, by trial and error, both eyes on the same object located at a fixation point, assuming that it is at a given depth, and at the same time, utilize the visual cues to determine the depth of nearby objects. Note that the depth of nearby objects may be determined by fixating (converging both eyes) on them.

Constraint satisfaction has been implemented in a constraint network. David Marr and Thomas Poggio ([29]1976) designed one for stereoscopic vision. In this paper constraint satisfaction has been designed into the NCM-visual system by the formation of an internal retinotopic depth-collective modality that “learns” the depth of regions that are offset from the fixation point on the basis of the visual cues listed by Marr and Poggio ([30]1979) (see section 2.5.2).

2.2 The Optical Apparatus For 3D Viewing

The description of the reverse engineered design of a biological 3D-SgM is based on Sir Charles Wheatstone ([60]1838, 1852) discovery of optical apparatus, the 3D-picture stereoscope, that can generate 3D-visual sensations. To generate a 3D- image, two cameras obtain two 2D-pictures with the difference in views coming from binocular parallax. The picture obtained by the left camera corresponds to the image of the left eye, whereas the picture obtained by the right camera, corresponds to the image of the right eye. From a biological perspective, the ability to perceive 3D-depth due to the distance between a person’s two eyes is called stereopsis. Stereopsis is the perception of depth produced by binocular retinal disparity. Stereopsis is one of more than 10-visual-depth cues that is used by the biological system to solve the visual correspondence problem[3].

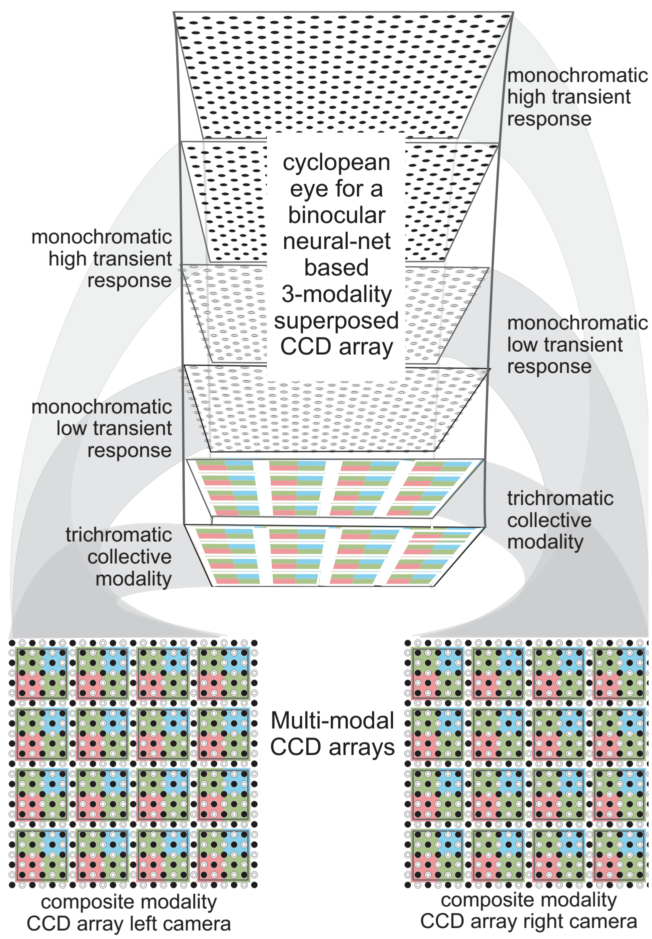

Figure 3 A multi-modal CCD-array that reverse engineers 3-collective modalities. The 3-modalities in each CCD-array are transmitted to 6-layers of the cyclopean eye.

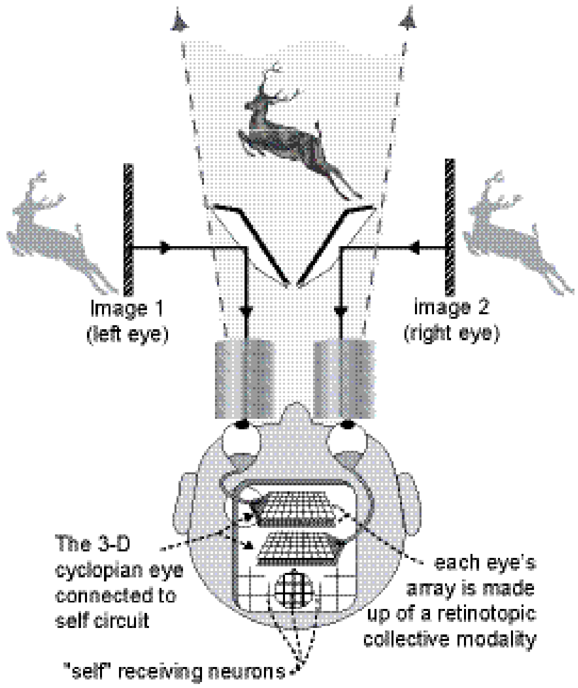

Figure 4 The Wheatstone stereoscope and the 3D-sensation generating mechanism.

2.2.1 Superposition of the two images into a single cyclopean eye that contains all the data necessary to generate the sensation of a 3D-image

The superposition of the two images, shown at the bottom of Figure 4 is deduced from the use of Wheatstone's principle applied to 3D-video production, illustrated in Figure 5. In the Figure, two prisms are adjusted by rotation so that the left (red) and right (green) pictures are superposed. When the pictures are properly superposed the central portions of the fields of view correspond to one another, however the right peripheral portion of the FOV is unique to the right eye whereas the left peripheral portion of the FOV is unique to the left eye. The two superposed images are projected onto a projection screen shown in Figure 5. In this paper, the projection screen is called a "cyclopean eye" for 3D-video production because it contains all the binocular data necessary for depth perception and the generation of the sensation of a 3D-image. Thus, the "cyclopean eye" of an optical system is defined as a superposition of two images, obtained by binocular disparity, that contain all the binocular data necessary for depth perception.

2.2.2 The reverse engineered cyclopean eye within the controller

The Wheatstone-video projection screen forms the basis for the design of the superposed cyclopean eye within the controller. However, it does not follow that the human brain also has within it a similar superposed cyclopean eye. The superposed cyclopean eye may be one of many alternative ways of presenting the 3D binocular data to a system that generates a 3D-image (The projection screen-cyclopean eye satisfies a necessary but not sufficient rationale for the existence of such a superposition in the human brain). Regardless of which implementation is used, the human brain, in order to generate a 3D-sensation, must simultaneously and in a coordinated manner organize and process the two images obtained by binocular disparity. And the design of the superposed cyclopean eye within the controller is a functional reverse engineered building path for the actual implementation used in the biological brain.

2.2.3 A hypothesized physiological structure of the biological cyclopean eye

In analyzing the operation of a Wheatstone stereoscope, it is necessary to make some functional assumptions about how the binocular data is processed in the brain. In the following sections, without any neurobiological evidence, it is assumed that the generation of 3D-sensation is implemented by means of a physiological structure found mostly in the LGNs that is similar to the reverse engineered superposed cyclopean eye within the NCM-controller[4]. The discussion of neurobiological evidence for alternative physiological implementations is presented in the discussion section 3. However, it is important to note that all alternative implementations are functionally similar, and that the reverse engineered superposed cyclopean eye is a good functional emulation of the biological physiological cyclopean eye.

2.2.4 Analyzing the Wheatstone 3D-Sensation-generating Mechanism

Figure 4 presents the design of a Wheatstone stereoscope that is outfitted with a 2-tube viewing system that constrains the view of the left eye to the picture obtained by the left camera and the view of the right eye to the picture obtained by the right camera.

The images the left and right camera must be presented to the left and right eye, in order to produce the sensation of a 3D- image. An illustration, presented at the top of Figure 4, shows the 3-dimensional sensation generated by the stereoscope[2].

The reverse engineered cyclopean eye at the bottom of Figure 4 is part of the Sensation-generating Mechanism (SgM) in the brain of an observer that "turns trigonometry into consciousness" ([38]Pinker, 1997). The illustration of the brain of the observer is based on the assumption that there exists a collective set of receptors similar to the overlaid collectives shown on the projection screen in Figure 5. In Figure 4, the two overlaid collectives that have 3D-sensation correlated with them consist of a neural network made up of the "visual receiving neurons of the cyclopean eye."

Figure 5 illustrates the use of Wheatstone's principle for 3D-video production. In order to abstract the 3D-data from the screen, the projection screen is viewed with filtered glasses, with a green and a red filter over respective left and right eyes. The filtered lenses separate the two images for presentation to the overlaid collectives of the 3D-cyclopean eye.

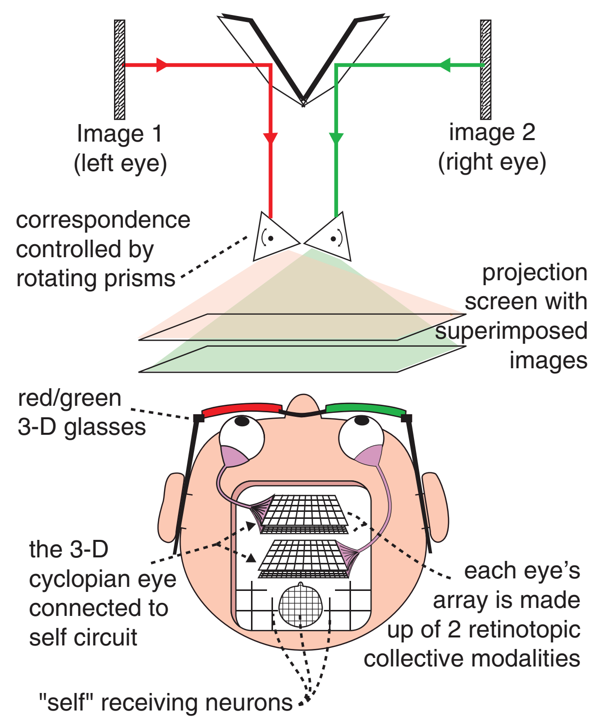

Figure 5 The basic principle for 3D-video viewing.

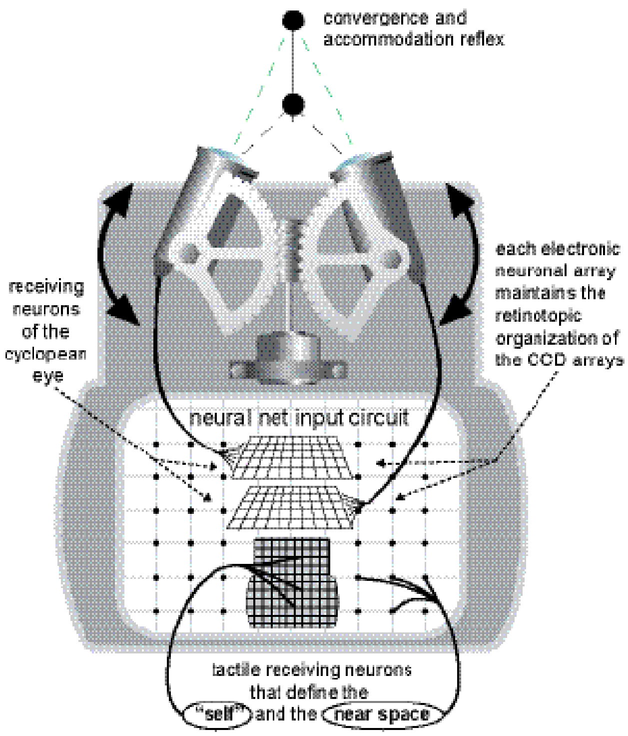

Figure 6 Correspondence matching of the images of the right and left cameras by reverse engineering the convergence and accommodation reflex associated with the rectus and ciliary eye muscles.

Charles Wheatstone ([61]1852) working in the field of psychophysics, also studied the characteristics of 3D-sensations and the design of the 3D-cyclopean eye (visual collectives and their modalities). In a variation of the stereoscope, an instrument that Wheatstone called the "pseudoscope," prisms and mirrors are so arranged that the right eye sees the left eye's view and vica versa. In this case the observer perceives a 3-dimensional figure, which Wheatstone called the "converse" of the original.

The significance of Wheatstone's pseudoscope is that it gives information about disparity selective neurons that superpose the right and left eye images on the LGNs, striate and extrastriate cortex). The information is illustrated in Figure 4 and 5 by noting that a) the superposed images on the projection screen must be properly aligned in order to be a SgM. b) Any change in the screen's superposed images is reflected in the overlaid alignment and superposition of the images in the brain. And c) the 3D-sensation of depth may be studied, as Wheatstone has done, as a function of changes in the superposed images on the projection screen.

2.3 Reverse Engineered Design of the Superposed Collective Modality Layers: The cyclopean eye in the brain and within the controller

The reverse engineered design is based the superposed projection screen shown in figure 5, the existence of multiple modalities in the human retina ([44]Rodiek, 1998), and the existence of overlaid image planes in the Field of View (FOV) of the robot (see Figure 7).

In this paper the superposition and correspondence of the two neural networks into a single neural network system is defined to be the electronic "cyclopean eye" of the robotic system. In the discussion section it is hypothesized that the electronic cyclopean eye reverse engineers a biological "cyclopean eye" that may have been observed in regions of the LGNs and striate cortex ([31]Mays, 2004; [38]Pinker, 1997), and extrastriate cortex ([37]Parker, 2004).

2.3.1 Physical requirements for generating the sensation of a 3D-image from the binocular disparity of two 2D-images

Figure 4 and Figure 5 illustrate the physical requirements that must be satisfied in order to generate a 3D-image from the binocular disparity of two 2D-images.

1. Binocular disparity recording is required: The two retinal receivers, or two CCD arrays of the two cameras must be separated from one another (disparity distance), and they must simultaneously record the same image viewed from the disparity perspective.

2. The images must be superposed and aligned so that the central portions of the FOVs correspond to one another, the right peripheral portion of the FOV is unique to the left retinal receiver (CCD-array) and the left peripheral portion of the FOV is unique to the right retinal receiver (CCD-array). Note that this occurs on the projection screen shown in Figure 5 for 3D-video production, on the image planes shown in Figure 7, and also in the brain with the formation of a biological 3D-cyclopean eye.

3. In order for stereopsis to occur the cyclopean images of the right and left eye must be presented separately (shown as tubes in Figure 4 and red-green glasses in Figure 5) to the receiving homunculus in the brain shown in Figures 4 and 5.

The physiological structure of the biological 3D-cyclopean eye must adhere to the physical requirements enumerated above in order to generate stereopsis.

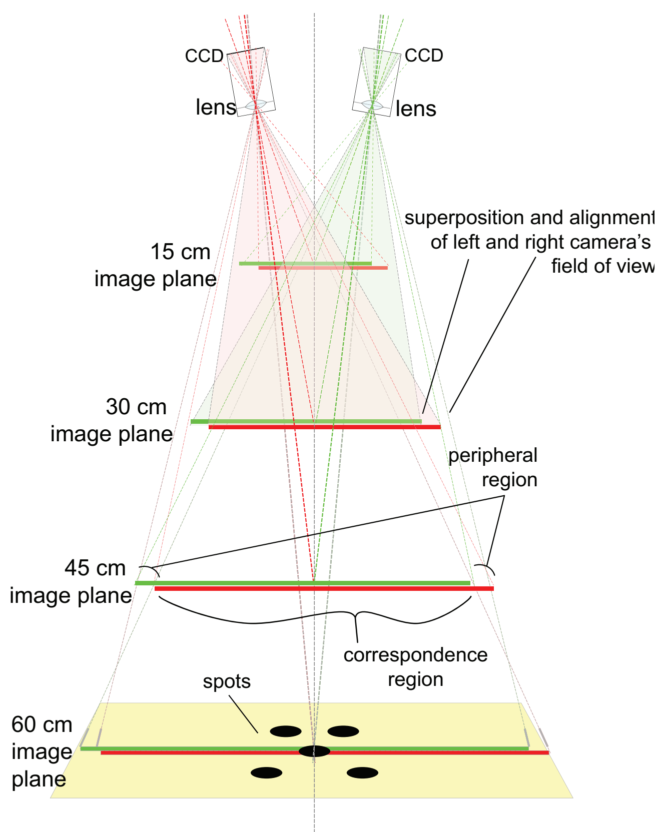

Figure 7 Four image planes. Each plane is determined by the binocular disparity and FOV of a 2-camera system. Each camera's LOS converges at convergent depths of 15, 30, 45, and 60 centimeters intersecting on the midline LOS. The FOV and areas of the right and left camera CCD-array determine the image-areas on the image plane. The two image-areas on the image plane of the right and left camera are superposed and aligned so that the central portions correspond to one another and peripheral portions are unique to the right and left camera.

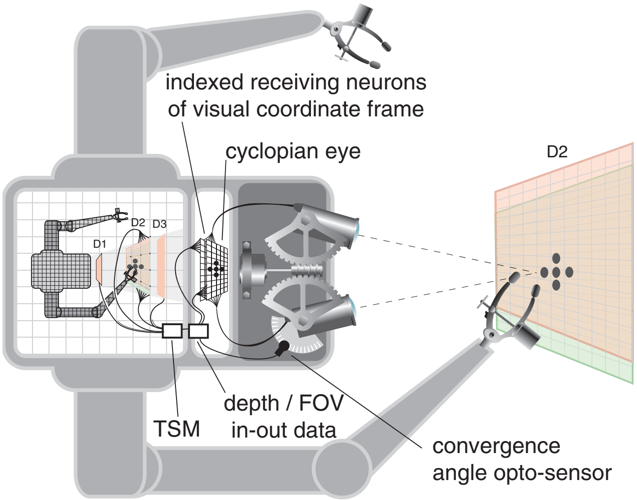

Figure 8 A visual coordinate frame within the controller. A visual coordinate frame within the controller is formed by all the indexed receiving neurons that locate spots of light on the image planes within a given FOV, and all FOVs designed into the system (see Table 1). The cyclopean eye is connected to the tactile "self identification and location"-circuit. During each frame period, the convergent angle opt-sensor determines the convergent-depth of the image plane and the TSM transmits the cyclopean eye data to the indexed locations (shown in the figure at plane position-D2).

2.3.2 Correspondence-matching the images of the right and left camera. Reverse engineering the biological cyclopean eye

Correspondence matching of the images of the right and left camera, within the cyclopean eye in the controller, is achieved by reverse engineering the biological convergence and accommodation reflex associated with the Rectus and Ciliary eye muscles. Figure 6 is an illustration of the reverse engineered biological convergence and accommodation reflex. The convergence reflex may be reverse engineered by a mechanical auto-focus constraint that couples the rotary motion of the two cameras so that they always converge at a near or far point, known as a fixation point, located on the midline between the cameras. The accommodation reflex is reverse engineered by relying on the camera's depth of field (lens aperture and focal length) to generate focused images at the near and far points on the LOS-midline. The "cyclopean eye," shown in Figure 6 as the superposition of receiving neurons from two eyes may imitate the superposition of layers in the LGNs[4].

2.4 Connectivity of the Reverse Engineered Cyclopean Eye to the NCM-circuit: The formation of a FOV-coordinate frame defined by the visual receptors and located within the controller

As described in the introductory part of section 2, the modalities and central connections of the visual receptors must give rise to a sensory FOV-coordinate frame, wherein all image spots within the FOV must be located and identified with respect to all the body parts of the itch-scratch robot. Furthermore the coordinate frame defined by the visual receptors must be consistent and calibrated with the coordinate frame defined by the tactile receptors of the itch-scratch robotic system.

2.4.1 The formation of coordinates based on superposed image planes within the FOV

The external FOV-coordinates are determined by image planes located at a set of convergent-depth points along the midline-LOS. Figure 7 shows four-image planes where the cameras are convergent on the midline-LOS at depth-distances of 15, 30, 45, and 60 centimeters from the two cameras. At each convergent point, called a fixation point, an image plane perpendicular to the midline-LOS is shown in Figure 7. The aerial extent of the right and left camera CCD arrays determines the areas covered by the image planes and the FOV of each image plane. On each image plane, the two FOV-areas imaged on each cameras CCD-array are also shown in Figure 8 at a D1, D2, and D3. Note that with the two cameras convergent at a single point, a) The area covered by the FOV of each camera corresponds to the area covered by the sensors of each CCD-array, b) There exists a one to one correspondence between a spot of light located on the image plane and a CCD-sensor located on the CCD-array (see the spots shown on the image plane in Figure 7 and the corresponding spots at D2 in Figure 8)), c) The retinotopic organization of the images on the image plane correspond to the images on the CCD arrays, d) The correspondence and alignment of the 2-images on any image-plane is lost when 2-images are projected to the 2-CCD-arrays. However this correspondence and alignment may re-occur in the design of the cyclopean eye, and also the projection screen shown in Figure 5.

The coordinate location of spots of light on any image plane, relative to the fixation-depth point of the image plane, may be determined from CCD-sensors in the CCD- array that are activated by the light-spots. Figures 7 and 8 show the spots of light on the image plane and Figure 8 shows the spots of light on the cyclopean eye that acts as a relay to the indexed receiving neurons of the visual coordinate frame.

A spot of light falling on the CCD-arrays and on the cyclopean eye, must be located (and maintain its specificity as a visual signal by the law of specific nerve energy) in a FOV-coordinate frame within the controller, that is consistent with, and calibrated with the coordinate frame defined by the tactile modalities of mechanoreceptors. The receiving neurons in the superposed layers of the cyclopean eye must be connected to a set of indexed receiving neurons in the tactile near space so that the location of the spot of light is consistent with the measure of the homunculus and the near space around the homunculus. Figure 8 illustrates the connectivity of the CCD arrays to the receiving neurons of the cyclopean eye and thence to the set of visual receiving neurons indexed to locations in the tactile near space. The number of receiving neurons with tactile indexed locations and in the cyclopean eye (not indexed) equals the number of CCD-sensors that make up each CCD-array. Five spots of light, one located at the center of the plane and 4-spots offset from the center, are shown on a superposed image plane in Figure 7. The corresponding positions of these 5-spots are also shown in the cyclopean eye and the receiving neurons in the indexed near space. The physical connectivity of each cyclopean eye receiving neuron to the tactile coordinate frame is determined by the "known" depth of the fixation point. The depth of the offset spots, which is a function of the alignment and correspondence of the two image-planes, is discussed in section 2.5.2.

Number of FOVs (3-FOVs)	Number of Convergent Depth positions (6-convergent depths): Depth	Angle	Number of spots on each image plane (equals the number of CCD-sensors in the arrays)
0 deg- ahead	6 cm	45 deg	2x100x120=24,000 spots on each image plane
	10 cm	30.9 deg	
45 deg- right	30 cm	11.3 deg	
	60 cm	5.7 deg	
	100 cm	3.4 deg	
45 deg- left	900 cm	0.4 deg	

Table 1. The total FOV-coordinate space in a prototype visual system: The total FOV-coordinate space may be defined by placing image planes at various convergence-depths along the FOV-midline. Six convergent locations and 3-FOVs are shown in the table. For each FOV in the prototype system, there are 24,000 spots on each image plane, and 6-image planes in each FOV. The number of indexed receiving neuron (forming coordinate points in the FOV-coordinate frame) for the total system designed with the 3-FOVs is 24,000 x6x3 = 432,000 receiving neurons.

The location of the spots of light (both center and offset spots) and the corresponding indexed receiving neurons in the near space is determined by calibration with the tactile coordinate frame used for sensory motor location of the robotic finger shown in Figure 8.

The number of coordinate-spots of light on the image plane in the vicinity of the robotic finger, that are resolved by the cyclopean eye, is equal to the number of CCD-sensors in the CCD-array. The position of each receiving neuron is indexed so that it corresponds to the position defined by an image/spot on the image plane in the vicinity of the sensory motor controlled robotic finger (see Figure 8). The depth of the offset neurons is discussed insection 2.5.2. The total FOV-coordinate space may be defined by placing image planes at various convergence-depths along the midline-LOS. Table 1 illustrates the number of convergent locations that were incorporated into a prototype design of a robotic visual system. Note that the indexed location of the visual receiving neurons that make up the FOV-coordinate space, is a physically significant parameter that defines the location of the spot of light in the FOV of the robotic system. The physically significant parameters in the cyclopean eye are the relative positions of receiving neurons with respect to one another. The location of the total superposed cyclopean eye is not a physically significant parameter (it may be located on the side, front, or back of the homunculus-coordinate frame)[4]. The depths of the offset spots, discussed in section 2.5.2, are deduced from visual cues discussed in section 2.5.2 and the depth of the fixation point located on the superposed and aligned receiving neurons shown in Figure 8.

2.4.2 The Search Engine: Programming-teaching the robot to locate and respond to spots of light. Task-initiating Triggers (TTs) and the Task Selector Module (TSM) of the visual NCM-system.

A visual multi-tasking robot with the visual system described in Table 1, may be programmed to search for spots of light in a region surrounding the robot. Each FOV (0, ± 45 degrees) may be searched by moving the point of convergence of the two cameras from a depth of infinity to a depth of 9 meters, 1 meter, 60, 30, 10, and 6 centimeters (see Table 1) Programming-teaching the robot to locate and respond to spots of light is a process of training the robot to move its head and body to determine a FOV-midline, and then sweep the depth of convergence from infinity to 6-centimeters in front of the robot. The search engine is used to search the external environment for Task-initiating Triggers (TTs) and obstacles that may be present along the trajectory ([50]Rosen & Rosen, 2006b). The Task Selector Module (TSM) and the Sequence Stepper Module (SSM) are the primary circuit elements used to detect TTs present in the input sensory signals.

A visual prototype robot may be trained with a single spot of light (variable color with parameters determined photometrically) similar to the ones shown in Figure 8, and 7. A spots of light of any color-hue at any location may be identified (photometrically) as a Task Initiating Trigger (TT) by the TSM. (Note that TSM locates obstacles and TT-spots of light at indexed locations of the Nodal Map Module, and that the Sequence Stepper Module may generate an obstacle-avoiding trajectory towards a TT-spot of light). During each frame period, a spot of light, detected by the Task Selector Module (TSM), is prioritized and may become the Task-initiating Trigger (TT)-activation point in the near space of the robot (similar to the itch-activated mechanoreceptors used as itch-TTs to activate an itch-scratch trajectory).

Thus, if a TT-spot of light activates any of the 432,000 FOV-receiving neurons located and indexed relative to the tactile receiving neurons that define the near space, then the sensory motor control system is trained to generate a finger trajectory of motion that is goal directed towards the spot of light. The training is similar to the process described for the tactile robotic system activated by itch-type TTs ([49], [50]Rosen & Rosen, 2006,a,b).

2.5 The Calibration Procedure

The problem is one of calibrating the 3D-coordinate space defined by the tactile sensors, with the 3D-image defined by the cyclopean eye. It is a problem of scaling the FOV-image so that it corresponds to the scale size measured by the tactile receiving neurons in the near space. The locations of the visual receiving neurons that correspond to the tactile receiving neurons in the near space regions (light spots in the FOV-space) have been described in the previous section and are shown in Figure 7. Figure 9 shows the calibration region where the tactile space is common with the 3D-image space. The calibration of the size and depth distance of the pencil (Figure 9) takes place between the indexed 3D-visual receiving neurons that define the pencil, and the indexed locations of the robotic finger that define the tactile space. The indexed locations of the receiving neurons must be calibrated to generate a one to one correspondence between a 3D-image of the pencil in the FOV-space and the pencil that is located in the near space defined by flailing limbs.

2.5.1 The depth of the neuron at the fixation point

The signals must be indexed or related to the sensory motor control system of the eyes, head, body, and limbs in order to view a 3D-image in the coordinate frame in which the system is operating. In the NCM-system indexing of the visual neurons is a function of the head orientation (0, ± 45 degrees), and the convergence angle of the opto-sensor that determines the fixation point of the converging cameras. The fixation point and the two superposed image planes associated with it are placed at the depth of the fixation point in the self location and identification coordinate frame. For example, the two image planes, shown in Figure 7 at a depth of 60 centimeters, are defined in Figure 8 as plane D2. The depth of the fixation point of D2 is determined by the convergence angle opto-sensor and may be projected to the exact indexed location of the self location and identification coordinate frame (the Nodal Map Module). However, only the visual fixation point in D2 is indexed to the proper depth of the self location and identification coordinate frame. The depth of offset spots shown in D2 may be determined and learned by the system by shifting the fixation point to those spots.

All the neurons of the 2-superposed image planes defined by a fixation

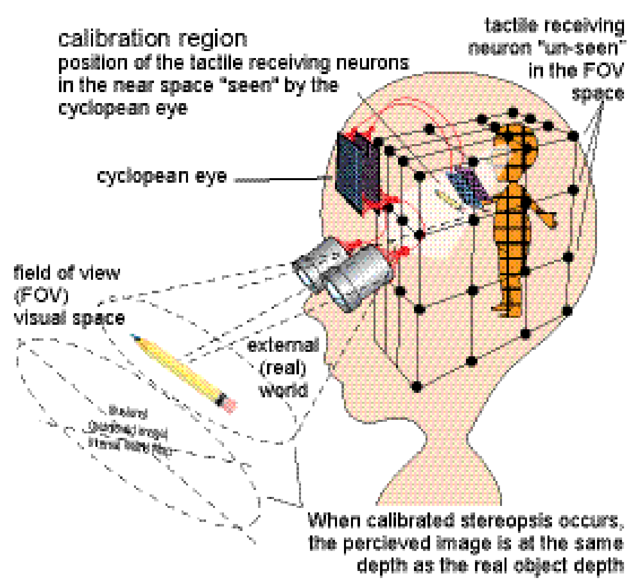

Figure 9 Calibrating the distance-measure in the FOV-visual space. The relative depth, distance and size of the pencil-image falls within the FOV of the cyclopean eye. The image-pencil is calibrated with the depth, distance and size of the object-pencil, which is determined by the tactile sensors and the tactile receiving neurons within the controller.

point are located on the 2D-surface at the corresponding fixation point within the controller (see layers in Figure 8 labeled "indexed receiving neurons of the visual coordinate frame). Only the indexed receiving neurons that are at the fixation point will register and be analyzed so that it exhibits the depth derived from the absolute disparity. Nearby neurons that are offset from the fixation point are not only non-corresponding but may represent images that are located at large distances further or nearer than the corresponding fixation point. The robot must learn, using all the visual cues listed by Marr and Poggio ([29],[30]1976, 1979), whether nearby neurons are located at greater or smaller depth-points than the fixation point. In the next section, it is noted that this may correspond to learning to find nearby non-corresponding points that exhibit artificially learned correspondence (or a form of physiological correspondence discussed in section 3). The only way the robot has of checking the depth of a nearby point is to converge and fixate on the nearby point and thereby determine the depth of the nearby spots. Once the depths of nearby points are established, by fixating on them, their location may be projected to the appropriate indexed locations of the Nodal Map Module. The sensorimotor control system of the robot then has the capability to move all its body and limbs relative to the location of the visual image in the indexed visual coordinate frame. It has self location and identification knowledge not only with respect to all body parts, but also with respect to the observed object located in the common coordinate frame.

2.5.2 The depth of neurons that are offset from the fixation point

An internal retinotopic depth collective modality may be formed in the microprocessor based portion of the controller. During each frame period, the internal depth collective is formed by following the design of Marr and Pogio ([30]1979) for a neural network that learns to determine retinotopic depth based on photometric visual cues applied to the system. The process includes A) fixating on the offset neurons, B) determining their disparity depth, C) correlating their disparity depth with any of the visual cues specified by Marr and Pogio ([30]1979), D) depending on either the correlated visual cue or the measured disparity depth, the offset neurons are now indexed into a single disparity depth selective neuron, located on the newly formed image plane of a retinotopic depth collective modality, and E) This newly formed retinotopic set of disparity depth selective neurons, located on a retinotopic depth-collective modality, may now be indexed to the correct corresponding 3D-position of the self location and identification coordinate frame (the indexed locations of the tactile 3D- coordinate frame in the Nodal Map Module).

The internal depth collective is designed to learn the correct depth-location of offset neurons by measuring visual cues detected during a given frame period, rather than shifting the fixation point to each offset neuron in order to determine its depth-location. Note that in the engineered NCM-system, if a retinotopic depth collective modality, described above, is formed in the various regions of the neural networks module of the controller, then all the data necessary to form a 3D-image which is calibrated with the 3D-tactile near space coordinate frame, now resides in the Nodal Map Modules. This data may be correlated with sensorimotor controls that includes obstacle avoidance as well as detection of objects, shapes, forms, color, and motion. The perceived images may be identified as visual-TT-patterns that may initiate the sensory motor control tasks of a multi-tasking system. On the other hand, in the biological visual system, it is noted in the discussion section, that if a retinotopic depth collective modality, described above, is formed in the various regions of the striate and extrastriate cortex then the retinotopic depth collective modality has all the data necessary to form the 3D-illusion generated by the Wheatstone stereoscope. Then, rather than using the photometric data to generate the visual cues, described above, the biological system may make use of the illusion of size, continuity, obscuration, etc. to determine the depth of the offset neurons on the image plane.

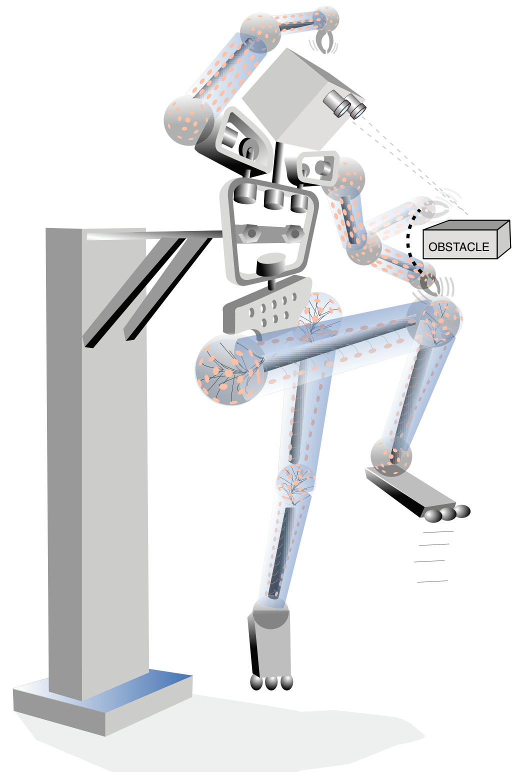

Figure 10. A pictorial representation of a laboratory set-up used to train a visual "itch-scratch"-robot to avoid obstacles. The robot is pictured re-planning a pre-planned itch-type trajectory in order to avoid a visual obstacle viewed along the pre-planned trajectory.

2.5.3 Programming the robot to locate and respond to spots of light on each image plane

A multi-tasking robot uses its visual system as a search engine that searches the space in the vicinity of the robot as described in 2.4.2. In order to program the robot to locate and respond to a spot of light appearing in the FOV coordinate frame, each spot of light (shown in Figure 7) may be viewed as a Task-initiating Trigger (TT) activation point (similar to the itch-TTs). The robot is trained to respond to each TT-spot of light by means of a sensory motor controlled trajectory that is goal directed towards the spot of light.

Programming-teaching the robot to locate and respond to spots of light is a process of training the robot to move its head and body to determine a FOV-midline, and then sweep the depth of convergence from infinity to 6-centimeters in front of the robot. For the prototype robot, if a TT-spot of light activates any of the 432,000 FOV-receiving neurons located and indexed relative to the tactile receiving neurons that define the near space, then the sensory motor control system is trained to generate a finger trajectory of motion that is goal directed towards the spot of light. The training process is identical to the process described for the tactile robotic system activated by itch-type TTs ([49], [50]Rosen & Rosen, 2006a,b, [45]2007a).

2.5.4 "Seeing" colors: Programming-teaching the robot to locate and respond to different colored spots of light

It is possible for the robot to distinguish between different colored spots of light since the robotic visual system is tri-chromatic (see Figure 2). Training the robot to distinguish different colors is accomplished by programming the robot to respond to differing TTs for different colors. The robot is sensitive to differences in color hue and may be designed with different TTs assigned to each color-hue. The robotic response is thus color-hue dependent, and the robot can thus distinguish between all the color-hues generated by the tri chromatic set of CCD-arrays (equivalent to the modality of the algebraic sum of the L, M, and S cones).

2.5.5 Training/programming the system to avoid obstacles

A pictorial representation of a laboratory set-up to train the itch-scratch robot for obstacle avoidance is shown in Figure 9. The robot is attached to its center of mass, and all itch-scratch trajectories are performed relative to the center of mass. In the engineered NCM-system, all the data necessary to form a 3D-image of the obstacle resides in the Nodal Map Modules that represent the 3D-tactile coordinate frame in which the NCM-robot is operating. The internal depth collective, described above, may transmit the photometric data of all detected obstacles to the indexed locations of the Nodal Map Module. The Sequence Stepper Module then detects those obstacles and generates a pre-planned trajectory so as to avoid the photometrically detected obstacles ([49],[50]Rosen & Rosen, 2006a,b, [45]2007a).

The response of a multitasking NCM-robot is determined by a Hierarchical Task Diagram (HTD), the top level specification of the system, and the Task Selector Module (TSM) that prioritizes and selects during each frame period the Task initiating Triggers (TTs) present in the incoming signal ([50]Rosen & Rosen, 2006b). The tasks on the HTD are activated by the TSM that may apply the highest priority-TT to the Nodal Map Module. The prioritized Task-initiating Triggers (TTs) are used to select the top level tasks and the lower level subtask on the HTD. For example, a visual, itch-NCM robot may be designed with two priority level-tasks that may change the state of the system, a top-level itch-monitoring set of tasks and a lower level-color-hue spot-monitoring set of tasks (see section 2.5.2). The priority levels of visual obstacles (generated by the TSM) are designed to be lower level tasks that do not change the state of the system (either the itch-activating state or color-hue spot discriminating monitoring state). Instead, the TSM transmits the photometric data of all detected obstacles via the internally generated retinotopic depth collective, to the indexed 3D-locations of the Nodal Map Module. The Sequence Stepper Module then detects those obstacles and generates a pre-planned trajectory so as to avoid the obstacle while performing any of the higher priority level tasks (Rosen & Rosen, [49],[50]2006a,b, [45]2007a, [52], [53]2003a,b).

3. DISCUSSION

The five most significant contributions of the visual NCM-circuit to the field of visual robotic neurobiology are:

[1] The development of a visual sensory motor control robotic system that operates a multitasking robotic system in the same 3D-frame of reference as the frame of reference of the 3D-image generated by the visual system.

[2] The development of a total functional flow of the visual signals, through the 3D-cyclopean eye and thence to indexed locations in the self location and identification coordinate frame, located within the controller, and corresponding to the 3D-space in which the robot is operating.

[3] In visual neurobiology, the relationship between neurons in the NCM-visual system, the observed cortical visual neurons, and the SgM that generate a 3D-illusion that corresponds to the real world objects that gave rise to the illusion. The generation of a sensation represents the end point in the neurobiological search for cortical visual neurons that facilitate binding or recombination of the various parallel processing paths.

[4] The relationship between visual and kinesthetic sensations of motion, based on the design of the visual NCM-system

[5] The contribution to the philosophical question: Does the electronic NCM-visual system experience a wheatstone-type 3D-illusion?

The following five sections discuss each of those contributions:

3.1 Visual Robotics

The visual NCM-circuit implements a major task of the brain ([17]Kandel, 2000- p.498), the integration into a single coordinate frame “three successive frames of reference for visual perception and the control of movement: A retinotopic frame of reference, a head centered frame of reference, and a body centered frame of reference.”[5]

The visual NCM-circuit does not calculate the “trigonometry” of the location of objects or obstacles relative to the robotic motion. It learns by performing itch-scratch type actions similar to those described by Rosen and Rosen ([49], [50]2006,a,b, [45]2007a) for the itch-robot, with the addition of various shaped objects and colors simulating the itch points, and various obstacles that may be placed along the itch-scratch trajectories. The itch points and the various shaped objects and colors are detected by the TSM, and processed by the Nodal Map Modules, and the Sequence Stepper Modules of the NCM-robot.

The learning/training, performed in the Nodal Map Module and Sequence Stepper Module ([50]Rosen & Rosen, 2006b) is a repetitive procedure that relates the convergent position of the two cameras, the motor-muscle position of the flailing limbs, the relative image-sizes and positions on the CCD-arrays, with the tactile (touch-feel) object depth-distance and size. It is a process of “teaching” a neural network to “see” the “ correct” size of an obstacle3, located along the itch-scratch trajectory, so that the pre-planned trajectory devised by the Sequence Stepper Module is an obstacle avoiding trajectory that actually avoids the obstacle. It is important to note a) that the resolution of the robotic visual system does not reverse engineer the resolution of the biological visual system (and the sizes of receptive fields have been increased accordingly), and b) That the reverse engineered visual-NCM system need not have a sensation generating “seeing”-modality in order to perceive every thing that humans “see”. This is a philosophical problem that is discussed in section 3.5.

3.2 A Comparison of the Total Functional Flow of the Visual Signals in the Visual-NCM with the Standard Model for Visual Seeing

In order to generate a 3D-image that corresponds to the 3D-spatial objects that gave rise to that image, the visual NCM system and the biological visual system must both conform to physical principles or optical laws of physics. The following section is a comparison of the functional flow through the NCM-visual system, with emphasis on functions that according to physical laws, must be similar in the biological and engineered visual systems, regardless of the structural form (engineering or anatomical structures) of the implementation. The functional flow through the NCM system is described in terms of engineering structures illustrated in Figures 8, whereas the structural form of the biological implementation is illustrated in Figure 11.

3.2.1 An overview of the “standard model”

An overview of the “standard model” ([43]Reisenhuber & Poggio, 2004) showing the visual pathways in the brain is presented in Figure 11. In the standard model it is hypothesized that the visual image is created by several relatively independent parallel processing channels. Each one appears to be specialized for the analysis of a different facet of the visual scene. In the standard model, collective modalities from the right and left eye, originating in the retinas, are projected through the optic nerves, to the optic chiasm and are superposed in the LGN-layers. The right eye and left eye superposed LGN layers are aligned to one another so as to reflect

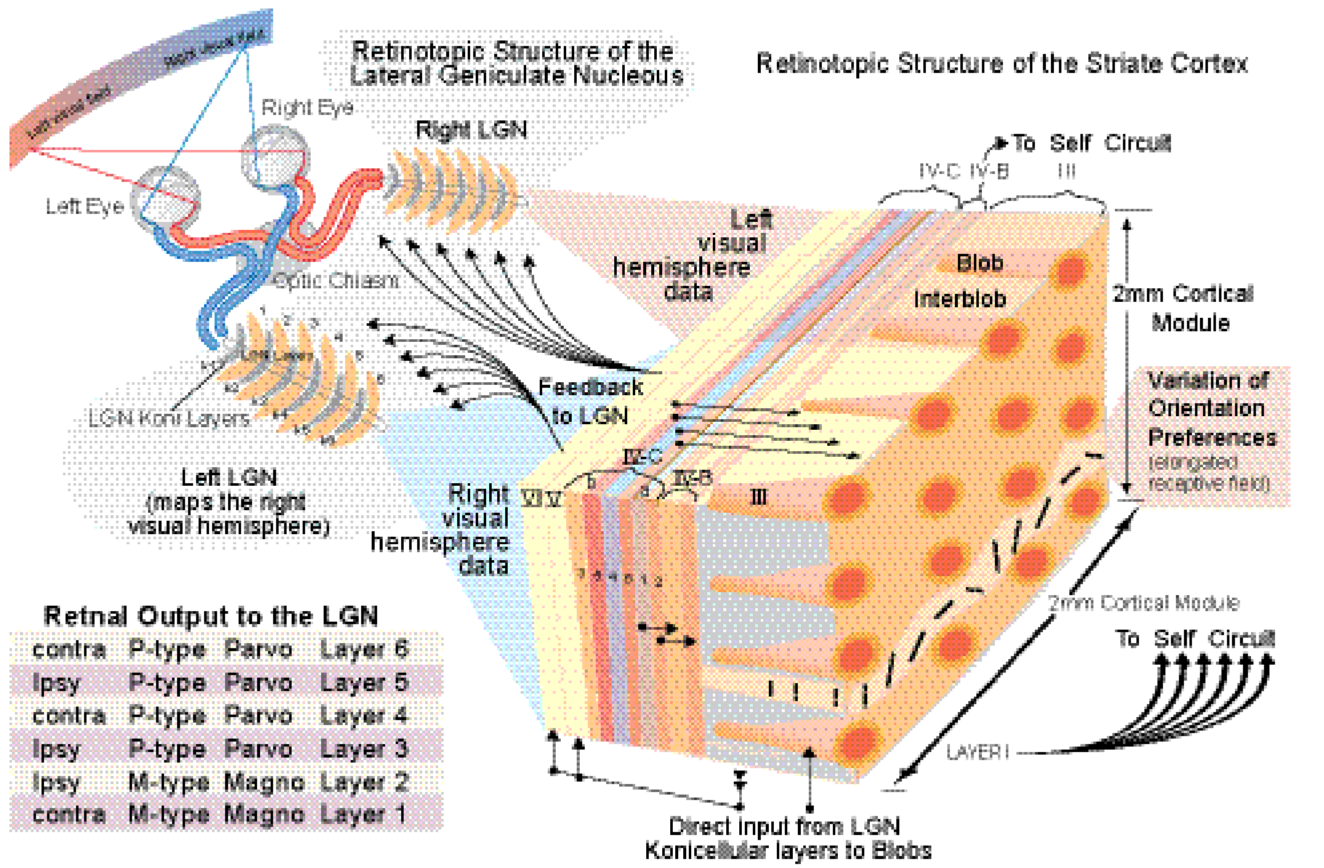

Figure 11. An overview of the standard model showing the visual pathways in the brain: This figure summarizes over fifty years of experimental and theoretical studies of the visual brain.

the total retinotopic organization of the retina4. The set of overlaid collective layers in the brain have been referred to as a biological "cyclopean eye." ([31]Mays, 2004; [38]Pinker, 1997). The LGNs interact with the retinotopic structure of the striate cortex and the striate cortex feeds into the extra-striate cortex ([17]Kandel et al, 2000, p.550)

Figure 11 summarizes over fifty years of experimental and theoretical studies of visual brain structures and associated processing (Hubel and Wiesel, [21]1959, [22]1962, [23]1968, [24]1998; [8]Chalupa et al, 2004; [17]Kandel et al 2000; [[14]Gazzaniga et al 2002; [4]Bear et al, 2001; [18]Haines, 2002; [44]Rodieck, 1998; [10],[11]DeValois, 2004; [41]Reid & Ursey, 2004; [20]Hess, 2004; [36]Olshausen, 2004; [56]Sterling, 2004; [37]Parker, 2004).

3.2.2 The functional flow through the NCM

The functional flow of visual signals through the visual NCM, shown in Figure 8, is from the retinal CCD-arrays to the cyclopean eye, thence parallel paths from the 3D-cyclopean eye and, and from the convergence angle opto-sensors and TSM, to the indexed receiving neurons of the visual coordinate frame that is calibrated with the self location and identification coordinate frame. The self-location and identification coordinate frame, located within the controller, is the end point of the functional flow of visual signals. The cyclopean eye shown in Figures 8, 4, 5, and 6, is analogous to the layers of the LGNs, whereas the indexed receiving neurons of the visual coordinate frame are analogous to the striate and extrastriate cortex (see Figure 12).

With training, the system obtains a form of "robotic knowledge" of the location of the visual objects with respect to the relative position of all body parts and all end joints, and learns to discriminate different objects, shapes, colors, depths, and motions. In the biological system, but not necessarily in the NCM-system, the system that generates "self knowledge" is the Sensation-generating Mechanism (SgM) that generates the Wheatstone-type modality-sensation of a 3D-image of the objects in the 3d-space external to the controller. The three functional requirements that must be satisfied, in both the biological system and the NCM system are:

[1] (in section 3.3.1) The signals of the right and left retina/CCD need to be superposed and the arrays must maintain the retinotopic

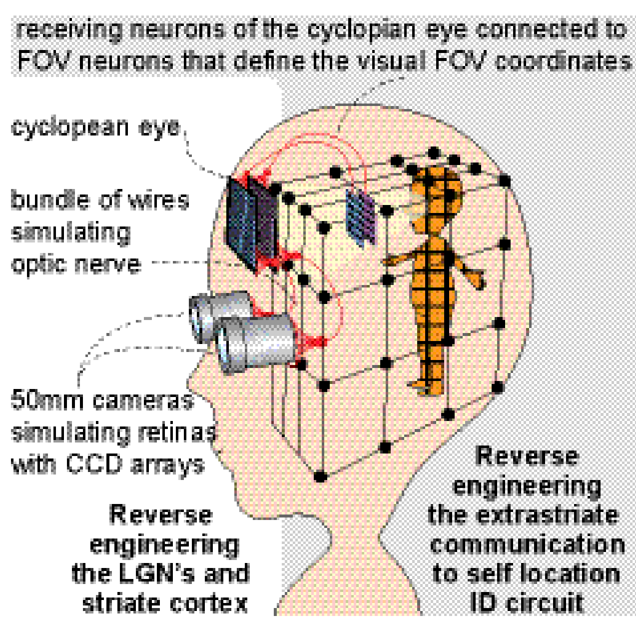

Figure 12 A functional overview comparison of the standard model with the visual electronic-NCM: a) The receiving neurons of the cyclopean eye are analogous to the retinotopic layers of the LGN. b) The indexed coordinate frame calibrated with the "self" location and identification circuit is analogous to the intermediate processing taking place in the striate and extra-striate cortex. c) The NCM-self location and identification coordinate frame is analogous to the retinal coordinate frames described by [17] Kandel et al, (2000)

organization of both retinas/CCDs.

[2] (in section 3.3.2) The signals must be brought into anatomical corresondence in order to determine the binocular depth of any fixation point. (physiological non-correspondence is discussed in the next section).

[3] (in section 3.3.3) The signals must be indexed or related to the sensory motor control system of the eyes, head, body, and limbs in order to view a 3D-image in the coordinate frame in which the system is operating.

3.3 Comparing the Implementation of Functional Requirements in the Electronic-NCM and Standard Model for Biological Vision

A functional overview comparison of the standard model with the visual-NCM leads to the following analogues (illustrated in Figure 12): a) the receiving neurons of the cyclopean eye are analogous to the retinotopic layers of the LGN, b) the generation of an indexed coordinate frame calibrated with the self location and identification circuit is analogous to the intermediate processing taking place in the striate and extrastriate cortex, and c) The NCM-self location and identification coordinate frame is analogous to the retinal coordinate frames described by Kandel, et al (2000). In the following sections the emphasis shall be on the comparison of depth perception in the two systems, rather than color, shape form and motion. However, with regard to the existence of multiple parallel processing channels in the visual system, it is noted that once the neurons of the cyclopean eye are indexed and keyed to the self location and identification frame of reference, the physiological locations (in the striate and extrastriate cortex) for processing depth, color, shape-form and motion is arbitrary, as long as the various locations that maintain the indexed retinotopic organization send indexed projections to the self location and identification coordinate frame.

3.3.1 Superposed retinotopic organization in the cyclopean eye

The electronic NCM: In the NCM system the collective modalities of the right and left CCD array are superposed in the cyclopean eye. However, the superposition need not be in binocular correspondence if the indexed location of the centers and relative displacement of the right and left image planes (see Figure 7), are known. Note that the only requirement place on the system is that each collective modality maintain the retinotopic organization of the CCD-array/retinas where the signals originated. Multiple collective modalites may be aligned in the cyclopean eye. Figure 3 illustrates 3 pairs of collective modalities aligned so as to maintain the retinotopic organization present in the multimodal CCD-array/retina. Note that the binocular disparity depth-data is coded at only one point (the fixation point) in each of the 3-pairs of collective modality layers.

The standard model: In the standard model illustrated in Figure 11, 6-ipsy-contra retinotopic layers are observed in each of the two LGN structures. Functional segregation and right –left eye superpositions analogous to the collective modalities shown in Figure 3, have been observed in the LGNs ([7]Casagrande, 2000-p.494-506; [28]Livingston & Hubel,1988). The LGNs are not redundant features since the right LGN sub-serves the left visual hemisphere, whereas the left LGN sub-serves the right visual hemisphere. Note that at this stage in the flow each layer must maintain a known relative set of retinotopic organizations but the layers need not be in binocular correspondence. Furthermore, without processing, only one point in each ipsy-contra pair is in anatomical binocular correspondence

3.3.2 Binocular correspondence to determine binocular depth at vaious points on an image plane whose depth is determined by the convergent fixation point

The electronic NCM: In the NCM system binocular correspondence is obtained in the indexed receiving neurons of the visual coordinate frame illustrated in the Figure 8. Note that in the two planes of the visual coordinate frame, only the fixation point is in anatomical correspondence. Nearby points are in non-correspondence, and the NCM system must shift the fixation point to those nearby points in order to bring them into anatomical correspondence. Note that although it may be sufficient that only one layered pair have a fixation point that exhibits anatomical correspondence, all 3-layered pairs were chosen to exhibit anatomical correspondence at the fixation point. Note that once the position of a pair of corresponding receiving neurons are indexed into a single neuron, this neuron, indexed and located in a coordinate frame, may encode an alteration in the disparity of a stimulus with precision that depends on the correspondence of the 2-corresponding neurons. Finally, from an engineering point of view, if nearby non-corresponding points on the same image plane, are at various depths differing from the depth of the fixation point, it is advantageous (see section 2.5.2) to generate a "learned" planar coordinate frame subserving a retinotopic depth collective modality in which each location has a disparity-depth assigned to it. A retinotopic depth collective modality has all the data of the 3D-illusion generated by the Wheatstone stereoscope.

The standard model: In the standard model, the biological study of binocular vision is now focused on a search for neuronal activity and neurons in the striate cortex and extrastriate cortex that exhibit characteristics of anatomical and physiological correspondence ([37]Parker, 2004-pp 779-791)[6]. In the biological system, similar to the NCM-depth collective modality described above, a system of binocular disparity based on retinal anatomical and physiological correspondence is firmly locked in the coordinate frame of each retina (Parker, 2004).

3.3.3 The signals must be indexed or related to the sensory motor control system

The signals must be indexed or related to the sensory motor control system of the eyes, head, body, and limbs in order to view a 3D-image in the coordinate frame in which the system is operating.

The electronic NCM: In the NCM-system, indexing depth-location of visual neurons is a function of the head orientation (0, ± 45 degrees), and the convergence angle of the opto-sensor that determines the fixation point of the converging cameras. The robot must learn, using all the visual cues listed by Marr and Poggio ([29]1976, [30]1979), (e.g. size or continuity, obscuration, etc), whether nearby neurons are located at the same depth as the fixated depth or are located at distances nearer or further than the fixation point. In the electronic- NCM, disparity selective neurons are organized and indexed into an internally generated retinotopic depth-collective modality, wherein every disparity selective neuron of that modality is indexed to the location of that neuron in the self location and identification coordinate frame within the controller. The totality of disparity selective neurons of that modality form a 3D-image in the coordinate frame within the controller that is similar to the 3D-illusion generated by the Wheatstone stereoscope. Once the 3D-image is established in the 3D-coordinate frame within the controller, the sensorimotor control system of the robot has the capability to move all its body and limbs relative to the location of the visual image in the indexed visual coordinate frame. It has self location and identification knowledge not only with respect to all body parts, but also with respect to the observed object located in the common coordinate frame.

The standard model: Much of present day research into the visual system is focused on a search for the physiological location in the brain of neuronal activity that can better explain some key visual characteristics of depth perception, color, shape-form and motion. There has been some significant progress made in all these areas. However, it is noted that if a retinotopic depth collective modality, similar to the one described above, is formed in the various regions of the striate and extrastriate cortex then the retinotopic depth collective modality has all the data necessary to form the 3D-illusion generated by the Wheatstone stereoscope.

Two examples will be presented, that are relevant to physiological locations shown in Figure 11 of biological neuronal activity and the design of a biological NCM-circuit:

3.3.4 Example 1: Indexed coordinate frames in the brain

The standard model: (quotes taken from Kandel et al ([17]2000, p.498)) " A major task of the brain is to construct three successive frames of reference for visual perception and the control of movement: A retinotopic frame of reference, a head centered frame of reference, and a body centered frame of reference. How are these frames of reference established? Some neurons in the parietal cortex have receptive fields that are modulated depending upon the position of the eye in the orbit. These neurons are therefore combining input from the retina with information about eye position-- "each time the eye moves, the head centered frame of reference must be updated" …Similar computations using head position information may be performed in the ventral premotor cortex and together with computations from the parietal cortex, they serve to establish a body centered coordinate frame of reference"

The electronic NCM: The visual NCM-circuit integrates into a single coordinate frame the retinotopic frame of reference (determined by eye position), a head centered frame of reference, and a body centered frame of reference. However, the physical location of indexed receiving neurons that make up the coordinate frame is arbitrary, as long as the indexing codes the locations of the multiplicity of related tactile and visual neurons.

Thus indexed neurons from the retinotopic visual system may be related to indexed motor neurons in parietal cortex, the ventral premotor cortex, and regions of the extrastriate cortex, as described in 3.4.5.

3.3.5 Example 2: The location of disparity selective neurons associated with NCM-receiving neurons that exhibit absolute and relative disparity

The standard model: Cortical area V1(the striate cortex) is the first site in the brain at which information from the two eyes is brought together by means of specific excitatory connections (sometimes to a single neuron) designed to create high precision binocular disparity. Such neurons can encode an alteration in the disparity of a stimulus with an accuracy that rivals that of psychophysical observers ([39]Prince, 2000). V1 is an important site for the initial registration and analysis of binocular absolute disparity ([40]Rashbass, 1961), whereas in V2- the finest stereoacuities are obtained with stimulus arrays that include relative disparities ([1]Andrew, 2001; [59]Westheimer, 1971).

Disparity-selective neurons have been identified not just within the striate cortex, but also throughout the visual areas of the extrastriate cortex [9](Cummings, 2001). "Cortical area V1 responds fundamentally to absolute disparity, while in three cortical areas V2 , the lateral division of the middle superior temporal area (MSTI) ([12]Eifuku and Wurts, 1999, [57]Thomas et al, 2002) and in cortical area V3A ([2]Backus et al 2001), there are reports of neurons that are sensitive to the manipulation of relative disparity as a parameter. Also the presence of neurons with selectivity for binocular disparity was discovered in cortical area V5/MT ([33]Mounsell and Van Essen, 1983), which as been associated with the perception of visual motion.

The electronic NCM: These biological disparity selective neurons are analogous to the electronic NCM-disparity selective neurons designed into the internally generated retinotopic depth collective modality. In the electronic- NCM, disparity selective neurons are indexed to the location of that neuron in the self location and identification coordinate frame within the controller. The totality of disparity selective neurons of that modality form a 3D-image in the coordinate frame within the controller. The sensorimotor control system of the robot has the capability to move all its body and limbs relative to the location of the 3D-image in the indexed visual coordinate frame. It has self location and identification knowledge not only with respect to all body parts, but also with respect to the observed object located in the common coordinate frame.

The following comparison may be made between the disparity selective neurons in the biological and electronic visual systems: The indexed central neuron exhibits anatomical correspondence and is a fixation point neuron (most likely found in the V1-region), whereas the indexed off-set neurons (most likely found in regions of the extrastriate cortex) exhibit physiological correspondence. Note that the locations of these neurons either in the neural network module of the NCM, or in the brain is arbitrary as long as the neurons are properly indexed. Properly indexed neurons may be simultaneously projected onto the correct indexed locations of the self-location and identification coordinate frame. A retinotopic depth collective modality, if it is formed in the striate and extrastriate cortex, would have all the 3D-data necessary to form the 3D-illusion generated by the Wheatstone stereoscope.

3.3.6 The end point in the neurobiological search for cortical visual neurons that facilitate biological vision.

The previous section 3.4.2 illustrated the termination point of the search for neurobiological cortical visual neurons that facilitate the formation of a Wheatstone-type 3D-illusion. The termination point is an internally generated, indexed retinotopic depth collective modality that is keyed to, and projected onto the indexed neurons of the self-location and identification coordinate frame. In this case the indexed retinotopic depth-collective modality forms the Wheatstone-type 3D-illusion generated by theWheatstone stereoscope.

The discovery of the termination point for the Wheatstone type Sensation-generating mechanism may facilitate the search for indexed collective modalities for color, shape-form, and motion. The identification of the indexed cortical visual neurons of each internally-generated collective modality (color, shape-form, motion) represents the termination point for those neurons that generate the sensation correlated with each collective modality. Most of the internally generated visual collective modality neurons that sub-serve the modalities of color, shape-form, and motion, are most likely to be found in the striate and extrastriate cortex. Figure 12 illustrates the engineering structures that may be analogous to the physiological structure for the end to end visual system. The separation of the multimodal retina into a set of multilayered collective modalities occurs in the LGNs and the set of superposed-layered receiving neurons received from the multi-modal CCD-array. In the striate and extrastriate cortex, the collective modalities of the LGN are indexed and keyed to the self identification and location coordinate frame. The only processing that takes place in the striate and extrastriate cortex is that collective modalities may be formed, as demonstrated in section 3.3.5, and these modalities may be related to and indexed to specific motor muscles (indexed in the self location and identification coordinate frame). The specific motor muscles may be the eye orientation muscles that determine the location of the retinotopic frame of reference, the head position-location head centered frame of reference, and orientation-position of the various parts of the body in a body centered frame of reference. Note, as described in section 3.3.4, indexed neurons from the retinotopic visual system may be related to indexed motor neurons in parietal cortex, the ventral premotor cortex, and as described in section 3.3.5, regions of the extrastriate cortex.

3.4 The Relationship Between the Visual and Kinesthetic Sensations of Motion: Retinotopic modalities related to proprioceptor modalities

The sensation of motion is mediated by the modalities of the retinal receptors in the eye, the modality of proprioceptive detection of movement associated with the muscles of the eye, head, and body and the modality of the vestibular apparatus that calibrates the visual-FOV coordinate frame with the proprioceptive coordinate frame. Each of those modalities is a SgM. The superposition of those modalities sub-serves the total sensation of motion ([19]Hess, Baker & Wilcox, 1999).

3.4.1 Proprioceptive and vestibular sensations

Vestibular and proprioceptive "self identification and location" is a major component in the perception of motion ([52],[53]Rosen, 2003a,b). It is therefore necessary to distinguish between the sensation of motion that is mediated by the proprioceptive and the vestibular sensors, and the visual perception of motion that is observed when the image is held steady on the retina and there exists relative motion between different parts of the image.

3.4.2 Motion of one part of the image relative to the other: Motion detected by the visual sensors

The visual system generates the sensation of motion when there is relative motion between parts of an image that is relatively stationary on the retina. In this case, two visual collective modalities may be operating simultaneously. A monochromatic high transient response modality, shown in Figure 3, may operate more effectively on the moving portion of the image[7]. On the other hand, the low transient response modality, shown in Figure 3, operates more effectively on the stationary part of the image since it integrates the successive output of 3-4 frame periods[8]. When these two modalities are super posed the total sensation is a high-resolution image for the relatively stationary part of the image, and a transient perception of motion (frame by frame) for the fast moving part of the image.

3.4.3 An Example of Saccadic Eye Movements: Motion Detected by the Somatic Sensors

In addition to frame-by-frame imaging the eye also detects proprioceptive position-motion. The proprioceptive sensors in the eye may detect quick rotations, called saccadic eye movements, to catch a new image of a fast moving target, at a predicted new site[9].

The Saccadic Motion Detection Mechanism: Rodieck ([44]1998) describes the biological saccadic and smooth muscular actions of the eyeball. Rodieck shows that it is the speed of the image, not the change in position that triggers the saccadic eye movement. With the image relatively steady on the retina, the only measurement that can be made on that image is a retinal speed assessment dx/dt (Where dx is so small that the image remains relatively steady on the retina). The organism, then by trail and error, learns instinctively to gauge, from the speed measurement of a fast moving object (dx/dt), the angular displacement of the saccade. It then generates a muscular pulse that quickly moves the eyeball through this angular displacement. If the speed assessment is correct, the line of sight will be at the final position of the fast moving object, and the object will be "seen" as a steady image on the retina.

The muscular proprioceptive sensors, the vestibular apparatus, and the retinal receptors mediate the sensation of motion associated with the vestibular/tactile/visual NCM. Conflicting data from the visual, proprioceptive, and vestibular sensors generally results in a sensation of disorientation dizziness, or "motion sickness".

3.5 A Philosophical Question: Does the electronic NCM-visual system experience a Wheatstone-type 3D-illusion?

The philosophical question posed by the authors: Does the visual NCM-system, described in the foregoing pages, "experience" a 3D-visual illusion similar to the illusion created by the 3D-Wheatstone stereoscope? ([48], [51] Rosen & Rosen, 2006c, 2007d)

3.5.1 The biological- NCM is a SgM whereas the Electronic –NCM may not be a SgM

The 3D-sensation is a subjective experience, an illusion of 3D-objects that is generated from the two 2D-images falling on the retinas of both eyes. The brain converts those 2-images into an illusion of 3D-objects that usually, but not always, are a high fidelity representation of the 3D-objects that gave rise to the two 2D-images[10].

3.5.2 The difference between the SgMs of the biological and electronic NCM

The NCM-system reverse engineers the modalities of the retinal receptors. With training, the electronic NCM-system obtains a form of "robotic knowledge" of the location of the visual objects with respect to the relative position of all body parts and all end joints, and learns to discriminate different objects, shapes, colors, and motions, the same as the biological visual system. In the biological system, but not necessarily in the electronic-NCM, the system that generates "biological self knowledge" is the Sensation-generating Mechanism (SgM) that generates the Wheatstone-type modality-sensation of a 3D-image of the objects in the 3d-space external to the controller. The reason that it does not follow that the electronic-NCM is a SgM is that the electronic form of "self knowledge" is a subset of the broad range of human data that may be used to define "biological self knowledge".

3.5.3 The electronic NCM generates a photometric 3D-image similar to the illusion experienced by humans

All data necessary to form the 3D-illusion is projected onto a 3D-coordinate frame within the controller, that is calibrated with the 3D-coordinates in which the robot is operating. Neurons that receive superposed-layered collective modalities in the cyclopean eye are properly indexed so that they may be simultaneously projected to disparity-selective neurons indexed to disparity-depth locations that are calibrated with the 3D-self location and identification coordinate frame. The indexed retinotopic depth-collective modality forms the Wheatstone-type 3D-illusion of the total FOV-space. Regardless of whether a 3D-sensation is experienced, a retinotopic depth collective modality has all the data necessary to generate a 3D-illusion (objects, obstacles, and flailing limbs located within the FOV) that is generally a high fidelity reproduction of the actual 3d-space in which the robot is operating.

3.5.4 Only the correlates of a subjective experience are amenable to measurement or detection.

In all medical and neuroscience textbooks, the modalities of tactile and visual receptors are defined in terms of the sensations evoked when receptors are activated. The law of specific nerve energy, or labeled line principle is generally invoked to explain the subjective experience sensation generated by the receptor. The visual receptors evoke sensations of color, shape and motion, whereas tactile receptors evoke sensations of touch-feel, flutter-feel, hot-cold feeling, and pain-pressure feeling. These sensations are subjective experiences that are unique to the subject, and the experience itself is not amenable to measurement or detection.

3.5.5 The closest that the authors can come to postulating that the electronic NCM is a SgM is as follows:

First, regardless of whether the electronic NCM-circuit is a SgM, images present in the FOV-coordinate frame of the NCM-robot may be detected, identified and discriminated as to depth, color, shape-form, and motion, and all sensory motor control functions are integrally related to the visual scene with a resolution determined by the resolution of the CCD-array.

Second, it is impossible to prove that the neuronal activity (and associated signal processing) of the biological NCM is a SgM without proving (or assuming) that a functional relationship or law such as the law of specific nerve energy that correlates subjective experiences with electronic neuronal activity (and associated signal processing) also applies to the biological NCM10 ([51] Rosen & Rosen, 2007d).

Third, it possible to perform psychophysical photometric experiments to determine the comparative degree that the electronic and biological NCM-systems discriminate between various colors, visual objects, and tactile touch, pressure pain.

Fourth, it may be philosophically significant that the multi-tasking robotic system operates as if it distinguishes (experiences?) different colors, shapes and obstacles, and responds to pressure, heat, cold, and pain, just like humans.

Fifth, it may be philosophically significant that the NCM- visual system is related to the long sought Neural Correlate of Consciousness (NCC) ([32]Metzinger, 2002) applied to the visual sensations-experiences experienced by verbalizing humans[10]?

NOTES

[1] Psychophysics is often regarded as a sub-discipline of psychology dealing with the relationship between physical stimuli and their subjective correlates. The modern study of sensation began in the 19th century with the pioneering work of E.H. Weber ([58]1846) and G. Fechner ([13]1860) in sensory psychophysics. Despite the diversity of sensations we experience, all sensory systems convey four basic types of information when stimulated, modality, location, intensity and timing. These four attributes of a stimulus yield sensation. An early insight into the neuronal basis of sensation came in 1826 when Johanne Müller advanced his “laws of specific sense energies.” The specificity of response in receptors underlies the “labeled line code,” the most important coding mechanism for stimulus modality ([17]Kandel et al, 2000).

[2] The subjective experience of “seeing” is a psychophysical phenomenon (The collective modality generates a 3-D sensation that Pinker ([38]1997) described as “the brain turns trigonometry into consciousness.”). The 3D-sensation is designed to be a hi-fidelity representation of the “real world objects” that gave rise to that sensation. For example, a colored spot of light in the 600 THz wavelength region, may activate a small scale collective of LM and S cone receptors. The modality of the small scale collective is the sensation of a color-hue between red and green. This sensation of the color-hue is a conscious experience that is quantitatively connected to the subject’s own photometric luminous efficiency function (determined by the photon catches in the 600 THz wavelength region and spectral sensitivities of the LM and S-cone receptors) and by the law of specific nerve energy. The importance of the law of specific nerve energy is that it generates a functional relationship between the conscious experience of the red-green color-hue, and the (photometric) physical signals that may be processed either by neural networks or sequential algorithmic programming of computers.

[3] The biological solution to an “ill-posed” problem: Constraint satisfaction in a biological system is implemented by constantly learning to calibrate the depth at a fixation point, with visual cues that determine the depth of region offset from the fixation point. Constraint satisfaction has been implemented in a constraint network designed for stereoscopic vision (Marr and Poggio, [29]1976, [30]1979). Some constraints listed by Marr ([27]1962), used to generate mathematical visual cues in a stereovision constraint network, are as follows: a) Stereopsis b) matter is cohesive and smooth. Neighboring patches of the world tend to lie on the same smooth surface. Or a LOS must end up on a surface in the world that is not drastically closer or further than the surface hit by a neighboring LOS, c) the LOS from one eye is assumed to end at a splotch on one, and only one, surface in the world (LOS of one eye should not end at two or more surfaces), d) the color-shape perceived by one eye should match the color-shape perceived by the other eye. The match-up has to represent a single position at a fixed distance. e) An object that is further appears smaller than the same object in placed at a nearer location. f) An object that obscures a portion of another object is nearer that the obscured object, etc.

[4] In the human brain there are multiple regions that exhibit retinotopic superposition, alignment, and correspondence of the right and left eye’s retinal images. For example, regions in the two LGNs and in various sections of the striate cortex. In this paper, the superposed outputs of the two CCD-arrays within the controller, is identified as the single cyclopean eye present in the system. Biological “cyclopean eyes” seem to be present in multiple regions of the brain. In the design of the reverse engineered visual system, it is noted that the number and location of cyclopean eyes are not physically significant parameters. Each cyclopean eye, regardless of its location, must maintain the retinotopic organization, alignment, and correspondence of the image planes shown in Figure 7.

[5] How are these frames of reference established? Comparison of biological and electronic NCM formation of coordinate frames: Kandel ([17]2000, p.498) gives a physiological answer to the question: “Some neurons in the parietal cortex have receptive fields that are modulated depending upon the position of the eye in the orbit. These neurons are therefore combining input from the retina with information about eye position-- “each time the eye moves, the head centered frame of reference must be updated” …Similar computations using head position information may be performed in the ventral premotor cortex and together with computations from the parietal cortex, they serve to establish a body centered coordinate frame of reference. The electronic-NCM sensory motor control system integrates all coordinate frames of reference into a single coordinate frame. In a functional sense, according to the design-development of the NCM-circuit, these frames are established as the robot learns self location and identification of all visual TT-patterns (different colored spots of light that activate (analogous to itch activation points) the modules of the NCM-sysem.

[6] In 1960 Hubel and Wiesel ([22]1962) discovered binocular summation within the striate cortex. Soon afterwards it was established that some of the straite cortical neurons posses receptive fields that are not in exact correspondence between the two eyes ([3]Barlow,1967; [5]Bishop, 1971; [35]Nikara, 1968). Some neurons respond best when an object is further than the binocular fixation point, others when it is nearer; Neurons with this type of receptive field are candidates for a physiological mechanism (physiological correspondence) that is responsible for binocular steriopsis.

[7] The high transient response modality may be analogous to the ganglion cells of the Magno-M collective (shown in the LGN layers in Figure 11), that operates more effectively on the moving portion of the image. The Magno-M collective modality is characterized by high temporal resolution (transient bursts) and low spatial resolution (large receptive fields) ([7]Casagrande & Xu. 2004). The M collective will therefore generate a image that varies its position on the retina on a frame by frame basis, and is more sensitive to internal motion but with lower spatial resolution.

[8] The low transient response modality may be analogous to the ganglion cells of the Parvo-Pc collective modality (shown in the LGN layers in Figure 11). This modality operates most effectively on the relatively stationary portion of the image. The Pc-collective modality is characterized by high spatial resolution (small receptive fields) and low temporal resolution, and a sustained discharge that may cover a few frame periods ([7]Casagrande & Xu, 2004; [4]Bear et al, 2001, p.293). The Parvo-Pc collective modality will thus generate a high-resolution color image of the stationary part of the image, since it can integrate the output of the ganglion cells over a few frame periods.

[9] In his first chapter of “The First Steps in Seeing”, R.W. Rodieck ([44]1998) points out that “What we see doesn’t move when we move our eyes”, “Saccadic and smooth eye movements are used to catch and hold images”, “the image of the visual world is always moving on the retina”, and “image motion elicits smooth pursuit” wherein it is the velocity (not position of the image on the retina), that initiates the smooth eye movement. As a consequence, during saccadic eye movement, the metaphor of the eye as a motion picture camera breaks down. Saccadic and smooth eye movements are used to catch and hold images steady on the retina when an animal is in vigorous motion, as during swift pursuit ([44]Rodieck, 1998 p.8 vision is dynamic). A series of saccades yields a series of steady state images (between each saccade). During each of the steady states (while the body and head is in motion) the convergence and focus of both eyes is directed on any object located along the FOV-centerline thus forming a streaming 3-dimensional image of the object that is a high fidelity representation of the moving object in the real world. Rodieck ([44]1998) points out that the mounting of the eyeball in the eye socket is the key factor in generating a relatively stationary and discernable image on the retina. To obtain a steady discernable image during bumpy/jerky motion it is necessary to reverse engineer the biological mounting of the eye in the eye socket. The eye’s saccadic and smooth eye movements that are used to catch and hold images in the center of the screen facilitate such a mounting. Thus the sensation of motion depends not only on the relative motion of an object on the retinal surface, but on the muscular activation of saccadic and smooth eye movements, head movements, and body motion that is required to hold the image on the retina (and thereby assure a high fidelity solution to the correspondence problem).

[10] The biological NCM-system is the equivalent to the Neural Correlate of

Consciousness (NCC)-circuit for visual perception. The question, "is there a Neural Correlate of Consciousness (NCC) in the brain ([32]Metzinger, 2002), has an answer. The existence of correlated subjective experiences is a fundamental observation in the field of psychophysics that gives rise to a "law" of neuroscience, the law of specific nerve energy (or the labeled line principle). Since "consciousness" is a subjective experience, the authors propose that the law of specific nerve energy, that couples subjective experiences with neuronal activity, may be the first step towards the study of the NCC (Rosen & Rosen, [51]2006c, [48]2007d).

REFERENCES

[1] Andrews, T. J., Glennerster, A. & Parker, A. J. (2001) Stereoacuity thresholds in the presence of a reference surface. Vis. Res., 41:3051-3061

[2] Backus, B. T. Fleet, T. D., Parker, A. J. & Heeger, D. J. (2001) Human cortical activity correlates with stereoscopic depth perception. J. Neurophysiol, 86:2054-2063

[3] Barlow, H. B., Blackmore, C. & Pettigrew, J. D. (1967) The neural mechanism of binocular depth discrimination. J. Physiol. (London) 193: 327-342

[4] Bear M. F., Convers, B. W., Paradiso, M. A. (2001) Neuroscience 2nd ed. Baltimore Md: Lippincott Williams & Wilkins

[5] Bishop, P. O., Henry, G. H., & Smith, T. J. (1971). Binocular interaction fields of single units in the cat striate cortex. J physiol. 216:39-68

[6] Brown, P. B. (2002) The electrochemical Basis of Neuronal Integration, Chapter 3, p 46-7 In Haines (2002).

[7] Casagrande, V. A. & Xu, X. (2004) Parallel visual pathway: A comparative perspective, in Chalupa and Werner (eds), (2004) pp.495-506.

[8] Chalupa L.M., & J.S. Werner (eds), (2004) The Visual Neurosciences Vol 1 and 2, MIT Press: Cambridge Mass

[9] Cumming, B. G. & DeAngelis, G. C. (2001) The physiology of stereopsis. Annu. Rev. lNeurosci. 24e:203-238.

[10] DeValois R. L. (2004) Neural coding of colors. (p. 1003) in Chalupa and Werner (2004).

[11] DeValois R. L., & DeValois, K.K. (1988) Spatial Vision. New York: Oxford Univ. Press

[12] Eifuku, S. & Wurtz, R. H. (1999) Response to Motion in extrastriate area MSTI: Disparity sensirtivity. J. Neurophysiol 82: 2463-2475

[13] Fechner, G. (1860) 1966. Elements of Psychophysics, Vol 1. DH Howes, E.G. Boring (eds), H. E . Adler (trans) New York: Holt, Rinehart and Winston

[14] Gazzaniga M. S., Ivry R.B. & Mangun, G.M. (2002) Cognitive Neuroscience New York: W.W. Norton and Co

[15] Grossberg, S (2004) Visual Boundaries and Surfaces (p. 1624-1639). in Chalupa and Werner (2004)

[16] Guyton, A. C. (1991) Textbook of Medical Physiology. Philadelphia: W.B. Saunders Co.

[17] Kandel E. R., Schwarts J. H. and Jessell T. M. (eds) (2000) Principles of Neural Science. N.Y: McGraw Hill

[18] Haines D.E. (ed) (2002) Fundamental Neuroscience 2nd ed. Churchill Livingston: Philadelphia PA

[19] Hess, R. F., Baker, Jr., & Wilcox, L. M. (1999), Comparison of Motion and Stereopsis: Linear and Nonlinear Performance. J. Opt. Soc. Am. A 987-994

[20] Hess, R. F. (2004), Spatial scale in Visual Processing (p. 1043) in Chalupa and Werner (2004)

[21] Hubel, D. H., and T. N. Wiesel, (1959). Receptive fields of single Neurons in the Cat's striate Cortex. J. Physiol. (Lond), 148: 574-591

[22] Hubel, D. H., and T. N. Wiesel, 1962. Receptive fields binocular Interaction and functional architecture in the cat's visual cortex. J. Physiol. (Lond), 160:106-154.

[23] Hubel, D. H., and T. N. Wiesel, 1968. Receptive fields and functional architecture of monkey striate cortex. J. Physiol. (Lond), 195:215-243

[24] Hubel, D. H., and T. N. Wiesel, 1998. Early exploration of the Visual Cortex. Neuron, 20: 401-412

[25] Julesz Bela (1971): Foundation of Cyclopean Perception. Chicago Univ, Press.

[26] Knobblouch, K. W. & Shevell S.K. (2004) Color Appearance in Chalupa and Werner (2004)

[27] Marr, D. (1962) Vision. San Francisco: W.H. Freeman

[28] Livingston, M. S., & Hubel, D. H. (1988) Segregation of form, color, movement and depth. Science 240:740-749

[29] Marr, D. & Poggio T. (1976) Cooperative Computation of Stereo Disparity. Science 194; 263-287.

[30] Marr, D. & Poggio T. (1979) A computational theory of human stereo vision, Proc. R. Soc. Lond. B 204:301-328

[31] Mays, L. E., (2004). Neural Control of Vergence Eye Movement in Chalupa and Werner (2004)

[32] Metzinger, T. (2002) Neural Correlates of Consciousness. Cambridge: MIT Press

[33] Mounsell, J. H., &^ Van Essen, D. C. (1983) Functional properties of neurons in middle temporal visual area of the macaquemonkey 2: Binocular interasctions and sensitivity to binocular disparity. J. Neurophysiol. 49:1148-1167

[34] Müller, J. (1826) 1833-1840. Handbuch der physiologie des Menchen für Vorlesungen, 2 vols. Coblenz: Holscher

[35] Nikara, T., Bishop, P. O., and Pettigrew, J. D. (1968). Analysis of retinal correspondence by studying receptive fields of binocular single units in cat striate cortex. Exp. Brain Res. 6:353-372

[36] Olshausen, B. A., (2004) Principle of Image Representation in the Visual Cortex. (p. 16030 in Chalupa and Werner (2004)

[37] Parker A. J. (2004) From binocular disparity to the perception of stereoscopic depth (p.779) in Chalupa and Werner (2004)

[38] Pinker, S. (1997) How the Mind Works, New York: WW Norton & Co

[39] Prince, S. J. Pointon, A. D., Cumming, B. G. & Parker, A. J. (2000) The precision of a single neuron responses in cortical area V1 during streoscopic depth judgements. J. Neurosci, 20:3387-3400.

[40] Rashbass, C. & Westheimer, G. (1961). Independence of conjugate and disjunctive eye movements. J. Physiol. (London) 159:361-364

[41] Reid, R. C. & Ursey, M. W. (2004) Functional connectivity in the pathways from retina to the striate cortex. (p.673) in Chalupa and Werner (2004)

[42] Redlake Inc. (2003) High-resolution MegaPlus Cameras. Internal Corporate publication, available for viewing at www.redlake.com/high_res/tech_articles/

[43] Reisenhuber M., and Pogio T. (2004). How the Visual Cortex Recognizes Objects: The tale of the Standard model. (p. 1640) in Chalupa and Werner (2004)

[44] Rodieck R.W. (1998) The first step in seeing Sunderland, Mass: sinauer Assoc. (p.299- Trichromacy theory)

[45] Rosen A., & Rosen D. B. (2007a). Sensorimotor Control by Reverse Engineering the Biological Modalities. Submitted for publication in the Neural Network Journal of the INNS.(may be previewed at www.mocon.org)

[46] Rosen, A. & Rosen, D. B. (2007b) A Robotic Optical Circuit that that generates a 3D-visual image: Solution to the inverse optics problem for robotic visual seeing by reverse engineering the neuro-

physiology of the modalities of the retinal receptors. IJCNN-2007 ieeexplore/servlet/opac

[47] Rosen, D. B. & Rosen, A. (2007c) A robotic neural net based visual sensory motor control system that reverse engineers the motor control functions of the human Brain. IJCNN-2007 ieeexplore/servlet/opac

[48] Rosen, A. & Rosen, D. B. (2007d) The Turing Machine Revisited: The computational clomplexity of a visually conscious machine. Does a Conscious machine exist? Presented at ASSC-2007 Las Vegas, and published at ASSC e-archive.

[49] Rosen, A., & Rosen, D. B. (2006a) A Neural Network Model of the Connectivity of the Biological Somatic Sensors. Neural Networks, IJCNN'06: (ISBN: 0-7803-9490-9 pp 299-306)

[50] Rosen, A., & Rosen, D. B. (2006b) An Electromechanical Neural Network Robotic Model of the Human Body and Brain: Proceedings of the ICONIP- 2006 Hong Kong; King et al (Eds) LNCS Part 1 pp. 105-116, Berlin Heidelberg: Springer-Verlag.

[51] Rosen, A., & Rosen, D. B. (2006c). The Design of a Sensation-generating Mechanism in the Brain: A first step towards a quantitative definition of consciousness. ASSC e-archive.

[52] Rosen D.B., & Rosen, A (2003a) The Design of a Volitional, Obstacle Avoiding Multi-tasking Robot. Machine Consciousness Technical Journal. 1:41-56

[53] Rosen, A., & Rosen, D. B. (2003b) The Design of an NCC circuit for Visual Perception. Machine Consciousness Technical Journal. 1:19-40

[54] Schor, C. M. (2004) Stereopsis (p1700)). in Chalupa and Werner (2004)

[55] Scientific Imaging technologies Inc (1994) An Introduction to scientific Imaging Charge-Coupled Devices. Internal corporate publication, available at www.site-inc.com

[56] Sterling, P. (2004) How retinal circuits optimize the transfer of visual information (p.234). in Chalupa and Werner (2004)

[57] Thomas, O. M. Cummings, B. G., & Parker, A. J. (2002). A specialization for relative disparity in V2. Nat. Neurosci. 5:472-477.

[58] Weber, E. H. (1846). Der Tastsinn und das Gemeingefühl. In: R Wagner (ed) Handwörterbuch der Physiologie, Vol 3, Part 2 pp 481-588, 709-728 Braunschweig: Vieweg

[59] Westheimer, G. (1979) Cooperative neural processes involved in stereo acuity. Exp. Brain Res. 36:585-597

[60] Wheatstone Charles (1838) On binocular vision: and on the stereoscope, an instrument for illustrating its phenomena. Report to the Brittish Association for the Advancement of Science Pt. 2 pp. 16-17. Also in Bibliotheque Universelle de Geneve, 17: 174-175.

[61] Wheatstone Charles (1852) Contributions to the physiology of vision part the second. On some remarkable and hitherto un-observed phenomena of binocular vision. Philosophical Transactions of the Royal Society of London. See also The Philosophical Magazine. 3: 241-267, and pp 504- 523.