Seeing With One Eye

A brief summary of adaptation to the loss of one eye
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(2020)

Esther G González, PhD
Department of Ophthalmology and Vision Sciences
University of Toronto
esther.gonzalez@utoronto.ca

Contents

Introduction

Research into the visual adaptation to monocularity started in the 1980's in the laboratory of Dr. Martin Steinbach at the Hospital for Sick Children and then continued at York University and the Toronto Western Hospital, among other institutions. The effects of low vision in one of the two eyes had been explored before and continues to be in many centres around the world, but the Steinbach laboratory's research was directed at true monocularity; that is, at seeing with one eye. The initial question was simple: after the loss of one eye, does the other eye suffer, remain as it was, or does it improve? If the brain makes use of ("recruits") the resources allocated to the removed eye, we would expect an overall improvement of visual function in the remaining eye. On the other hand, if the brain, being designed to control and analyze the information provided by two eyes, is handicapped by the loss of one, we would expect the opposite. The answer, like many other things in science, was very complex. In a nutshell, it was found that while some functions improve, others remain unchanged, and still others are diminished. Throughout, however, the research found that the capacity for adaptation of the human brain—also known as plasticity—is such, that the deficits, when found, are relatively minor, that other sensory modalities such as hearing are also improved and that the brain undergoes changes whose function we have yet to discover. Overall, this research has given us valuable insights into the workings of human vision in particular and the human brain in general.

What follows is a selective, non-technical summary of the close to 40 scientific papers dedicated to the topic of seeing with one eye with an emphasis on issues that parents and patients affected by retinoblastoma may find informative.[1,2,3] A bibliography at the end of this document lists some publications for those who would like to examine these themes in more depth as well as some useful resources. The first part of this document, The Human Eye, describes the main structures of the eye and the second, Binocular Vision and Adaptation to Binocularity summarizes what we know about seeing with one eye.

Part I: The Human Eye

Seeing, like all our other senses, appears effortless and direct; but the more we learn about it, the more we appreciate that seeing is anything but a simple process. Over 32 areas of the brain have been shown to take part in the process of vision.

The human eye is a complex organ. Its main function is to transform light into the electrical signals that the brain uses, but also to begin their analysis, and this is why the eye is considered to be the beginning of the brain. Another function of the eye is to feed information to the system that coordinates our periods of sleep and wakefulness called *circadian rhythms*, as well as the control of other reflexes such as the *pupillary light reflex*. What follows is a brief description of the most important structures of the eye.

Cornea

Starting from the front, we first encounter the ***cornea***, a transparent layer that is better appreciated from the side, as in Figure 1.1. The cornea is the most powerful lens of the eye which means that light is more bent by it than by any other structure. Figure 1.2 shows the same structures of the eye as viewed from the front.

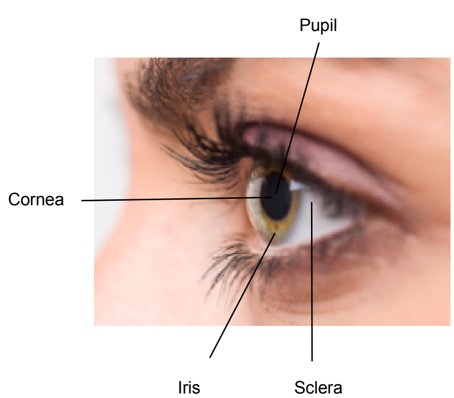


Figure 1.1. Side view of the eye.

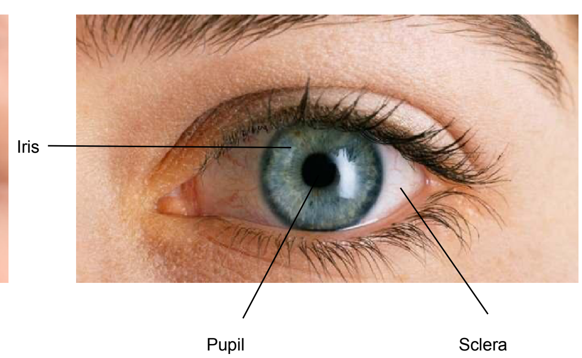


Figure 1.2. Front view of the eye.

Iris

The ***iris*** is the coloured part of the eye. Its tissue is pleated like the bellows of an accordion with an aperture in the centre called the ***pupil***.

Pupil

The pupil's size changes with the amount of light that enters the eye, like the diaphragm of a camera. A small or contracted pupil protects the rest of the eye in bright light, and a large or dilated pupil allows as much light as possible in darkness. These reflexive responses are known as the *pupillary light reflex*.

When seen straight ahead, the colour of the pupil is black, but under certain conditions it can also be red. This "red eye" is produced by the camera's flashlight reflecting the colour of the retina and it is easily corrected by most smart phones and electronic cameras. A white pupillary reflex or Leukocoria, on the other hand, is an abnormal white reflection from the retina and is an indication of a serious medical condition such as retinoblastoma. Leukocoria may appear also in low indirect light (Figure 1.3).

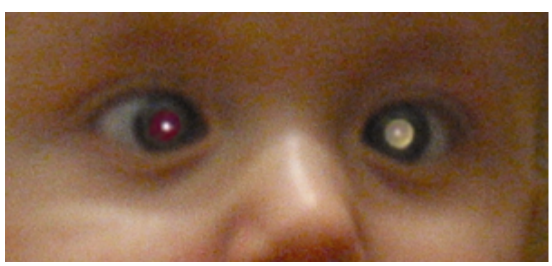


Figure 1.3. Leukocoria in the left eye and "red eye" in the right eye.

Lens

After the iris comes the ***lens*** whose shape changes when we focus near or far, becoming rounder or flatter as part of the process called *accommodation*. In this way the lens helps to focus light on the retina which is the innermost layer at the back of the eye. With age or disease, the lens can become hard and opaque reducing the quality of vision. This "cataract" can be removed by surgery and a new plastic lens inserted in its place.

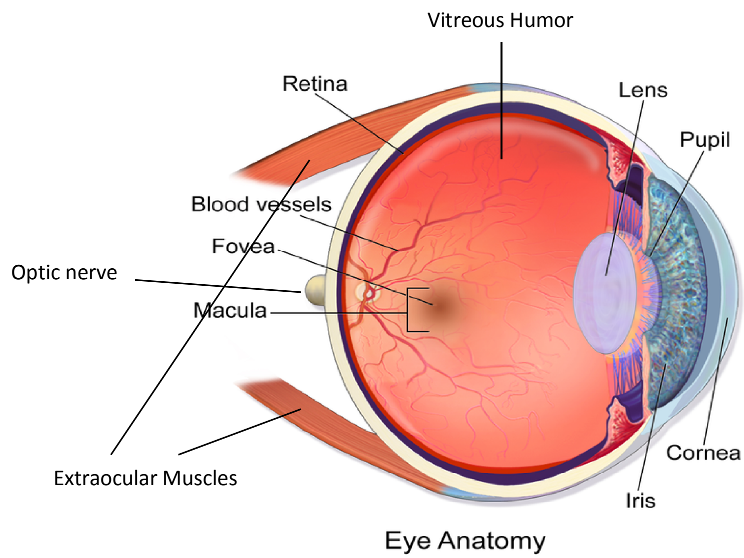


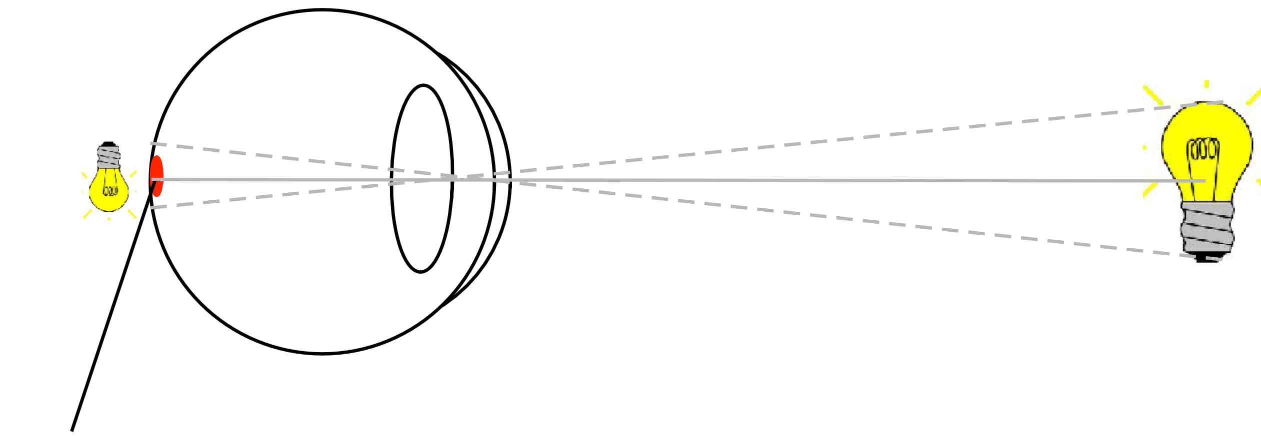
Figure 1.4. A cross section diagram of the most important structures of the human eye. Note the location of the optic nerve and two of the six extraocular muscles.

Vitreous Humor

The ***vitreous humor*** is a transparent, colourless, gelatinous mass that fills the space between the lens and the retina. It helps keep the retina in its place.

Retina

The ***retina*** is the innermost layer of the eye on which the optics create a two-dimensional image of the world (see Figure 1.5). The retina translates that image into electrical neural impulses that are sent to the brain in order to create visual perception, but the job of the retina is more than that of the film or the image sensor of a camera because



visual processing begins here.

Figure 1.5. Image of an object on the retina. Note the inversion of the visual target.

There are two kinds of light-sensing cells or photoreceptors in the retina: rods and cones. Rods function mainly in dim light and provide mostly black-and-white vision. Cones function in well-lit conditions and are responsible for the perception of colour, as well as the high-acuity vision we need for tasks such as reading. Cones are tightly packed in the central area of the retina which is called the ***macula*** and in its centre, the ***fovea***, rods are virtually absent. The peripheral area surrounding the macula provides progressively lower resolution information.

A third type of light-sensing cell, the photosensitive ganglion cell, is important for the control of *circadian rhythms* and of reflexes such as the *pupillary light reflex*. The neural signals from the rods and cones are processed by other neurons and converge in retinal ganglion cells whose axons, like a fiber optic cable, form the optic nerve that conducts the visual impulses from the retina to the brain. Approximately half of the nerve fibers in the optic nerve carry information from the fovea, while the remaining half carry information from the periphery of the retina.

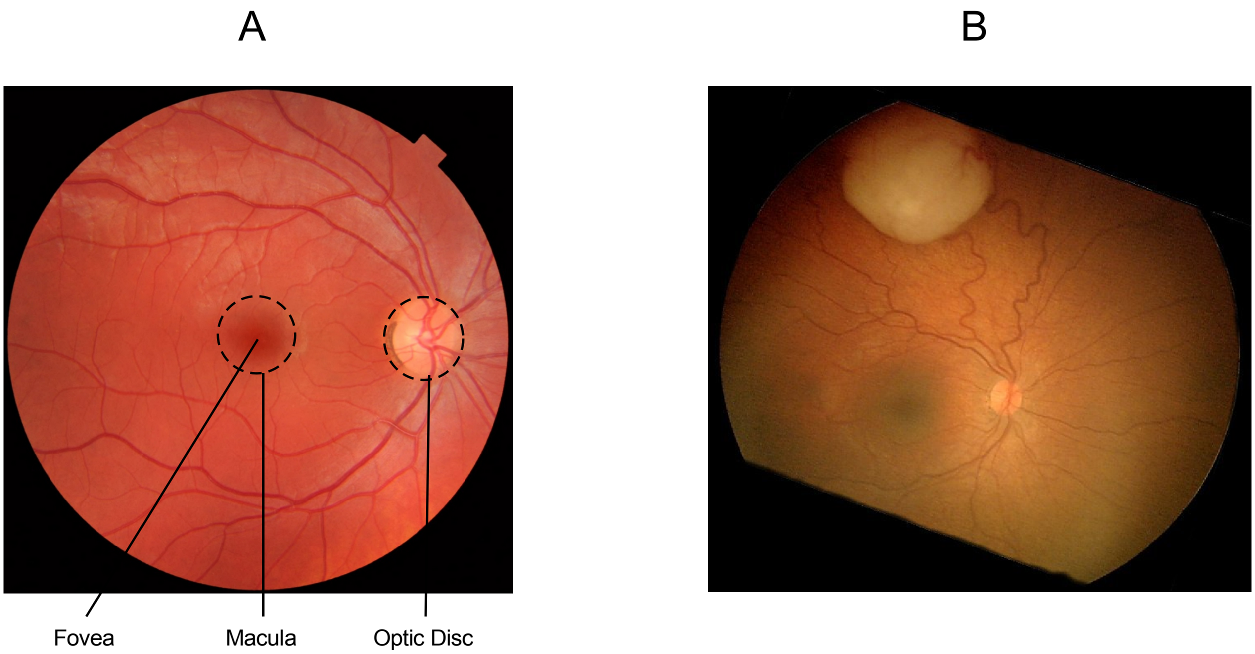


Figure 1.6. (A) The normal retina of a right eye as seen straight ahead. (B) The retina of a right eye with a retinoblastoma tumor in the periphery.

Optic Disc

The ***optic disc*** is the point where the ganglion cell's axons exit the eye. There are no rods or cones in this area which creates a small blind area in each eye. Normally we are not aware of this blind spot because the brain has a mechanism by which the missing information is filled-in with visual information from the surrounding area. Various kinds of treatments can damage some photoreceptors and create blind spots on the retina. Just like at the optic disc, the brain fills-in the missing information. Figure 1.7 is a demonstration of the normal blind spot.

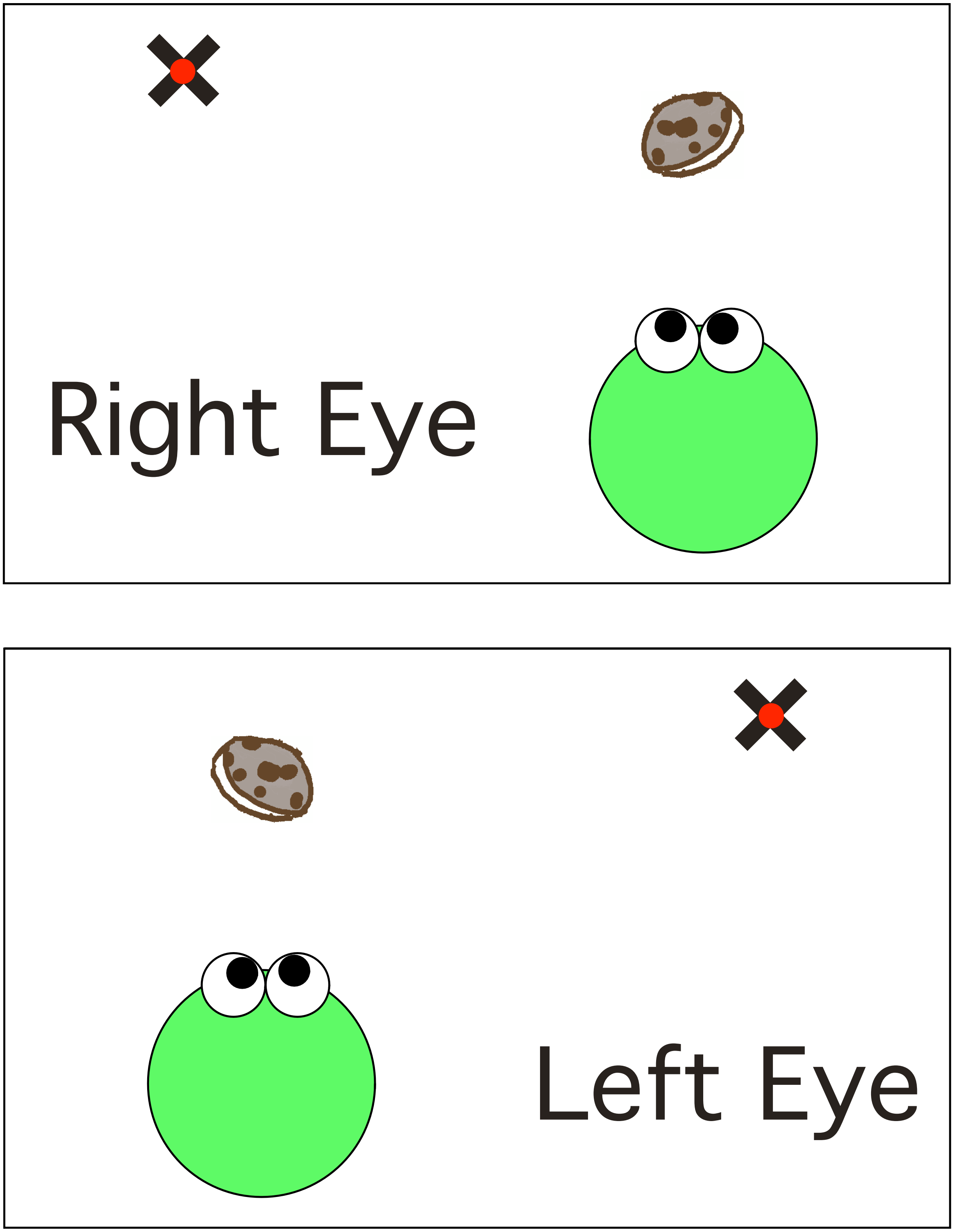


Figure 1.7. Demonstration of the blind spot. First, select the panel corresponding to the eye that you will be using, then cover the other

with a piece of paper. Look at the panel from a distance of about 20 cm and fixate on the red dot inside the cross. Then slowly move away from the picture and you will notice that the cookie will disappear, and then reappear as you keep moving away. The green character and the name of the eye will not disappear. Moving back and forth makes the cookie disappear when its image falls on you blind spot and reappear when it falls away from the blind spot.

Part II: Adaptation to Monocularity

As mentioned in the Introduction, the question of how the visual system adapts to monocularity is not a simple one. We have evidence that, for certain visual functions, the brain appears to recruit the resources that were to be allocated to the removed eye, assigns them to the remaining eye making it a "super" eye.[1-3] On the other hand, some functions that require binocular vision for their development from childhood are diminished, but the capacity for adaptation, or plasticity of the human brain makes these deficits relatively small and most can be overcome by learning. We also found plasticity changes in the brain whose function we have yet to discover.

I will concentrate this discussion around topics of monocular vision of interest to parents and survivors and will end with a brief discussion of the brain plasticity that has been documented after the loss of one eye.

Seeing Fine and Faint Details (acuity and contrast sensitivity)

Visual acuity is the ability to perceive fine details and ***contrast sensitivity*** is the ability to perceive faint details. Acuity is usually measured with charts that have high contrast (black letters) or low contrast (grey letters). The visual acuity and contrast sensitivity of people who have only one eye are enhanced compared to two-eyed controls.[4-8] For spatial vision, in other words, enucleated observers have compensated for the loss of binocularity.[9-12]

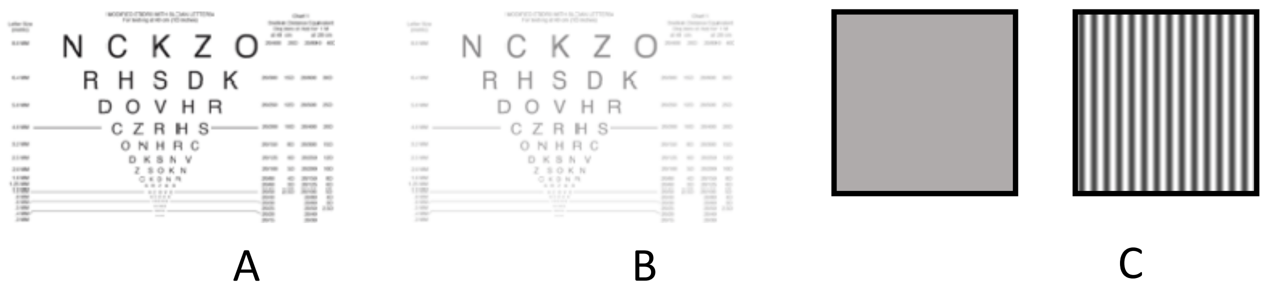


Figure 2.1. Primary measures of spatial vision: acuity tests in high and low contrast (Panels A and B), and a contrast sensitivity test (Panel C). When the lines become invisible (i.e., they are below threshold), it is not possible to determine which is the square with the lines.

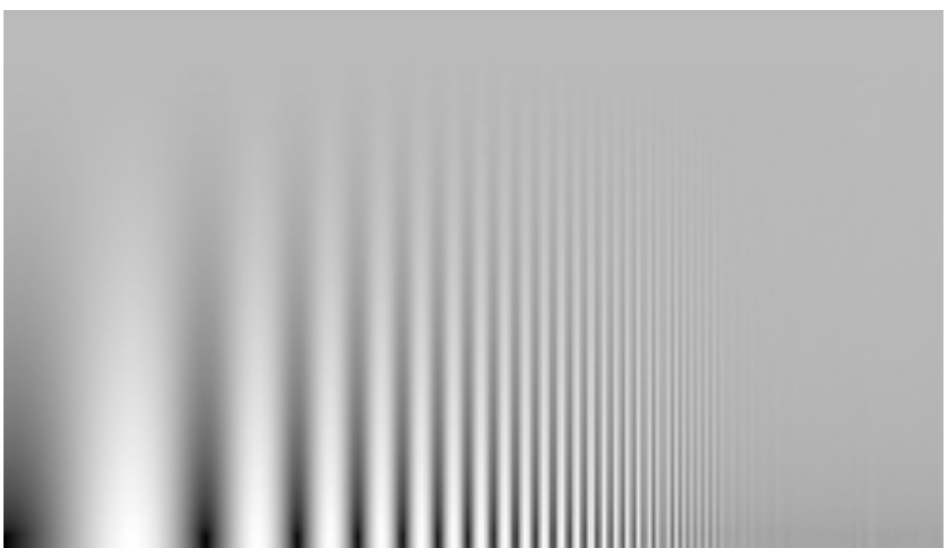


Figure 2.2. This is a diagram of what is known as a *contrast sensitivity function*. Note that you can see the lines with medium thickness better than the very fine ones which means that small objects require more contrast in order to be seen. Surprisingly, the lines with medium thickness require less contrast than the very wide lines.

Because acuity and colour are best at the fovea, retinal treatments try to avoid this area. Figure 2.3 is a demonstration of how visual acuity decreases with a target's distance from the fovea.

Figure 2.3. This figure illustrates how, in order to identify all the letters equally well while fixating in the centre, they have to increase in size as the distance from the centre increases. In other words, while fixating steadily on the red dot, all the letters are equally legible. This demonstration has to be viewed with one eye.

Seeing Clearly in Depth (depth of field)

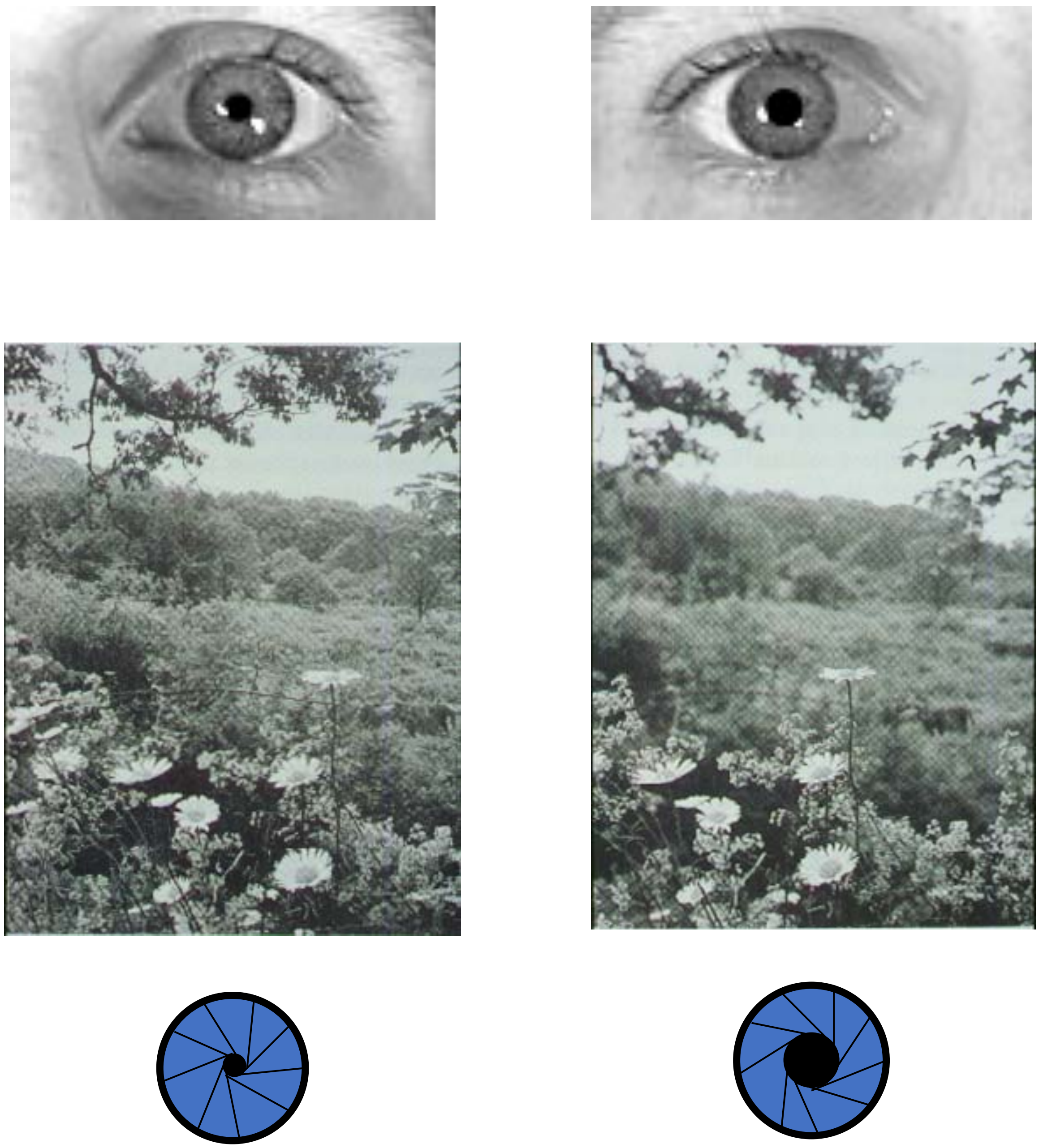


Figure 2.4. The eye on the left shows a smaller pupil and a larger depth of field than the eye on the right. Note how the picture on the right appears fuzzier than the one on the left. The cartoons below show the pupil as the diaphragm of a reflex camera.

Photographers have to take into account the ***depth of field*** when taking pictures. The depth of field refers to the sharpness of objects in the scene and it depends on how much light is allowed into the camera. The visual system of people with one eye produces a smaller pupil, or ***miosis***, which produces a larger depth of field and reduces distortions allowing them to see better with the remaining eye. Provided there is enough light, this is another adaptation to monocularity.[13]

Depth Perception (the 3-dimensional world)

Like all predators, human have frontal eyes and excellent depth perception. The brain's task is to transform the two-dimensional flat images produced in each eye into a perception of our three-dimensional world. Stereoscopic vision, (the word "stereo", from the Greek στερεός, means solid) is accomplished by the brain by using many different types of information in the environment. These are called *depth cues*.

Depth cues can be come from one or the two eyes. Monocular, or cues that require only one eye, include perspective, objects partially obstructing other objects, the relative and familiar sizes of things, shading, textures, blur, etc., but one of the most powerful monocular cues for depth is ***motion parallax***.

Of the binocular cues, the most important cue for depth is called ***disparity***, and comes from the fact that the two eyes occupy different places on the head and get slightly different images of the world. The brain combines these two flat images and creates a solid 3D percept. This is behind popular entertainments such 3-D movies and stereoscopic photos (Figure 2.5). By definition, monocular people do not have binocular disparity, but they can use ***motion parallax*** instead.

Figure 2.5 Antique Holmes stereoscope.

Motion parallax is produced by the lateral movement of a person while she/he fixates on an object (e.g., the red crayon 🖍 in Figure 2.6). Objects nearer than the fixation point (e.g., the hand 👍) will have relative motion in the opposite direction (leftward) to the observer's movement. Objects away from the point of fixation (e.g., the book📖) will move in the same direction as the observer (rightward). Because the observer is fixating on the crayon, it looks shaper, while the hand and the book are blurry or not accommodated. The brain computes all these relative motions without us being aware of how this is done.

The information that motion parallax provides to the brain is geometrically equivalent to disparity. Young enucleated children do not normally use motion parallax to determine depth but they eventually learn to do so as they grow up.[14-15] This learning can be accelerated by parents who can teach their children to move their head up, down and laterally when going down steps, picking up something, pouring a glass of water, etc. Immediately after they are taught to move their head, monocular children become just as good as children with two eyes at estimating depth.[14] The movements of the head do not need to be very large to be useful.[14-16]

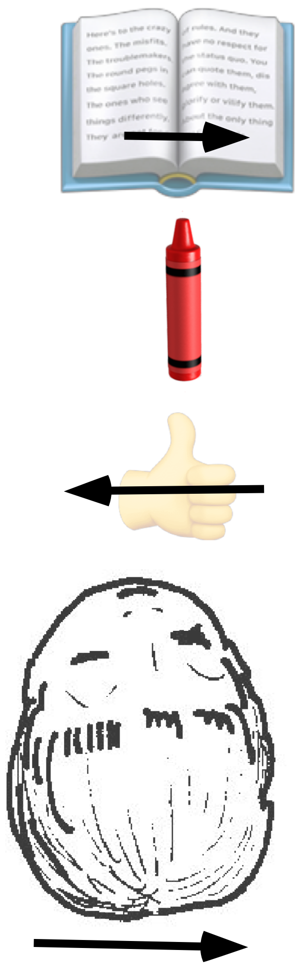


Figure 2.6. Demonstration of motion parallax. The observer is viewing with the right eye and fixating on the red crayon.

Figure 2.7. Owls, like humans, use motion parallax and disparity as cues for depth. Even young owls move the head from side to side and up and down in order to judge distance.[17-18]

Field of view (the observable world from a single eye)

When a person views the world with one eye rather than two, they lose about a ¼ of the field of view in front of them. This limitation is not too large because we humans move the eyes with great accuracy and speed which, combined with the movements of the head, allow a monocular person to cover the field of view of the missing eye and perform tasks such as driving with only a bit of extra training and care.

Figure 2.8. Ernst Mach's 1886 depiction of his right field of view. He drew his eyebrow, nose, and moustache, respectively, in order to show the top, left and bottom limits.

Perceiving the Direction of Things

We have two eyes yet experience a singular view of the world as if we had one single eye in the centre of the forehead. We use our midline as the origin from which we judge the direction of things in space,[19] but what does the one-eyed observer experience, since the viewing eye is displaced laterally with respect to the midline? One-eyed children align objects not at, but close to the location of the remaining eye.[20] This creates a conflict in that their centre of visual direction does not correspond to their midline and explains some of the difficulties that some have when blowing birthday candles, going through doors and bumping on the frames, or centering a car on a lane when learning to drive. One coping strategy for some is to turn the head.[21-22]

Knowing the source of these difficulties will help parents to facilitate adaptation. In fact, in some aligning tasks one-eyed adults can be more accurate than people with binocular vision.[23]

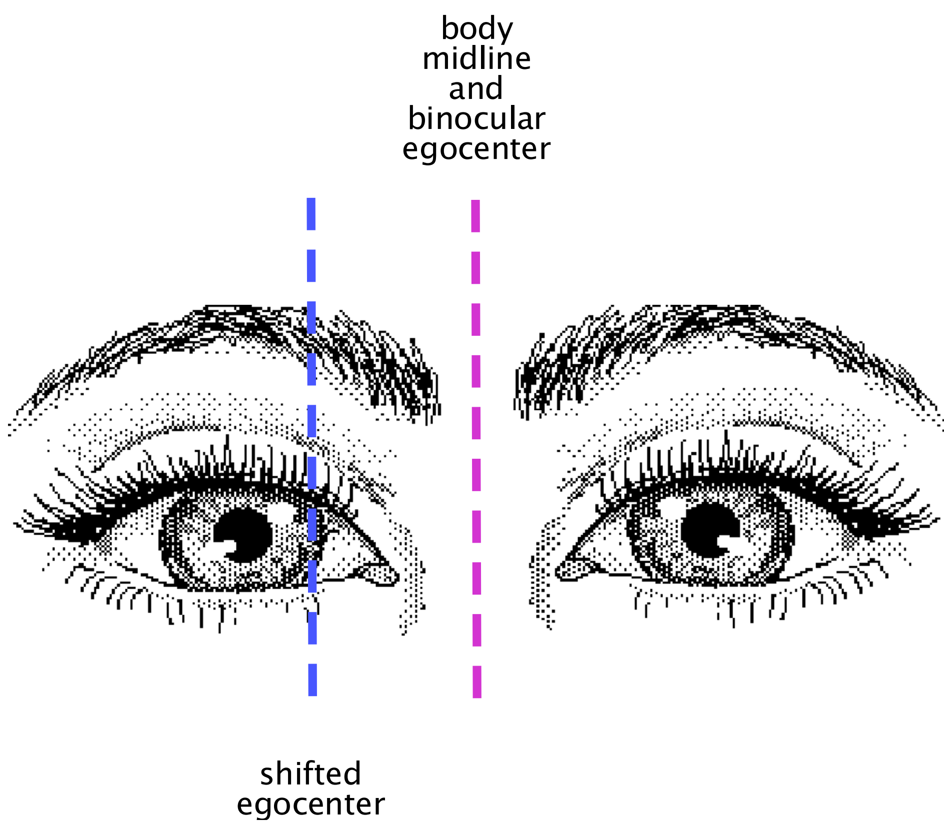


Figure 2.9. On average, the centre of visual direction of children with one eye shifts 70% toward the viewing eye; in this case, the right eye.

Motion and Face Perception

Certain visual function such as the perception of motion[24-29] and faces[30-31] require binocular vision for their normal development and one-eyed people perform less well than binocular people. These deficits, however, have been shown to be small.

Movements of the Eyes

The human brain is designed to receive information from and to control the movements of two eyes. For this, it controls 6 pairs of extraocular muscles with great accuracy, so that the image of the targets we fixate on fall on the fovea, a dip in the inner retinal surface, only 1.5 mm wide (Figure 2.10). Studies of the movements of the eyes have found no deficits in people with one eye.[26,32-33]

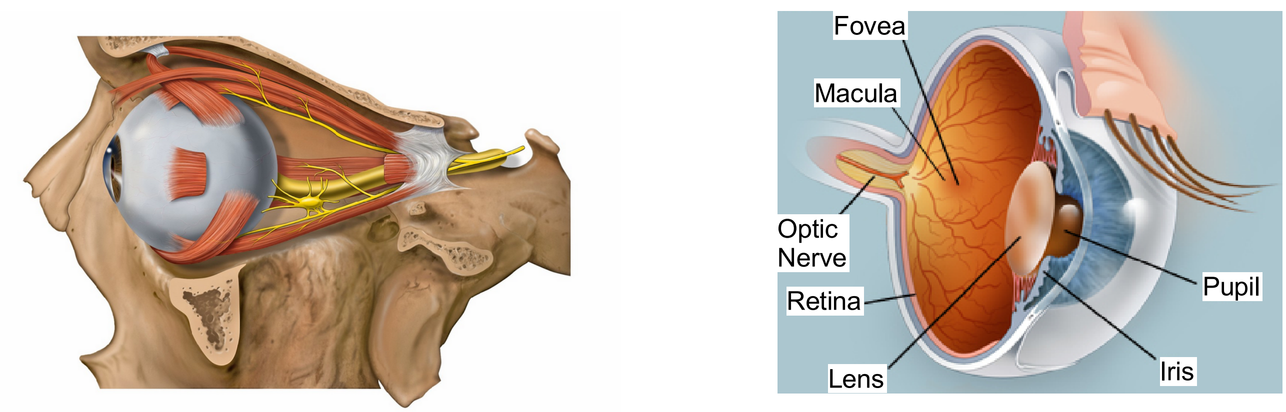


Figure 2.10. The six extraocular muscles and cross section of the eye indicating the fovea.

Multisensory Adaptation

The brain itself is not mature at birth and the parts that allow for vision are still developing and maturing even past adolescence. An important question is then, what happens to the brain cells in the visual parts of the brain that they should have been receiving signals from the eye that was removed? We already know that some are they recruited by the remaining eye, but what about other senses?[34-35]

As noted above, some visual functions are enhanced in one-eyed people. Recent data have shown that people with one eye also have enhanced sound localization and are less susceptible to some auditory illusions.[36-37] The partial vision loss from early monocular enucleation results in changes in the brain that extend into the auditory system.

High resolution images of the brain have found that some of the parts of the brain dedicated to vision are actually bigger than they should be given that they have only one eye.[38] Enucleation produces white matter changes throughout the visual system that we cannot yet relate to changes in vision or other sensory functions, so more research is needed.[34,38]

Acknowledgments

None of this research would have been possible without the retinoblastoma survivors and their families. There could not have been a better group of partners in this enterprise. After the Ocular Motor Laboratory moved from SickKids to the Toronto Western Hospital and the Steeves laboratory was established at York University, they agreed to make the journey, some coming from quite far. It was not because of an interest in the minimal tokens of appreciation—a small toy or parking money that we were almost embarrassed to provide—but because of the enthusiastic desire to participate in the journey of science which, for most, would likely not bear a useful or immediate fruit. Gratitude was also behind all to this because our collaborator in this programme was Brenda Gallie. Without her help and support nothing could have taken place. All of us, scientists and participants, are deeply indebted to her.

Finally, I am particularly grateful to Linda Lillakas, Jennifer Steeves and Luminita Tarita Nistor for their comments and help with this review.

Esther G González.

Credits

Part I:

Figure 1.1: https://yoursightmatters.com/women-eye-side-view/

Figure 1.2: https://www.thehealthsite.com/diseases-conditions/top-8-interesting-facts-about-the-human-eye-179180/

Figure 1.3: Leucokoria: By J Morley-Smith (talk) - Own work, Public Domain,
https://commons.wikimedia.org/w/index.php?curid=6463697

Figure 1.4: Blausen.com staff (2014). "Medical gallery of Blausen Medical 2014". WikiJournal of Medicine 1 (2). DOI:10.15347/wjm/2014.010. ISSN 2002-4436., CC BY 3.0,
https://commons.wikimedia.org/w/index.php?curid=29025015

Figure 1.5: Esther G González.

Figure 1.6: (A) Häggström, Mikael (2014). "Medical gallery of Mikael Häggström 2014". WikiJournal of Medicine 1 (2). DOI:10.15347/wjm/2014.008. ISSN 2002-4436. Public Domain.or by Mikael Häggström, used with permission. - Own work, CC0,
https://commons.wikimedia.org/w/index.php?curid=18776091

(B) Tero Kivelä - Meilahti Hospital, Department of Ophthalmology, CC BY 2.5, https://commons.wikimedia.org/w/index.php?curid=3187806

Figure 1.7: Esther G González.

Part II:

Figure 2.1: Esther G González.

Figure 2.2: Esther G González.

Figure 2.3: Modified from http://anstislab.ucsd.edu/2012/11/20/peripheral-acuity/

Figure 2.4. Esther G González.

Figure 2.5: Antique Holmes stereoscope. By Davepape, Public Domain, https://commons.wikimedia.org/w/index.php?curid=961098

Figure 2.6: Esther G González.

Figure 2.7: Esther G González.
Figure 2.8: Figure modified from Ernst Mach's 1886 depiction of his left visual field. Mach E. [The Analysis of Sensations]. Jena, Germany: Gustav Fischer; 1886:14. Available at: https://archive.org/details/beitrgezuranaly00machgoog. Accessed November 16, 2016.

Figure 2.9: Esther G González.

Figure 2.10: Extraocular muscles by Patrick J. Lynch, medical illustrator CC BY 2.5, https://commons.wikimedia.org/w/index.php?curid=1498186
Internal view of the eye modified from https://www.webmd.com/eye-health/picture-of-the-eyes#1.

Resources

1. Brady FB. *A Singular View, The Art of Seeing with One Eye.* 307B Maple Avenue West, Vienna, VA 22180, 6th edition, 2004.
This is an excellent, beautifully illustrated, non-technical first-person account of living with one eye written by a flight engineer. The book went out of print in 1985, but a 4th edition was prepared when the late Mr. Brady negotiated with his publisher to regain the copyright. The book is available from:
http://asingularview.com/singviewpages/ordering.html

2. Canadian Retinoblastoma Society:

To join the Society or for more information
on the programs and supports available,
please visit our website at
www.rbsociety.ca

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contact us directly at:
Canadian Retinoblastoma Society
Tel. (905) 933-0016 Fax. (905) 669-6124
E-mail: cdnrbsociety@gmail.com

3. Livingstone M, Gallant R. *My Prosthetic Eye: Visiting the Ocularist.*
This is an essential resource for parents and patients available from:
https://wechope.org/wp-content/uploads/2020/03/My-Prosthetic-Eye-Book.pdf

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