Notes

Chapter 1: Stereoblind

1 ***He was describing the development of the visual system, highlighting experiments done on walleyed and cross-eyed kittens.***

Hubel DH, Wiesel TN. Binocular interaction in striate cortex of kittens reared with artificial squint. *Journal of Neurophysiology* 28 (1965): 1041–59.

Hubel DH, Wiesel TN. *Brain and Visual Perception: The Story of a 25-Year Collaboration.* Oxford: Oxford University Press, 2005.

2 ***We have two eyes, he said, but only one view of the world.***

An excellent review of stereovision is found in Hubel DH. *Eye, Brain, and Vision*. New York: Scientific American Library, 1995. Also available online at http://hubel.med.harvard.edu/bcontex.htm.

3 ***The classroom didn't seem entirely flat to me.***

See chapter 7 for a more detailed discussion of nonstereoscopic cues to depth.

4 ***Many of the great students of optics, including Euclid, Archimedes, da Vinci, Newton, and Goethe, never figured out how we see in stereoscopic depth.***

For a fascinating review of the history of our knowledge of binocular vision, see

Howard IP, Rogers BJ. *Seeing in Depth*. Ontario: I. Porteus, 2002, vol. 1, ch. 2.

Crone RA. *Seeing Space*. Exton, PA: Swets and Zeitlinger Pubs., 2003.

6 ***The teddy bear located to your left casts its image on corresponding points on the right side of both your retinas, while the rattle, to the right, casts its image on corresponding points on the left side of both retinas.***

In figure 1.3, the block is located at the fixation point. The bear, block, and rattle all fall on a line called the horopter, or, more specifically, the apparent frontoparallel plane horopter. Although this line is slightly curved, we interpret the bear, the rattle, and all other objects along this horopter as located in the same plane as the block. See, for example,

Steinman SB, Steinman BA, Garzia FP. *Foundations of Binocular Vision: A Clinical Perspective*. New York: McGraw-Hill Cos., 2000, ch. 4.

6 ***In 1838, Wheatstone explained how the relative position of the images on the two retinas allows us to see in 3D.***

Wheatstone C. Contributions to the Physiology of Vision.—Part the First. On some remarkable, and hitherto unobserved, Phenomena of Binocular Vision. *Philosophical Transactions of the Royal Society of London* 128 (1838): 371–94.

10 ***I thought about people who were totally colorblind.***

Individuals with a hereditary form of total colorblindness are described in

Sacks O. *The Island of the Colorblind*. New York: Alfred A. Knopf, 1996.

10 ***With this knowledge, could they see in their mind's eye what they couldn't see in the real world?***

Many philosophers have pondered this question. For example, Frank Jackson posed the famous thought experiment about Mary the Neuroscientist. Mary is brilliant and knows everything there is to know theoretically about color and color vision. However, she has lived all her life in a black-and-white room, her entire body covered in black-and-white clothes, so that she saw absolutely no color. Finally, Mary is let out of her room. She sees red for the first time. Is red what she imagined? Had she been able to imagine any of the colors that she now sees? Has she learned something new about the world?

Jackson F. What Mary didn't know. *Journal of Philosophy* 83 (1986): 291–95.

Also see Ludlow P, Nagasawa Y, Stoljar D (eds.). *There's Something about Mary: Essays on Phenomenal Consciousness and Frank Jackson's Knowledge Argument.* Cambridge, MA: MIT Press, 2004.

Thanks to Greg Frost-Arnold for introducing me to Mary.

11 ***If you learn to read braille even as an adult, the number of neurons in your brain that receive touch input from your reading index finger increases.***

Pascual-Leone A, Torres F. Plasticity of the sensorimotor cortex representation of the reading finger of braille readers. *Brain* 116 (1993): 39–52.

11 ***In the 1990s, scientists studied the brains of violinists with magnetic source imaging, and they found that more neurons in the motor cortex of violinists were devoted to the control of the fingers of the left than the right hand.***

Elbert T, Pantev C, Wienbruch C, Rockstroh B, Taub E. Increased cortical representation of the fingers of the left hand in string players. *Science* 270 (1995): 305–7.

13 ***You might think that Jenny's experiments indicated that Dan's ability to sense and move had degenerated while he was in space. Instead, Dan had adapted to a radically new environment, the microgravity of outer space.***

Reschke MF, Bloomberg JJ, Harm DL, Paloski WH. Space flight and neurovestibular adaptation. *Journal of Clinical Pharmacology* 34 (1994): 609–17.

Reschke MF, Bloomberg JJ, Harm DL, Paloski WH, Layne C, McDonald V. Posture, locomotion, spatial orientation, and motion sickness as a function of space flight. *Brain Research Reviews* 28 (1998): 102–17.

14 ***Since my misaligned eyes saw different things, they competed for input onto visual cortical neurons, and on each neuron, one or the other eye won out.***

Hubel DH, Wiesel TN. Binocular interaction in striate cortex of kittens reared with artificial squint. *Journal of Neurophysiology* 28 (1965): 1041–59.

Wiesel TN, Hubel DH. Comparison of the effects of unilateral and bilateral eye closure and cortical unit responses in kittens. *Journal of Neurophysiology* 28 (1965): 1029–40.

15 ***But even at the turn of twenty-first century, the latest papers and books, though full of evidence of the adaptability of the adult brain, still didn't question the critical period in relation to stereovision.***

See, for example, Gilbert CD, Sigman M, Crist RE. The neural basis of perceptual learning. *Neuron* 31 (2001): 681–97.

Begley S. *Train Your Mind, Change Your Brain: How a New Science Reveals Our Extraordinary Potential to Transform Ourselves*. New York: Ballantine Books, 2007, 77–78.

In contrast, other papers and books, largely written after 2002, suggest that substantial plasticity may extend beyond the critical period.

Bao S, Chang EF, Davis JD, Gobeske KT, Merzenich MM. Progressive degradation and subsequent refinement of acoustic representations in the adult auditory cortex. *Journal of Neuroscience* 23 (2003): 10765–75.

Doidge N. *The Brain That Changes Itself*. London: Penguin Books, 2007.

Fahle M, Poggio T. *Perceptual Learning*. Cambridge, MA: MIT Press, 2002.

Kasamatsu T, Watabe K, Heggelund P, Scholler E. Plasticity in cat visual cortex restored by electrical stimulation of the locus coeruleus. *Neuroscience Research* 2 (1985): 365–86.

Keuroghlian AS, Knudsen ET. Adaptive auditory plasticity in developing and adult animals. *Progress in Neurobiology* 82 (2007): 109–21.

Levi DM. Perceptual learning in adults with amblyopia: A reevaluation of critical periods in human vision. *Developmental Psychobiology* 46 (2005): 222–32.

Li RW, Klein SA, Levi DM. Prolonged perceptual learning of positional acuity in adult amblyopia: Perceptual template retuning dynamics. *Journal of Neuroscience* 28 (2008): 14223–29.

Reports over the past century indicate that an individual, blinded since birth or early childhood, is unlikely to gain functional vision even if sight is restored in adulthood. See

Gregory RL, Wallace J. Recovery from early blindness: A case study. In Gregory RL (ed.), *Concepts and Mechanisms of Perception*. London: Duckworth, 1974, 65–129.

Sacks OW. To see and not see. In *An Anthropologist on Mars*. New York: Alfred A. Knopf, 1995.

Von Senden M. *Sight and Space: The Perception of Space and Shape in the Congenitally Blind before and after Operation*. Glencoe, IL: Free Press, 1932.

However, Dr. Pawan Sinha, a neuroscientist at MIT, has studied patients in his native India who were blinded by cataracts or other conditions throughout early childhood. Some of the individuals in Sinha's study developed functional vision after surgery performed in late childhood or even adulthood.

Ostrovsky Y, Andalman A, Sinha P. Vision following extended congenital blindness. *Psychological Science* 17 (2006): 1009–14.

In addition, the following book recounts the struggle to regain vision by an individual who was blinded by a chemical accident at age three and regained sight as an adult.

Kurson R. *Crashing Through: A True Story of Risk, Adventure, and the Man Who Dared to See*. New York: Random House, 2007.

These reports indicate that significant visual plasticity does extend beyond a critical period in early life.

15 ***Had I looked at papers and books written by a small subset of optometrists, I would have encountered clinicians who had developed procedures to rehabilitate people's vision, even the vision of individuals like me with a lifelong strabismus.***

Etting GL. Strabismus therapy in private practice: Cure rates after three months of therapy. *Journal of the American Optometric Association* 49 (1978): 1367–73.

Flax N, Duckman RH. Orthoptic treatment of strabismus. *Journal of the American Optometric Association* 49 (1978): 1353–61.

Ludlam WM. Orthoptic treatment of strabismus: A study of one hundred forty nine non-operated, unselected, concomitant strabismus patients completing orthoptic training at the Optometric Center of New York. *American Journal of Optometry and Archives of the American Academy of Optometry* 38 (1961): 369–88.

Ludlam WM, Kleinman BI. The long range results of orthoptic treatment of strabismus. *American Journal of Optometry and Archives of the American Academy of Optometry* 42 (1965): 647–84.

Press, LJ. *Applied Concepts in Vision Therapy*. St. Louis, MO: Mosby, 1997.

Chapter 2: Mixed-Up Beginnings

17 ***My parents first noticed my misaligned eyes when I was only three months old.***

Clinical tests confirmed that my strabismus developed within the first year of life since, as an adult, I had latent nystagmus and an asymmetric optokinetic response with poor monocular optokinetic nystagmus in the nasotemporal direction.

18 ***Since some children with crossed eyes straighten them spontaneously, the doctor suggested that my parents wait to see if I outgrew the condition.***

Cases in which the esotropia does not resolve usually involve infants with constant eye turns.

Fu VL, Stager DR, Birch EE. Progression of intermittent, small-angle, and variable esotropia in infancy. *Investigative Ophthalmology and Visual Science* 48 (2007): 661–64.

Pediatric Eye Disease Investigator Group. Spontaneous resolution of early-onset esotropia: Experience of the Congenital Esotropia Observational Study. *American Journal of Ophthalmology* 133 (2002): 109–18.

19 My muscles were functioning fine, but the coordination of the two eyes was off.

Lennerstrand G. Strabismus and eye muscle function. *Acta Ophthalmology Scandinavia* 85 (2007): 711–23.

Tychsen L, Richards M, Wong A, Foeller P, Burkhalter A, Narasimhan A, Demer J. Spectrum of infantile esotropia in primates: Behavior, brains, and orbits. *Journal of AAPOS* 12 (2008): 375–80.

The vast majority of infants who develop strabismus develop a non-paralytic form of esotropia. In a classic paper by FD Costenbader, 36 out of 1,152 infantile esotropes, or only 3.1 percent, had a paralytic form of strabismus.

Costenbader FD. Infantile esotropia. *Transactions of the American Ophthalmologial Society* 59 (1961): 397–429.

20 A baby's sensory world is actually very different from an adult's.

Daw NW. *Visual Development.* New York: Springer, 2006.

Slater A (ed.). *Perceptual Development: Visual, Auditory, and Speech Perception in Infancy.* East Sussex, UK: Psychology Press, 1998.

20 But newborns have some innate perceptual skills—babies, at just nine minutes old, exhibit a preference for looking at a human face.

Goren CC, Sarty M, Wu PY. Visual following and pattern discrimination of face-like stimuli by newborn infants. *Pediatrics* 56 (1975): 544–49.

20 In addition, the eyes of a very young infant are not always straight.

Nixon RB, Helveston EM, Miller K, Archer SM, Ellis FD. Incidence of strabismus in neonates. *American Journal of Ophthalmology* 100 (1985): 798–801.

Archer SM, Sondhi N, Helveston EM. Strabismus in infancy. *Ophthalmology* 96 (1989): 133–37.

Horwood A. Neonatal ocular misalignments reflect vergence development but rarely become esotropia. *British Journal of Ophthalmology* 87 (2003): 1146–50.

21 ***To establish when the brain starts comparing the images from the two eyes, scientists at the Massachusetts Institute of Technology (MIT) placed Polaroid goggles on healthy babies whose parents had agreed to have them participate in experiments.***

Shimojo S, Bauer Jr J, O'Connell KM, Held R. Pre-stereoptic binocular vision in infants. *Vision Research* 26 (1986): 501–10.

22 ***After four months, however, the brain determines whether the input comes from the right or left eye, and the babies begin to experience binocular rivalry.***

This period may correlate with the stage when afferents from the lateral geniculate nucleus have segregated into right-eye and left-eye ocular dominance columns in layer 4C of the visual cortex.

Shimojo S, Bauer Jr J, O'Connell KM, Held R. Pre-stereoptic binocular vision in infants. *Vision Research* 26 (1986): 501–10.

Daw NW. *Visual Development*. New York: Springer, 2006, 52–54.

23 ***Scientists have surmised, therefore, that the ability to converge the eyes, to fuse two images together, and to appreciate stereoscopic depth may all develop at about the same time.***

Thorn F, Gwiazda J, Cruz AA, Bauer JA, Held R. The development of eye alignment, convergence, and sensory binocularity in young infants. *Investigative Ophthalmology and Visual Science* 35 (1994): 544–53.

Birch EE, Shimojo S, Held R. Preferential-looking assessment of fusion and stereopsis in infants aged 1–6 months. *Investigative Ophthalmology and Visual Science* 26 (1985): 366–70.

Daw NW. *Visual Development*. 2nd ed. New York: Springer, 2006.

23 ***"Infantile esotropia" appears at about two to three months of age, while a second type of strabismus, "accommodative esotropia," usually develops later, at around two to three years.***

Archer SM, Sondhi N, Helveston EM. Strabismus in infancy. *Ophthalmology* 96 (1989): 133–37.

Nixon RB, Helveston EM, Miller K, Archer SM, Ellis FD. Incidence of strabismus in neonates. *American Journal of Ophthalmology* 100 (1985): 798–801.

Press LJ. *Applied Concepts in Vision Therapy*. St. Louis, MO: Mosby, 1997.

Von Noorden GK. *Binocular Vision and Ocular Motility*. 5th ed. St. Louis, MO: Mosby, 1996.

23 ***There may be multiple causes of a poor ability to fuse and the development of crossed eyes.***

Daw NW. *Visual Development*. 2nd ed. New York: Springer, 2006.

Major A, Maples WC, Toomey S, DeRosier W, Gahn D. Variables associated with the incidence of infantile esotropia. *Optometry* 78 (2007): 534–41.

von Noorden GK. *Binocular Vision and Ocular Motility*. 5th ed. St. Louis, MO: Mosby, 1996, ch. 9.

24 ***Infants learn about space through vision, touch, and their own movements.***

White BL, Castle P, Held R. Observations on the development of visually-directed reaching. *Child Development* 35 (1964): 349–64.

Bruner JS. *Processes of Cognitive Growth: Infancy.* Worcester, MA: Clark University Press, 1968.

Volume 37, number 3 (2006) of the journal *Optometry and Vision Development* is devoted almost entirely to infant vision.

Gesell A, Ilg FL, Bullis GE. *Vision: Its Development in Infant and Child*. Santa Clara, CA: Optometric Extension Program Foundation, 1998. (You can obtain books from the Optometric Extension Program via http://oep.excerpo.com.)

24 ***In a classic study, scientists at MIT showed that accurate reaching in cats develops only when the kittens are able to watch their own limbs as they move them.***

Held R., Hein A. Movement-produced stimulation in the development of visually guided behavior. *Journal of Comparative and Physiological Psychology* 56 (1963): 872–76.

24 ***Their developing visual skills reinforce their emerging motor skills and vice versa.***

Daw NW. *Visual Development.* 2nd ed. New York: Springer, 2006, ch. 3.

26 ***"I see two images but only one is real."***

Observations similar to Sarah Merhar's are discussed in the following two papers:

McLaughlin SC. Visual perception in strabismus and amblyopia. *Psychological Monographs: General and Applied* 78 (1964): 1–23.

Brock FW. Space perception in its normal and abnormal aspects. *Optometric Weekly*, August 29 and September 5, 1946.

Sarah has subsequently undertaken optometric vision therapy with

Drs. Theresa Ruggiero and Cathy Stern, and her double vision has almost completely resolved.

28 ***To make it easier to disregard one eye's input, I turned in the eye that was not doing the looking.***

When I undertook optometric vision therapy at age forty-eight, I could see this misalign-and-suppress mechanism at work in my own visual system. With therapy procedures, I learned to bring the images from both eyes into consciousness and could therefore discover where my two eyes were aiming. Let's say I looked at two dots, one red and one green, arranged side by side. While wearing red/green lenses, each color dot could be seen by only one eye. I might first look at the green dot with just the left eye open. Then, I would open both eyes. For a tiny fraction of a second, the red dot seen by the right eye would appear in the right place with respect to the green dot seen by the left eye. Then, very quickly, the red dot would move out of alignment. Presumably, throughout life, this unconscious action had moved the image from one eye out of alignment, making it easier for me to discount the image from the nonfixating eye.

28 ***Dr. Fasanella could not give them an answer then, but recent research has shown that young infants, even with normal vision, can move each eye more effectively toward the nose than away from it.***

Atkinson J. Development of optokinetic nystagmus in the human infant and monkey infant. In R. D. Freeman (ed.), *Developmental Neurobiology of Vision*. New York: Plenum, 1979.

Naegele JR, Held R. The postnatal development of monocular optokinetic nystagmus in infants. *Vision Research* 22 (1982): 341–46.

Norcia AM. Abnormal motion processing and binocularity: Infantile esotropia as a model system for effects of early interruptions of binocularity. *Eye* 10 (1996): 259–65.

Teller DY, Succop A, Mar C. Infant eye movement asymmetries: Stationary counterphase gratings elicit temporal-to-nasal optokinetic nystagmus in two-month-old infants under monocular test conditions. *Vision Research* 33 (1993): 1859–64.

This mechanism may explain why crossed eyes are by far more common than walleye in very young babies. Results of studies with macaque monkeys support this idea. Macaques have a visual system similar to our own. In one study, prism goggles were put over the monkeys' eyes on their first day of life. The prism lenses shifted the visual field of one eye outward and that of the other eye upward. Now the visual fields of the two eyes were misaligned, preventing the possibility of binocular fusion and presumably causing double vision and visual confusion. Although the prisms shifted the visual field of one eye outward, the monkeys did not compensate by moving the eye outward. Instead, they turned in the eye behind the prism. If the prisms were left on the monkeys for the first twelve weeks of life, then they developed a constant esotropia. In this way, like children who cannot fuse, they may have developed a strategy to ignore or suppress the input from one eye. That strategy involved turning in the nonfixating eye.

Tychsen L. Causing and curing infantile esotropia in primates: The role of decorrelated binocular input. *Transactions of the American Ophthalmological Society* 105 (2007): 564–93.

29 ***People who have been cross-eyed since early childhood see much less depth using motion parallax than people with normal binocular vision, and this, along with the lack of stereopsis, greatly compromises depth perception.***

Nawrot M, Frankl M, Joyce L. Concordant eye movement and motion parallax asymmetries in esotropia. *Vision Research* 48 (2008): 799–808.

Thompson AM, Nawrot M. Abnormal depth perception from motion parallax in amblyopic observers. *Vision Research* 39 (1999): 1407–13.

A poor sense of depth through motion parallax in infantile esotropes may result from poor pursuit movements of the eyes.

Naji JJ, Freeman TC. Perceiving depth order during pursuit eye movement. *Vision Research* 44 (2004): 3025–34.

Nawrot M, Joyce L. The pursuit theory of motion parallax. *Vision Research* 46 (2006): 4709–25.

Birch EE, Fawcett S, Stager D. Co-development of VEP motion response and binocular vision in normal infants and infantile esotropes. *Investigative Ophthalmology and Visual Science* 41 (2000): 1719–23.

Norcia AM. Abnormal motion processing and binocularity: Infantile esotropia as a model system for effects of early interruptions of binocularity. *Eye* 10 (1996): 259–65.

Tychsen L. Causing and curing infantile esotropia in primates: The role of decorrelated binocular input. *Transactions of the American Ophthalmological Society* 105 (2007): 564–93.

Tychsen L, Lisberger SG. Maldevelopment of visual motion processing in humans who had strabismus with onset in infancy. *Journal of Neuroscience* 6 (1986): 2495–508.

Tychsen L, Hurtig RR, Scott WE. Pursuit is impaired but the vestibulo-ocular reflex is normal in infantile strabismus. *Archives of Ophthalmology* 103 (1985): 536–39.

Valmaggia C, Proudlock F, Gottlob I. Optokinetic nystagmus in strabismus: Are asymmetries related to binocularity? *Investigative Ophthalmology and Visual Science* 44 (2003): 5142–50.

29 ***As a result, many cross-eyed babies show delays in mastering tasks like grasping a toy or holding a bottle, and older children with the same problems may even show abnormalities in gait and posture.***

Birnbaum MH. Gross motor and postural characteristics of strabismic patients. *Journal of the American Optometric Association* 45 (1974): 686–96.

Drover JR, Stager DR, Morale SE, Leffler MN, Birch EE. Improvement in motor development following surgery for infantile esotropia. *Journal of AAPOS* 12 (2008): 136–40.

Slavik BA. Vestibular function in children with nonparalytic strabismus. *Occupational Therapy Journal of Research* 2 (1982): 220–33.

33 ***This is true for many children with strabismus, particularly if they have surgery after the first year of life, the presumed critical period for the development of stereovision.***

In fact, the well-respected ophthalmologist and strabismic expert Stewart Duke-Elder wrote in 1976, "Insofar as the cure of squint [strabismus] is measured in terms of the restoration of binocular vision, *operation cannot by itself effect a cure*; it is merely a mechanical expedient to orientate the eyes."

Duke-Elder S, Wybar K. *System of Ophthalmology*, Vol. VI: *Ocular Motility and Strabismus.* St. Louis, MO: C. V. Mosby Co., 1973, 489.

Clinical studies indicate that no more than 20 percent of patients who undergo strabismic surgery after the age of two acquire stereopsis, while 20 to 80 percent of patients who receive surgery in the first year develop some binocular vision and stereopsis.

Birch EE, Felius J, Stager Sr DR, Weakley Jr DR, Bosworth RG. Preoperative stability of infantile esotropia and post-operative outcome. *American Journal of Ophthalmology* 138 (2004): 1003–9.

Birch EE, Stager Sr DR. Long-term motor and sensory outcomes after early surgery for infantile esotropia. *Journal of AAPOS* 10 (2006): 409–13.

Birch EE, Stager DR, Everett ME. Random dot stereoacuity following surgical correction of infantile esotropia. *Journal of Pediatric*

Ophthalmology and Strabismus 32 (1995): 231–35.

Helveston EM, Neely DF, Stidham DB, Wallace DK, Plager DA, Spunger DT. Results of early alignment of congenital esotropia. *Ophthalmology* 106 (1999): 1716–26.

Hiles DA, Watson BA, Biglan AW. Characteristics of infantile esotropia following early bimedial rectus recession. *Archives of Ophthalmology* 98 (1980): 697–703.

Kushner BJ, Fisher M. Is alignment within 8 prism diopters of orthotropia a successful outcome for infantile esotropia surgery? *Archives of Ophthalmology* 114 (1996): 176–80.

Park MM. Stereopsis in congenital esotropia. *American Orthoptic Journal* 47 (1997): 99–102.

In the last twenty years, many investigators who study the effects of strabismic surgery on vision have concluded that the critical factor in achieving stereopsis may not be the *age* at the time of surgery but rather the *duration* of eye misalignment. This makes sense if we consider strabismic ways of seeing as adaptations to the disorder. The longer the eyes are misaligned, the longer the child has to cope with uncorrelated input from the two eyes and the longer is the period during which adaptations, such as suppression and anomalous correspondence, set in. If these adaptations provide the infant with a single view of the world and allow the baby to move with reasonable accuracy, then the child may not change his or her way of seeing even after surgery.

Mohindra I, Zwaan J, Held R, Brill S, Zwaan F. Development of acuity and stereopsis in infants with esotropia. *Ophthalmology* 92 (1985): 691–97.

Wright KW, Edelman PM, McVey JH, Terry AP, Lin M. High-grade stereo acuity after early surgery for congenital esotropia. *Archives of Ophthalmology* 112 (1994): 913–19.

Birch EE, Fawcett S, Stager DR. Why does early surgical alignment improve stereoacuity outcomes in infantile esotropia? *Journal of AAPOS* 4 (2000): 10–14.

Ing MR, Okino LM. Outcome study of stereopsis in relation to duration of misalignment in congenital esotropia. *Journal of AAPOS* 6 (2002): 3–8.

34 ***Babies who can fuse images and develop stereopsis after surgery are more likely to keep their eyes aligned and require no further operations.***

Arthur BW, Smith JT, Scott WE. Long-term stability of alignment in the monofixation syndrome. *Journal of Pediatric Ophthalmology and Strabismus* 26 (1989): 224–31.

Chapter 3: School Crossings

38 ***Yet, many school administrators and physicians have long questioned the connection between vision and learning.***

Helveston EM, Weber JC, Miller K, Robertson K, Hohberger G, Estes R, Ellis FD, Pick N, Helveston BY. Visual function and academic performance. *American Journal of Ophthalmology* 99 (1985): 346–55.

Learning disabilities, dyslexia, and vision. A subject review. *Pediatrics* 102 (1998): 1217–19. A joint policy statement of the American Academy of Pediatrics, the American Academy of Ophthalmology, and the American Association for Pediatric Ophthalmology and Strabismus. Available online at http://aappolicy.aappublications.org/cgi/content/full/pediatrics;102/5/1217

In contrast, the American Academy of Optometry and the American Optometric Association issued a joint statement indicating that vision-related reading problems do exist.

Vision, learning and dyslexia: A joint organizational policy statement of the American Academy of Optometry and the American Optometric Association. Available online at http://aaopt.org/userfiles/imagesPOSITION_PAPERS_BV/img_3124863_Policy_Statement_On_Vision_Learning_And_Dyslexia.doc.

38 ***Although the exact role of vision in learning is a subject of intense debate, many scientific studies support a connection between vision and reading.***

For review, see Kulp MT, Schmidt PP. Effect of oculomotor and other visual skills on reading performance: A literature review. *Optometry and Vision Science* 73 (1996): 283–92.

Cooper J. Summary of research on the efficacy of vision therapy for specific visual dysfunctions. *Journal of Behavioral Optometry* 9 (1998): 115–19. Also available online at http://visiontherapy.org/vision-therapy/vision-therapy-studies.html.

Griffin JR, Grisham JD. *Binocular Anomalies: Diagnosis and Vision Therapy*. New York: Butterworth-Heinemann, 2002.

Maples WC. Visual factors that significantly impact academic performance. *Optometry* 74 (2003): 35–49.

39 ***For example, one paper published in 2007 examined the visual skills of 461 high school students who read at two or more levels below the established level for their grade.***

Grisham D, Powers M, Riles P. Visual skills of poor readers in high school. *Optometry* 78 (2007): 542–49.

39 ***Additional papers have demonstrated a correlation between reading skill level and the ability to see with stereopsis.***

Kulp MT, Schmidt PP. Visual predictors of reading performance in kindergarten and first grade children. *Optometry and Vision Science* 73 (1996): 255–62.

Kulp MT, Schmidt PP. A pilot study. Depth perception and near stereoacuity: Is it related to academic performance in young children? *Binocular Vision and Strabismus Quarterly* 17 (2002): 129–34.

In addition, a lack of stereopsis in people with strabismus and amblyopia is correlated with a poor ability to read letters on eye charts, that is, to interpret visually complicated patterns.

McKee SP, Levi DM, Movshon JA. The pattern of visual deficits in amblyopia. *Journal of Vision* 3 (2003): 380–405.

39 ***But recent experiments examining the movement of both eyes together during reading have yielded some important surprises.***

Kirby JA, Webster LAD, Blythe SI, Liversedge SP. Binocular coordination during reading and non-reading tasks. *Psychological Bulletin* 134 (2008): 742–63.

Liversedge SP, Rayner K, White SJ, Findlay JM, McSorley E. Binocular coordination of the eyes during reading. *Current Biology* 16 (2006): 1726–29.

40 ***When I read with my right eye, the image of the word fell on the fovea of my right eye and on the blind spot of my turned left eye.***

My reading adaptation is an example of the "blind spot mechanism" and has been observed in many other strabismics.

Pratt-Johnson JA, Tillson G. *Management of Strabismus and Amblyopia: A Practical Guide.* New York: Thieme Medical Pubs., 1994.

Rutstein RP, Levi DM. The blind spot syndrome. *Journal of the American Optometric Association* 50 (1979): 1387–90.

For a conflicting opinion, see Olivier P, von Noorden GK. The blind spot syndrome: Does it exist? *Journal of Pediatric Ophthalmology and Strabismus* 18 (1981): 20–22.

If I could move my eyes with enough precision to have the image of the letters fall on the blind spot of one eye, then why didn't I move my eyes instead in a way that caused the images to fall on the fovea of both eyes? The fovea is a much smaller target than the blind spot, so bifoveal fixation requires much more precise eye alignment than the strategy I used.

42 ***After all these years of doctor's visits and school tests, Michelle finally learned that Eric's difficulties resulted from a visual condition called con-***

vergence insufficiency, a common but often undiagnosed cause of reading troubles.

Rouse MW, Borsting E, Hyman L, Hussein M, Cotter SA, Flynn M, Scheiman M, Gallaway M, De Land PN. Frequency of convergence insufficiency among fifth and sixth graders. The Convergence Insufficiency and Reading Study (CIRS) group. *Optometry and Vision Science* 76 (1999): 643–49.

Textbooks on optometric vision therapy that include descriptions of convergence insufficiency are listed below:

Griffin JR, Grisham JD. *Binocular Anomalies: Diagnosis and Vision Therapy*. New York: Butterworth-Heinemann, 2002.

Press, LJ. *Applied Concepts in Vision Therapy*. St. Louis, MO: 1997.

Scheiman M, Wick B. *Clinical Management of Binocular Vision: Heterophoric, Accommodative, and Eye Movement Disorders.* 2nd ed. New York: Lippincott Williams & Wilkins, 2002.

See also this reference for a *New York Times* account of the condition: Novak L. Not autistic or hyperactive: Just seeing double at times. *New York Times*, September 11, 2007. Available online at www.nytimes.com/2007/09/11/health/11visi.html.

Some individuals with convergence insufficiency manage to get through grade school without too many problems but "hit a wall" when greater demands are placed on their visual system in graduate school. Oliver Waldman and Garry Brown both suffered from convergence insufficiency, and both encountered significant problems when in law school or when taking the written medical boards, respectively. It was at that point that they learned about, and engaged in, optometric vision therapy, and only then were they able to realize their career goals.

42 ***According to a recent National Eye Institute study of 221 children, the most effective treatment for Eric's condition is a combination of office-based and home-based vision therapy.***

Convergence Insufficiency Treatment Trial Study Group. Randomized clinical trial of treatments for symptomatic convergence insufficiency in children. *Archives of Ophthalmology* 126 (2008): 1336–49.

See the National Eye Institute press release on the above report at http://covd.org/Portals/0/NEIPressRelease.pdf.

Scheiman M, Mitchell GL, Cotter S, Cooper J, Kulp M, Rouse M, Borsting E, London R, Wensveen J. Convergence Insufficiency Treatment Trial Study Group. A randomized clinical trial of treatments for convergence insufficiency in children. *Archives of Ophthalmology* 123 (2005): 14–24.

Chapter 4: Knowing Where to Look

47 ***In his thoughtful and moving memoir,* Touching the Rock, *John Hull recounts what it is like to be blind.***

Hull JM. *Touching the Rock: An Experience of Blindness*. New York: Pantheon Books, 1990.

47 ***If we didn't have legs and arms for climbing trees and fingers for manipulating objects, we would never have needed such a complicated visual system or brain.***

Many optometrists, scientists, and philosophers have recognized the important connection between vision and movement.

Birnbaum MH. Behavioral optometry: A historical perspective. *Journal of the American Optometric Association* 65 (1994): 255–64.

Churchland PS, Ramachandran VS, Sejnowski TJ. A critique of pure vision. In Koch C, Davis JL (eds.), *Large Scale Neuronal Theories of the Brain*. Cambridge, MA: MIT Press, 1994. Available online at http://philosophy.ucsd.edu/faculty/pschurchland/papers/kochdavis94critiqueofpurevision.pdf.

Daw NW. *Visual Development*. 2nd ed. New York: Springer, 2006, 31.

Gibson JJ. *The Ecological Approach to Visual Perception.* Hillsdale, NJ: Lawrence Erlbaum Associates, 1986.

Harmon DB. *Notes on a Dynamic Theory of Vision*. Santa Ana, CA: Optometric Extension Program Foundation, 1958.

Noe E. *Action in Perception*. Cambridge, MA: MIT Press, 2004.

48 ***You gaze directly at the curve a second or two before rounding the bend, then turn your head in the direction of your gaze and masterfully steer the car around the curve.***

Land MF, Lee DN. Where we look when we steer. *Nature* 369 (1994): 742–44.

50 ***Your sensed visual direction—the direction in which you are looking—is not the direction in which either eye is pointing but one that seems to emanate from the center of your forehead.***

Brock FW. A comparison between strabismic seeing and normal binocular vision. *Journal of the American Optometric Association* 31 (1959): 299–304.

50 ***For most people, images that fall on corresponding retinal points appear in the same subjective visual direction.***

This observation was first described in the second century AD by Ptolemy in Books II and III of his *Optics*. See Howard IP, Rogers BJ. *Seeing in Depth*. Ontario: I. Porteus, 2002, vol. 1, ch. 2.

52 ***While this turn of events may seem surprising, similar cases have been documented in which the amblyopic eye regains vision following severe impairment of the "good" eye.***

El Mallah MK, Chakravarthy U, Hart PM. Amblyopia: Is visual loss permanent? *British Journal of Ophthalmology* 84 (2000): 952–56.

Tierney DW. Vision recovery in amblyopia after contralateral subretinal hemorrhage. *Journal of the American Optometric Association* 60 (1989): 281–83.

Vereecken EP, Brabant P. Prognosis for vision in amblyopia after the loss of the good eye. *Archives of Ophthalmology* 102 (1984): 220–24.

Wilson ME. Adult amblyopia reversed by contralateral cataract formation. *Journal of Pediatric Ophthalmology and Strabismus* 29 (1992): 100–102.

54 ***Bruce's unusual way of seeing is called anomalous correspondence, an adaptation that often takes months or years of childhood strabismus to develop.***

Brock FW. Investigation into anomalous correct projection in cases of concomitant squints. *American Journal of Optometry* 16 (1939): 39–77.

Brock FW. Anomalous projection in squint. Its cause and effect. New methods of correction. Report of cases. *American Journal of Optometry* 16 (1939): 201–21.

Brock FW. Space perception in its normal and abnormal aspects. *Optometric Weekly* 37 (1946): 1193–96, 1202, 1235–38.

Steinman SB, Steinman BA, Garzia RP. *Foundations of Binocular Vision: A Clinical Perspective.* New York: McGraw-Hill Cos., 2000.

Von Noorden GK. *Binocular Vision and Ocular Motility*, 5th ed. New York: Mosby, 1996, ch. 13.

55 ***In his book* The Organism, *Goldstein stresses that a patient's symptoms are often a response to, or coping mechanism for dealing with, his or her disorder.***

Goldstein K. *The Organism: A Holistic Approach to Biology Derived from Pathological Data in Man.* New York: Zone Books, 1995.

55 ***With Goldstein's research in mind, Brock noted that a strabismic "speaks a different language."***

Brock FW. Conditioning the squinter to normal visual habits. *Optometric Weekly* 32 (1941): 793–801, 819–24.

57 ***Like Rachel, my friend Tracy Gray suffered from a twisted posture associated with her vision.***

Darell Boyd Harmon did extensive studies on the connections between vision and posture among 160,000 school children.

Harmon DB. *Notes on a Dynamic Theory of Vision*. Santa Ana, CA: Optometric Extension Program Foundation, 1958 (obtained via http://oep.excerpo.com).

62 ***Instead, it is built upon orthoptic procedures developed in the late 1800s by the French ophthalmologist Louis Emile Javal.***

Duke-Elder S, Wybar K. *System of Ophthalmology.* Vol. VI: *Ocular Motility and Strabismus.* St. Louis, MO: C. V. Mosby Co., 1973.

Griffin JR, Grisham JD. *Binocular Anomalies: Diagnosis and Vision Therapy*. New York: Butterworth-Heinemann, 2002, ch. 9.

Javal E. *Manuel du strabisme*. Paris: Masson, 1986.

Press LJ. *Applied Concepts in Vision Therapy*. New York: Mosby, 1997, ch. 1.

Revell MJ. *Strabismus: A History of Orthoptic Techniques*. London: Barrie & Jenkins, 1971, 15–23.

62 ***As mentioned in chapter 1, laboratory experiments indicate that eye misalignment during a "critical period" in early life disrupts the development of binocular neurons.***

Daw NW. Critical periods and strabismus: What questions remain? *Optometry and Vision Science* 74 (1997): 690–94.

Crawford MLG, Harwerth RS, Smith EL, von Noorden GK. Keeping an eye on the brain: The role of visual experience in monkeys and children. *Journal of General Psychology* 120 (1993): 7–19.

Daw NW. Critical periods in the visual system. In Hopkins B, Johnson SP (eds.), *Neurobiology of Infant Vision*. Westport, CT: Praeger Pub., 2003.

Daw NW. *Visual Development*. New York: Springer, 2006, ch. 9.

Hubel DH, Wiesel TN. Binocular interaction in striate cortex of kittens reared with artificial squint. *Journal of Neurophysiology* 28 (1965): 1041–59.

Hubel DH, Wiesel TN. *Brain and Visual Perception: The Story of a 25-Year Collaboration.* Oxford: Oxford University Press, 2005.

62 ***As a result, ophthalmologists, in the late 1900s, began to operate on strabismic infants within the first year of life.***

Tychsen L. Can ophthalmologists repair the brain in infantile esotropia? Early surgery, stereopsis, monofixation syndrome, and the legacy of Marshall Parks. *Journal of AAPOS* 9 (2005): 510–21.

62 ***Surgery on such young children has been partially successful in allowing for the development of stereovision.***

Birch EE, Fawcett S, Stager DR. Why does early surgical alignment improve stereoacuity outcomes in infantile esotropia? *Journal of AAPOS* 4 (2000): 10–14.

Birch EE, Felius J, Stager Sr DR, Weakley Jr DR, Bosworth RG. Preoperative stability of infantile esotropia and post-operative outcome. *American Journal of Ophthalmology* 138 (2004): 1003–9.

Birch EE, Stager Sr DR. Long-term motor and sensory outcomes after early surgery for infantile esotropia. *Journal of AAPOS* 10 (2006): 409–13.

Ing MR, Okino LM. Outcome study of stereopsis in relation to duration of misalignment in congenital esotropia. *Journal of AAPOS* 6 (2002): 3–8.

Park MM. Stereopsis in congenital esotropia. *American Orthoptic Journal* 47 (1997): 99–102.

Wright KW, Edelman PM, McVey JH, Terry AP, Lin M. High-grade stereo acuity after early surgery for congenital esotropia. *Archives of Ophthalmology* 112 (1994): 913–19.

63 ***The babies are simply too young to participate in vision therapy procedures.***

However, a caretaker (parent, babysitter, or therapist) can perform some therapy procedures with a cross-eyed infant to encourage abduction (moving the eyes outward), promote awareness of the visual periphery, and reduce cross-fixation (the tendency to use the right eye to see the left side of the visual field and vice versa.)

Gingham fabrics can be used on crib bumpers, chair coverings, and wall paper. The repeating patterns on these fabrics present the same stimulus pattern to both eyes, even eyes that are misaligned, and may help promote fusion. See Press LJ. *Applied Concepts in Vision Therapy*. St. Louis, MO: Mosby, 1997, 99–100.

63 ***In a study to determine the effectiveness of this training, 149 patients (none of whom had undergone any surgery) received treatment sessions twice a week for twelve weeks.***

Ludlam WM. Orthoptic treatment of strabismus: A study of one hundred forty-nine non-operated, unselected, concomitant strabismus patients completing orthoptic training at the Optometric Center of New York. *American Journal of Optometry and Archives of the American Academy of Optometry* 38 (1961): 369–88.

Ludlam WM, Kleinman BI. The long range results of orthoptic treatment of strabismus. *American Journal of Optometry and Archives of the American Academy of Optometry* 42 (1965): 647–84.

63 ***Several other investigators confirmed these important and groundbreaking studies.***

Etting GL. Strabismus therapy in private practice: Cure rates after three months of therapy. *Journal of the American Optometric Association* 49 (1978): 1367–73.

Flax N, Duckman RH. Orthoptic treatment of strabismus. *Journal of the American Optometric Association* 49 (1978): 1353–61.

63 ***Optometrists have always been at the forefront of lens development, designing, for example, the first contact lenses as well as low-vision devices (tools for reading and distance viewing used by people with severe vision loss).***

Schaeffer J. Contact lens pioneers. *Review of Optometry* 144 (2007). Available online at http://www.revoptom.com/index.asp?ArticleType=SiteSpec&page=contactlens/index.htm.

64 ***In 1971, a subgroup of optometrists particularly interested in vision therapy founded the College of Optometrists in Vision Development (COVD) in order to standardize therapy protocols and develop a rigorous test for board certification in optometric vision therapy.***

Press LJ. *Applied Concepts on Vision Therapy.* New York: Mosby, 1997, ch. 1.

Information on COVD can be found at http://covd.org.

In addition, the American Academy of Optometry has instituted a diplomate program of the Section on Binocular Vision and Perception for optometrists who specialize in binocular vision disorders.

65 ***Dr. Ruggiero went on to explain that my eyes, though cosmetically straight, were still both horizontally and vertically misaligned.***

Following are results from my optometric tests performed on November 20, 2001.

Wirt circles	No measurable stereoacuity
Random dot E test	Fail
Keystone skills	Alternating fixation, no superimposition or fusion
Worth 4 dot	Left-eye suppression at intermediate and far distance (twenty feet); double vision (diplopia) at near (sixteen inches)
Red lens test	Initially left-eye suppression and then diplopia
Maddox rod	Right hypertropia of 5.5 prism diopters at distance, 4 prism diopters at intermediate, and 3 prism diopters at near
Cover test	Constant left-eye esotropia at distance, intermediate, and near. 8 prism diopters of left esotropia at far; 25 prism diopters of left esotropia at near with right hypertropia at all viewing distances
Fusion	Binocular fusion not possible at any viewing distance or direction of gaze; simultaneous awareness led to diplopia
Motility	No restriction of gaze; latent nystagmus
Refraction	Right eye: –1.00–0.75 x 55 Left eye: –1.25–0.50 x 65
Acuity	Right eye, w/o glasses: 20/50; w/ glasses: 20/20 Left eye, w/o glasses: 20/60; w/ glasses: 20/20 Both eyes w/glasses: 20/20

Chapter 5: Fixing My Gaze

70 ***In fact, the act of planning the movement, which is largely unconscious, and the movement itself may sensitize our eyes, ears, and fingers.***

Gibson JJ. Observations on active touch. *Psychological Review* 69 (1962): 477–91.

Rosenbaum DA. *Human Motor Control.* San Diego, CA: Academic Press, 1991, 23.

70 ***In a series of extraordinary experiments, Paul Bach-y-Rita and his colleagues demonstrated the importance of self-directed movement in perceiving the world.***

Bach-y-Rita P. Tactile sensory substitution studies. *Annals of the New York Academy of Sciences* 1013 (2004): 83–91.

71 ***In fact, this important skill involves a large number of brain regions.***

For books on gaze holding and eye movements, consider

Berthoz A. *The Brain's Sense of Movement.* Cambridge, MA: Harvard University Press, 2000.

Leigh RJ, Zee DS. *The Neurology of Eye Movements.* Philadelphia: F. A. Davis Co., 1991.

71 ***So, when you look steadily at an object, you must continually refresh the image by moving your eyes subtly, for instance, by slowly sweeping them across the object and making small, quick jerks.***

Daw NW. *Visual Development*. 2nd ed. New York: Springer, 2006, 31.

Martinez-Conde S, Macknik SL, Hubel DH. Microsaccadic eye movements and firing of single cells in the striate cortex of monkeys. *Nature Neuroscience* 3 (2000): 251–8.

Martinez-Conde S, Macknik SL, Hubel DH. The role of fixational eye movements in visual perception. *Nature Reviews. Neuroscience* 5 (2004): 229–40.

73 ***This abnormal movement, called latent nystagmus, is often seen in people who have been cross-eyed since infancy.***

Brodsky MC. Visuo-vestibular eye movements: Infantile strabismus in three dimensions. *Archives of Ophthalmology* 123 (2005): 837–42.

Richards M, Wong A, Foeller P, Bradley D, Tychsen L. Duration of binocular decorrelation predicts the severity of latent (fusion maldevelopment) nystagmus in strabismic macaque monkeys. *Investigative Ophthalmology and Visual Science* 49 (2008): 1872–78.

Tychsen L. Infantile esotropia: Current neurophysiologic concepts. In Rosenbaum AL, Santiago AP (eds.), *Clinical Strabismus Management*. Philadelphia: W. B. Saunders, 1999, 117–38.

74 ***Smooth pursuit movements of the eyes are often abnormal in people who have been cross-eyed since infancy, and this deficit may result from poor development of stereovision.***

Birch EE, Fawcett S, Stager D. Co-development of VEP motion response and binocular vision in normal infants and infantile esotropes. *Investigative Ophthalmology and Visual Science* 41 (2000): 1719–23.

Norcia AM. Abnormal motion processing and binocularity: Infantile esotropia as a model system for effects of early interruptions of binocularity. *Eye* 10 (1996): 259–65.

Tychsen L, Lisberger SG. Maldevelopment of visual motion processing in humans who had strabismus with onset in infancy. *Journal of Neuroscience* 6 (1986): 2495–508.

Tychsen L, Hurtig RR, Scott WE. Pursuit is impaired but the vestibulo-ocular reflex is normal in infantile strabismus. *Archives of Ophthalmology* 103 (1985): 536–39.

Valmaggia C, Proudlock F, Gottlob I. Optokinetic nystagmus in strabismus: Are asymmetries related to binocularity? *Investigative Ophthalmology and Visual Science* 44 (2003): 5142–50.

75 ***When some astronauts first return from space, they complain that the world appears to move when they turn their heads or walk, an effect that could cause serious problems if they have to perform emergency procedures right after landing.***

Reschke MF, Bloomberg JJ, Harm DL, Paloski WH. Space flight and neurovestibular adaptation. *Journal of Clinical Pharmacology* 34 (1994): 609–17.

Reschke MF, Bloomberg JJ, Harm DL, Paloski WH, Layne C, McDonald V. Posture, locomotion, spatial orientation, and motion sickness as a function of space flight. *Brain Research Reviews* 28 (1998): 102–17.

77 ***The astronauts who adapt most easily to spaceflight are the "head lockers," those who move their eyes, head, and body in unison when they are first afloat in space.***

Amblard B, Assaiante C, Vaugoyeau M, Baroni G, Ferrigno G, Pedotti A. Voluntary head stabilisation in space during oscillatory trunk movements in the frontal plane performed before, during and after a prolonged period of weightlessness. *Experimental Brain Research* 137 (2001): 170–79.

78 ***Optometrist A. M. Skeffington is often considered the father of vision therapy.***

Francke AW. Our optometric heritage. *Visions* (COVD newsletter) 38 (2008): 4.

78 ***Observations like this one led optometrists Amiel Francke and Robert Kraskin to design balance boards in the mid-1900s to use in vision therapy.***

Francke AW. Our optometric heritage. *Visions* (COVD newsletter) 38 (2008): 4.

79 ***When asked how he did this, he said that when you play on a basketball court long enough, "you develop a sense of where you are."***

McPhee J. A *Sense of Where You Are: A Profile of William Warren Bradley*. New York: Farra, Straus and Giroux, 1978, 22.

80 ***In* Living in a World Transformed, *Hubert Dolezal examines what it is like to see without peripheral vision by wearing a set of tubes over his eyes for one week.***

Dolezal H. *Living in a World Transformed.* New York: Academic Press, 1982, 57–79.

84 ***I find the looking-soft technique useful in all sorts of places.***

My improved vision helps me appreciate music in a number of other ways. I sing in a chorus, and as I learned to make better use of my peripheral vision, I was able to follow the musical score and the conductor's baton at the same time. I have always been a pretty sloppy pianist, but as my vision improved, I could read the sheet music with my central vision, while using my peripheral vision to move my hands accurately around the keyboard. I began to play Chopin's *Grand Waltz*, a piece that I had thought was beyond me.

Although I did not receive vision therapy until age forty-eight, learning to play the piano as a child may have helped me with my future vision training. My father sometimes insisted that I play a piece perfectly three times in a row before I could get up from the piano bench. This led to some tearful afternoons. While this kind of discipline may have been excessive, it did teach me how to practice. I learned to break the difficult passages in the music down into smaller parts, work on each, and then put them back together again into a musical whole. I realized that I could get better with practice, a concept that we all know but often do not embrace or follow. Since playing the piano requires using the two hands differently, I learned to pay attention to both sides of my body at the same time. What's more, playing the piano developed my sense of rhythm. Learning all of these skills contributed to my later success with vision training in a way that all the book learning in school never could have.

85 ***Certainly, more fingers are moved and more work is done while opening the whole hand, but it takes more neuronal input to lift only one finger.***

Schieber MH. How might the motor cortex individuate movement? *Trends in Neurosciences* 13 (1990): 440–45.

86 ***Suppression is strongest under natural, daytime viewing conditions, under conditions when a strabismic most needs a single view of the world.***

Jampolsky A. Characteristics of suppression in strabismus. *AMA Archives of Ophthalmology* 54 (1955): 683–96.

McLaughlin SC. Visual perception in strabismus and amblyopia. *Psychological Monographs: General and Applied* 78 (1964): 1–23.

Press LJ. *Applied Concepts in Vision Therapy*. New York: Mosby, 1997, 211.

88 ***If I turned on the input from both eyes, I asked Dr. Ruggiero, wouldn't I see double?***

In fact, many patients, such as Sarah Merhar, Pat Duffy, mentioned in chapter 8, and Margaret Lundin, mentioned below, were able to reduce or eliminate their double vision using optometric vision therapy.

In 1973, when Margaret Lundin was twenty-one years old, she had a benign but large tumor removed from her left frontal sinus. When she woke up from the operation, she had double vision. Glasses with prisms and eye muscle surgery reduced, but did not eliminate, her double vision. Margaret recently consulted Dr. Ruggiero, who began vision therapy with her, and for the first time in over thirty years, she learned to coordinate her eyes in order to see a single, stereoscopic view of the world.

Chapter 6: The Space Between

89 ***It must be repeated here that, before stereopsis is actually experienced by the patient . . .***

Brock FW. Anomalous projection in squint. Its cause and effect. New methods of correction. Report of cases. *American Journal of Optometry* 16 (1939): 201–21.

89 ***The disparity between these two images was too great for me to automatically make corrective convergence or divergence eye movements.***

Studies on strabismics indicate that they do not make normal vergence movements.

Burian HM. Fusional movements in permanent strabismus. *Archives of Ophthalmology* 26 (1941): 626–52.

Kenyon RV, Ciuffreda KJ, Stark L. Dynamic vergence eye movements in strabismus and amblyopia: Symmetric vergence. *Investigative Ophthalmology and Visual Science* 19 (1980): 60–74.

Kenyon RV, Ciuffreda KJ, Stark L. Dynamic vergence eye movements in strabismus and amblyopia: Asymmetric vergence. *British Journal of Ophthalmology* 65 (1981): 167–76.

Schor CM, Ciuffreda KJ. *Vergence Eye Movements: Basic and Clinical Aspects.* Boston: Butterworth Pubs., 1983.

90 ***Not content to test merely what his patients could not see, he performed many thoughtful experiments to determine what and how his patients did see.***

Brock FW. Investigation into anomalous correct projection in cases of concomitant squints. *American Journal of Optometry* 16 (1939): 39–77.

Brock FW. Anomalous projection in squint. Its cause and effect. New methods of correction. Report of cases. *American Journal of Optometry* 16 (1939): 201–21.

Brock FW. Binocular vision in strabismus. *Optometric Weekly* 35 (1945): 1417–18; 36 (1945): 67–68, 179–80, 291–93, 401–3, 575–77, 687–89, 773–75, 1099–100, 1131–33, 1253–56; 37 (1946): 71–74, 231–36.

Brock FW. Space perception in its normal and abnormal aspects. *Optometric Weekly* 37 (1946): 1193–96, 1202, 1235–38.

Greenwald I. *Effective Strabismus Therapy*. Santa Ana, CA: Optometric Extension Program Foundation, 1979, available online at http://oep.excerpo.com.

Greenwald I. *Strabismus: Brock's Influence on New Therapies*. Santa Ana, CA: Optometric Extension Program Foundation, 1982/3, vols. 1 and 2, available at http://oep.excerpo.com.

90 ***In so doing, he taught us that you can learn a lot from a simple piece of string.***

Brock FW. The string as an aid to visual training. *Optometric Extension Program: Visual Training at Work*, series 4, no. 9 (1955): 29–33.

92 ***This area is called Panum's fusional area, and I could also fuse the images of those parts of the string that fell within this area.***

Mitchell DE. A review of the concept of "Panum's fusional areas." *American Journal of Optometry and Archives of American Academy of Optometry* 43 (1966): 387–401.

Ogle KN. *Researches in Binocular Vision*. Philadelphia: W. B. Saunders Co., 1950.

93 ***Movement alone enhances our perception.***

Gibson JJ. Observations on active touch. *Psychological Review* 69 (1962): 477–91.

Rosenbaum DA. *Human Motor Control.* San Diego, CA: Academic Press, 1991, 23.

94 ***Most importantly, he realized that stable, clear binocular vision and stereopsis could be achieved only if the strabismic actively positioned his or her eyes, or made what Brock called a "fusion effort."***

Brock FW. The fusion range in stereoscopic vision: Part 6: The perception of depth. *Optometric Weekly* 33 (1942): 777–79.

Brock realized that a strabismic was unlikely to achieve fusion and see in stereoscopic depth as long as his eyes were in a strabismic posture. In classical orthoptic procedures, the patient may look into a stereoscope or amblyoscope whose arms have been adjusted for his strabismic angle. While the patient looks through the stereoscope, the same image is cast on both foveas. Since the patient's eyes are still in a strabismic posture, however, he will have a difficult time overcoming his strabismic adaptations in order to fuse the images. Brock's techniques differed from classical orthoptics because he emphasized that the patient must move his eyes out of the strabismic posture into better alignment, and only then was fusion and stereopsis possible. The Brock string was one tool I used to learn how to align my eyes.

Like me, Jennifer Clark transformed her view of the world by discovering and changing the way she moved her eyes. Jennifer is from Gourock, Scotland, has a PhD in biology, and for several years worked in a scientific laboratory. Then, at age twenty-eight, she got a job in bioinformatics, which led to hours of computer work. At that point, Jennifer told me, her "near vision just shut down." Soon she could barely read at all. She had only one area of clear vision off to the side. Jen went on a search for a doctor who could help her and finally found optometrist Carolyn Hurst of St. Neots, England. Caroline diagnosed Jennifer's problem as a severe case of double vision with convergence insufficiency and accommodative dysfunction.

When we look at a near object, we do more than turn in our eyes. The lenses of our eyes also change shape, or, in technical terms, accommodate, so that the object that we are fixating appears in sharp focus. The coupling of these two processes, aiming and focusing the eyes, develops in the first year of life, is fine-tuned throughout childhood, and works automatically for most people. Jennifer was unable to converge her eyes to fuse the image from each eye and see singly, and so everything she saw was doubled and blurred. As she had never seen a completely clear single image, Jennifer hadn't learned to use the accommodation (focusing ability) of her eyes to keep the image clear at any distance.

One day, four months into her vision therapy, Jennifer had a revelation. Caroline Hurst had explained that she could use the Brock string to determine where her eyes were aiming since this was the point on the string where the two string images crossed. Jennifer discovered for herself that when she looked down the string, the point most sharply in focus was not the point at which the string images crossed. She now had a way to determine the plane in which her eyes converged and the plane in which her eyes were focused. She realized that instead of trying to look at the place where the two string images crossed, she should be looking at the part of the string that was most in focus. Very soon after introducing this modification, she was able to get the focused part of the string to move up to the place where the string images crossed. Jennifer was now converging at the same place on the string where she was focusing. It was shortly after she mastered this task that she began to see in 3D.

My story and first experience with stereopsis has been described in Oliver Sacks's article,"Stereo Sue." *The New Yorker*, June 19, 2006, 64–73.

My story was also described by Robert Krulwich in a *Morning Edition* program on National Public Radio. See "Going Binocular: Susan's First Snowfall," June 26, 2006, at www.npr.org/templates/story/story.php?storyId=5507789.

96 *During this period, I reread* **The Man Who Mistook His Wife for a Hat.**

Sacks O. *The Man Who Mistook His Wife for a Hat.* New York: Summit Book, 1985, 56–62.

99 ***How strong or weak an individual synaptic connection becomes depends upon when and with whom it is active.***

This basic idea was first formulated by Donald Hebb in 1949.

Hebb DO. *The Organization of Behavior: A Neuropsychological Theory.* New York: John Wiley & Sons, 1949.

An excellent review of neuronal correlates of learning can be found in Kandel ER. *In Search of Memory: The Emergence of a New Science of Mind*. New York: W. W. Norton & Co., 2006.

99 ***By a process called long-term potentiation, the previously ineffective connection between the left-eye pathway and the postsynaptic neuron can be strengthened, perhaps to the point where stimulation of the left-eye neuron alone can get the postsynaptic cell to fire.***

In the laboratory, synaptic changes due to long-term potentiation have been well studied in the adult mammalian visual cortex. See Artola A, Singer W. Long-term depression of excitatory synaptic transmission and its relationship to long-term potentiation. *Trends in Neurosciences* 16 (1993): 480–87.

Artola A, Brocher S, Singer W. Different voltage-dependent thresholds for inducing long-term depression and long-term potentiation in slices of rat visual cortex. *Nature* 347 (1990): 69–72.

Kirkwood A, Bear MF. Hebbian synapses in visual cortex. *Journal of Neuroscience* 14 (1994): 1634–45.

Kirkwood A, Bear MF. Homosynaptic long-term depression in the visual cortex. *Journal of Neuroscience* 14 (1994): 3404–12.

101 Now a binocular neuron, even a very weakly binocular neuron, received correlated input from the two eyes.

In young cats, covering one eye results in the loss of binocular neurons in the visual cortex and in reduced visual acuity of the covered eye. However, brief periods of normal binocular vision, which provides correlated binocular input to visual cortical cells, promote recovery of normal visual acuity in the deprived eye.

Mitchell DE. A special role for binocular visual input during development and as a component of occlusion therapy for treatment of amblyopia. *Restorative Neurology and Neuroscience* 26 (2008): 425–34.

Kind PC, Mitchell DE, Ahmed B, Blakemore C, Bonhoeffer T, Sengpiel F. Correlated binocular activity guides recovery from monocular deprivation. *Nature* 416 (2002): 430–33.

Mitchell DR, Kind PC, Sengpiel F, Murphy K. Short periods of concordant binocular vision prevent the development of deprivation amblyopoia. *European Journal of Neuroscience* 23 (2006): 2458–66.

Schwarzkopf DS, Vorbyov V, Mitchell DE, Sengpiel F. Brief daily binocular vision prevents monocular deprivation effects in visual cortex. *European Journal of Neuroscience* 25 (2007): 270–80.

101 For example, one eye may have blocked or inhibited connections from the other eye onto a visual neuron, and this inhibitory effect may have been reduced when I was able to aim both eyes accurately at the same place in space.

An additional mechanism for the loss of binocularity in strabismics may be the formation of inhibitory connections between the right- and left-eye pathways. These connections may prevent a neuron from receiving input from both eyes. Only the uninhibited pathway causes the so-called monocular neuron to fire. Indeed, in laboratory experiments, application of drugs that block inhibition reveals that 30 to 50 percent of the monocular neurons in the brains of strabismic cats actually receive connections from both eyes. When I gained stereovision, inhibitory connections between the pathways from the two eyes may have been reduced.

Burchfiel JL, Duffy FH. Role of intracortical inhibition in deprivation amblyopia: Reversal by microiontophoretic bicuculline. *Brain Research* 16 (1981): 479–84.

Chino YM, Smith III EL, Kazuyuki Y, Cheng H, Hamamoto J. Binocular interactions in striate cortical neurons of cats reared with discordant visual input. *Journal of Neuroscience* 14 (1994): 5050–67.

Fagiolini M, Hensch TK. Inhibitory threshold for critical-period activation in primary visual cortex. *Nature* 404 (2000): 183–86.

Hensch TK. Critical period plasticity in local cortical circuits. *Nature Reviews. Neuroscience* 6 (2005): 877–88.

Mower GD, Christen WG, Burchfiel JL, Duffy FH. Microiontophoretic bicuculline restores binocular responses to visual cortical neurons in strabismic cats. *Brain Research* 309 (1984): 168–72.

Sengpiel F, Blakemore C. The neural basis of suppression and amblyopia in strabismus. *Eye* 10 (1996): 250–58.

Sillito AM, Kemp JA, Blakemore C. The role of GABAergic inhibition in the cortical effects of monocular deprivation. *Nature* 28 (1981): 318–20.

Sillito AM, Kemp JA, Patel H. Inhibitory interactions contributing to the ocular dominance of monocularly dominated cells in the normal cat striate cortex. *Experimental Brain Research* 41 (1980): 1–10.

Smith EL, Chino YM, Ni J, Cheng H, Crawford ML, Harwerth RS. Residual binocular interactions in the striate cortex of monkeys reared with abnormal binocular vision. *Journal of Neurophysiology* 78 (1997): 1353–62.

Furthermore, drugs or conditions that alter synaptic inhibition may also modulate plasticity in the visual cortex.

Maya Ventencourt JF, Sale A, Viegi A, Baroncelli L, De Pasquale R, O'Leary OF, Castren E, Maffei L. The antidepressant fluoxetine restores plasticity in the adult visual cortex. *Science* 320 (2008): 385–88.

Sale A, Maya Vetencourt JF, Medini P, Cenni MC, Baroncelli L, De Pasquale R, Maffei L. Environmental enrichment in adulthood promotes amblyopia recovery through a reduction of intracortical inhibition. *Nature Neuroscience* 10 (2007): 679–81.

102 ***In their book* Phantoms in the Brain*, V. S. Ramachandran and S. Blakeslee define the term* quale *(plural:* qualia*) as "the raw feel of sensations such as the subjective quality of 'pain' or 'red' or 'gnocchi with truffles.'"***

Ramachandran VS, Blakeslee S. *Phantoms in the Brain: Probing the Mysteries of the Human Mind.* New York: Quill William Morrow, 1998.

103 ***Frederick Brock was a strabismic.***

Dr. Brock was an intermittent exotrope. Brock FW. *Lecture Notes on Strabismus*. Meadville, PA: Keystone View Co.

Chapter 7: When Two Eyes See As One

107 ***In fact, by discovering and exploiting these cues, the artists of the past were in many ways vision scientists.***

Fascinating books on vision and art include the following:

Gregory RL, Gombrich EH. *Illusion in Nature and Art*. New York: Charles Scribner's Sons, 1973.

Livingstone M. *Vision and Art: The Biology of Seeing*. New York: Harry N. Abrams, 2002.

Zeki S. *Inner Vision*. New York: Oxford University Press, 1999.

112 ***He came to visit and, a year later, wrote an article, "Stereo Sue," for* The New Yorker *magazine.***

Sack O. Stereo Sue. *The New Yorker*, June 19, 2006, 64–73.

112 ***A week after the article's publication, I was interviewed on National Public Radio.***

"Going Binocular: Susan's First Snowfall." June 26, 2006, *Morning Edition* on National Public Radio. Available online at www.npr.org/templates/story/story.php?storyId=5507789.

115 ***Fusing large images, called peripheral fusion, is an important step in gaining stereopsis because it helps align the eyes and trigger accurate convergence and divergence movements.***

Burian HM. Fusional movements: Role of peripheral retinal stimuli. *Archives of Ophthalmology* 21 (1939): 486–91.

Brock FW. Pitfalls in orthoptic training of squints. *Optometric Weekly* 32 (1941): 1185–89.

118 ***I experienced another curious effect with the rope circle vectogram that optometrists call the small in, large out (SILO) phenomenon.***

Press LJ. *Applied Concepts in Vision Therapy*. St. Louis, MO: Mosby, 1997, 232–34.

Scheiman M, Wick B. *Clinical Management of Binocular Vision: Heterophoric, Accommodative, and Eye Movement Disorders*. 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2002, 130–33.

121 ***I was quite happy about "getting" some random dot stereograms because many scientists believe that seeing images in these stereograms, images***

that cannot be seen with monocular cues alone, is the ultimate proof that a person has stereopsis.

Bela Julesz pioneered the use of random dot stereograms in perceptual studies.

Julesz B. *Foundations of Cyclopean Perception*. Chicago: University of Chicago Press, 1971.

Random dot stereograms are often used as a clinical test for stereopsis, but I question whether these stereograms provide the best measure of the emergence of stereopsis in individuals with amblyopia and strabismus. Not only must the patient use retinal disparity cues to see random dot stereograms, but he must give these cues top priority in his interpretation of the figure. If the patient has been stereoblind since early childhood, he has depended upon monocular cues to interpret distance and depth. These monocular cues may continue to dominate even after he gains stereopsis, and monocular cues will tell him that the stereogram is a flat drawing. In his interpretation of real objects in the real three-dimensional world, monocular and retinal disparity cues usually provide correlated, not conflicting, information and will combine to give a view seen in compelling depth.

In addition, many strabismics and amblyopes suffer from the crowding phenomenon. They can identify a letter on an eye chart more easily if the letter is seen in isolation rather than being flanked by other letters.

Irvine RS. Amblyopia ex anopsia. Observations on retinal inhibition, scotoma, projection, light difference discrimination and visual acuity. *Transactions of the American Ophthalmological Society* 46 (1948): 527–75.

Von Noorden GK. *Binocular Vision and Ocular Motility*. New York: Mosby, 1996, 225–28.

Levi DM, Song S, Pelli D. Amblyopic reading is crowded. *Journal of Vision* 7 (2007): article 21, 1–17.

The crowding phenomenon can make it difficult to see individual dots or clusters of dots in random dot stereograms. With this in mind, Westheimer and McKee came up with a stereopsis test that, like random dot stereograms, lacks monocular cues but can be seen by someone who has stereopsis but experiences crowding.

Westheimer G, McKee SP. Stereogram design for testing local stereopsis. *Investigative Ophthalmology and Visual Science* 19 (1980): 802–809.

Finally, it is possible to see random dot stereograms even with poor stereovision. For example, Tara Fitzpatrick is an exotrope who had surgery that cosmetically aligned her eyes. However, she has had no vision therapy. When she fixates with one eye, the other eye turns out, although the turn is not noticeable to the casual observer. She can pull her eyes into position to see a random dot stereogram. However, posturing her eyes for stereovision takes a great deal of effort, so she does not normally do this. Instead, she uses one eye for distance viewing and the other eye for near. Although she can see a random dot stereogram, she does not see like a person with normal stereovision.

123 This new sense of immersion in space is completely captivating and enchanting.

I was fascinated to read on the Internet a piece by music critic Nick Coleman, who lost hearing in one ear. Music now seemed flat to him. It lost its emotionality, its spaciousness; it no longer surrounded and inhabited him. He even quoted from "Stereo Sue," Oliver Sacks' account of my story, in which I described my joy at being "inside" a snowfall. The sense of immersion that I gained when I learned to see with two eyes is what he lost when he could no longer hear through two ears.

Coleman N. Life in mono. *Guardian*, February 19, 2008. Available online at www.guardian.co.uk/lifeandstyle/2008/feb/19/healthandwellbeing.classicalmusicandopera.

123 Indeed, Rachel Cooper, who had a form of amblyopia (lazy eye), notes that before gaining stereopsis, "It felt like I was here and everything I was looking at was over there."

See online at http://children-special-needs.org/lazy_eye/lazy_eye.html.

125 Although the estimate of the object's exact location or depth is not precise, you have an impression of its "nearerness" or "furtherness."

This sensation is called qualitative stereopsis.

Ogle KN. Disparity limits of stereopsis. *AMA Archives of Ophthalmology* 48 (1952): 50–60.

Westheimer G, Tanzman IJ. Qualitative depth localization with diplopic images. *Journal of the Optical Society of America* 46 (1956): 116–17.

Brock FW. Visual training—Part III. *Optometric Weekly* 46–50 (1955–59).

Brock FW. A comparison between strabismic seeing and normal binocular vision. *Journal of the American Optometric Association* 31 (1959): 299–304.

125 It was this newfound sense of stereo depth for objects all around me that gave me the powerful feeling of being enveloped by the world.

Margaret Corbit, a fifty-nine-year-old artist with amblyopia, also described to me how her sense of space changed when she consulted a developmental optometrist and recently gained stereovision. Like me, she used to see the world in a few discrete planes. There might be a flat plane of objects seen in detail close to her, another plane at mid-distance, and then a vague flat background. She drew and painted that way too. Margaret also struggled to draw in perspective, but without a good sense of depth and distance, she was not particularly bothered by this problem. In fact, she hesitated to go for vision therapy because she was not sure that gaining stereopsis would be good for her art. She worried that seeing in stereo would compel her to render things in proper depth and perspective and that this would take the fun out of drawing. Now she can turn her stereopsis on and off and is captivated by her new stereovision and sense of space. So far, her experience is enriching her playful treatment of these concepts in her art.

126 I learned that the same neurons and circuits that give us stereopsis may also provide us with our sensation of depth through motion parallax.

Bradley CD, Qian N, Anderson RA. Integration of motion and stereopsis in middle temporal cortical area of macaques. *Nature* 373 (1995): 609–11.

Pack CC, Born RT, Livingstone MS. Two-dimensional substructure of stereo and motion interactions in macaque visual cortex. *Neuron* 37 (2003): 525–35.

Roy JP, Komatsu H, Wurtz RH. Disparity sensitivity of neurons in monkey extrastriate area MST. *Journal of Neuroscience* 12 (1992): 2478–92.

Upadhyay UD, Page WK, Duffy CJ. MST responses to pursuit across optic flow with motion parallax. *Journal of Neurophysiology* 84 (2000): 818–26.

126 What's more, experiments by neurobiologist Mark Nawrot and his colleagues at North Dakota State University have identified the signals coming into the brain that provide us with our sense of depth through motion parallax.

Nawrot M, Joyce L. The pursuit theory of motion parallax. *Vision Research* 46 (2006): 4709–25.

Also see Naji JJ, Freeman TC. Perceiving depth order during pursuit eye movement. *Vision Research* 44 (2004): 3025–34.

Psychophysical experiments on humans also indicate that depth perception from stereopsis and motion parallax are not independent processes.

Bradshaw MF, Rogers BJ. The interaction of binocular disparity and motion parallax in the computation of depth. *Vision Research* 36 (1996): 3457–68.

126 ***The same researchers have also reported that individuals with crossed eyes and amblyopia have a poor sense of depth through motion parallax.***

Nawrot M, Frankl M, Joyce L. Concordant eye movement and motion parallax asymmetries in esotropia. *Vision Research* 48 (2008): 799–808.

Thompson AM, Nawrot M. Abnormal depth perception from motion parallax in amblyopic observers. *Vision Research* 39 (1999): 1407–13.

127 ***So, I went back to the library to read about structure from motion and was not surprised to learn that the capacities to see depth through stereopsis and to determine structure from motion are linked.***

Richards W, Lieberman HR. Correlation between stereo ability and the recovery of structure-from-motion. *American Journal of Optometry and Physiological Optics* 62 (1985): 111–18.

130 ***With my new outlook, all of my senses were awakened.***

These experiences were beautifully described by Rebecca Penneys, an accomplished concert pianist and professor of piano whose eyes began to cross at age two. Although she had three surgeries, she did not gain stereovision until she engaged in optometric vision therapy with optometrist Ray Gottlieb in her forties. She writes,

> Thinking back on it all again makes me want to reiterate that having full depth perception affected my whole personality and being, and was one of the most positive and incredible experiences of my life. It changed my hearing, my perceptual abilities in general, made me happier. I was able to learn faster and understood everything more completely from that moment on. It was an enormous "a-ha." The *stress* of seeing was replaced by the *joy* of sight.

131 ***Most surprising to me was that the change in my vision affected the way that I thought.***

A fascinating discussion of the connection between vision and thought can be found in the following book:

Arnheim R. *Visual Thinking.* Berkeley: University of California Press, 1969.

Chapter 8: Nature and Nurture

133 ***Although clinical tests in Dr. Ruggiero's office confirmed that I now saw in stereo, I was not totally convinced.***

Following are the records contrasting the results of my clinical tests on November 20, 2001 and January 22, 2008.

	November 20, 2001	January 22, 2008
Wirt circles	No measurable stereoacuity	Stereoacuity of 70 arcseconds
Random dot E test	Fail	Pass
Keystone skills	Alternating fixation, no superimposition or fusion	Binocular vision with superimposition and fusion
Worth 4 dot	Left-eye suppression at intermediate and far distance (20 feet). Double vision (diplopia) at near (16 inches)	See all four dots to fifteen feet.
Cover test	Constant left-eye esotropia at distance, intermediate, and near. 8 Prism diopters of left esotropia at far; 25 prism diopters of left esotropia at near with right hypertropia at all viewing distances	Orthophoric at all viewing distances; small right hyperphoria
Fusion	Binocular fusion not possible at any viewing distance; simultaneous awareness led to diplopia	Fusion at all viewing distances and directions of gaze
Refraction	Right eye: –1.00–0.75 x 55 Left eye: –1.25–0.50 x 65 Near vision: +1.25	Right eye: –1.25–0.50 x 62 Left eye: –1.50–0.75 x 72 Near vision: +2.50
Visual acuity	Right eye: w/o glasses: 20/50; w/glasses: 20/20 Left eye: w/o glasses: 20/60; w/glasses: 20/20 Both eyes w/glasses: 20/20	Right eye: w/o glasses: 20/30; w/ glasses: 20/20 Left eye: w/o glasses: 20/40; w/glasses: 20/20 Both eyes w/glasses: 20/16

133 Some doctors argued that I must have had Duane's syndrome.

For information on Duane's syndrome, see Von Noorden GK. *Binocular Vision and Ocular Motility*. 5th ed. New York: Mosby, 1996, 430–37.

134 ***In the late 1800s, two great scientists, Ewald Hering and Hermann Von Helmholtz, hotly debated the nature-versus-nurture question with regard to vision.***

Howard IP, Rogers BJ. *Seeing in Depth*. Ontario: I. Porteus, 2002, 41–46.

Turner SR. Vision studies in Germany: Helmholtz versus Hering. *Osiris* 8 (1993): 80–103.

135 ***At that time, treatment for crossed eyes was heavily influenced by Claud Worth, an ophthalmologist and author of* Squint: Its Causes, Pathology and Treatment.**

Worth C. *Squint: Its Causes, Pathology, and Treatment.* Philadelphia: P. Blakiston's Son & Co., 1903. Available online at http://books.google.com/books?id=I0cSAAAAYAAJ&dq=worth,+squint&printsec=frontcover&source=bl&ots=fOhT4UTb4n&sig=parvBDlDOo_c8gEck-lSfudZnT8&hl=en&sa=X&oi=book_result&resnum=1&ct=result#PPP1,M1.

Van Noorden GK. The development of the art and science of strabismology outside North America: Part II. *Journal of AAPOS* 5 (2001): 134–38.

135 ***But in 1939, thirty-six years after the first edition of* Squint *was published, Chavasse challenged Worth's theory by postulating that the ability to fuse depended upon a series of reflexes that developed during childhood.***

Chavasse FB. *Worth's Squint on the Binocular Reflexes and the Treatment of Strabismus*. 7th ed. London: Bailliere, Tindall and Cox, 1939.

135 ***For example, in a paper published in 1951, developmental biologist and Nobel laureate Roger Sperry demonstrated that neuronal circuitry between the eye and brain in fish and amphibians was "hardwired."***

Sperry RW. Developmental patterning of neural circuits. *Chicago Medical School Quarterly* 12 (1951): 66–73.

Sperry RW. The eye and the brain. *Scientific American* 194 (1956): 48–52.

Both of these articles are available online at www.rogersperry.info.

136 ***One such behavior, known as imprinting, was first noted by the naturalist Douglas Alexander Spalding in 1873 and described in detail in the 1930s by the great animal behaviorist Konrad Lorenz.***

Lorenz K. The companion in the bird's world. *Auk* 54 (1937): 245–73. Available online at http://elibrary.unm.edu/sora/Auk/v054n03/p0245-p0273.pdf.

Spalding DA. Instinct, with original observations on young animals. *Macmillan's Magazine* 27 (1873): 282–93; reprinted in *Animal Behavior* 2 (1954): 2–11.

A delightful book by Lorenz on animal behavior is

Lorenz KZ. *King Solomon's Ring*. New York: Thomas Y. Crowell Co., 1952.

136 ***These were among the observations and ideas under discussion by scientists at the time that David Hubel and Torsten Wiesel began their studies of the mammalian visual system.***

Hubel DH, Wiesel TN. *Brain and Visual Perception: The Story of a 25-Year Collaboration.* Oxford: Oxford University Press, 2005.

137 ***By observing the responses of individual neurons to patterns of light, Hubel and Wiesel uncovered some of the underlying neural mechanisms for vision.***

Hubel DH. *Eye, Brain, and Vision*. New York: Scientific American Library, 1995. Also available online at http://hubel.med.harvard.edu/bcontex.htm.

138 ***In the primary visual cortex, Hubel and Wiesel discovered binocular neurons.***

Other investigators have extended the monocular/binocular classification of neurons by looking at the response of neurons to simultaneous input from both eyes. Some neurons, for example, may appear monocular if the stimulus is presented to only one eye at a time. Thus, a given neuron may respond, for example, if only the left eye is stimulated and, according to Hubel and Wiesel's original scheme, would be classified as monocular. However, the same neuron may show a stronger or weaker response if the stimulus is presented to both eyes simultaneously rather than just to one eye. Thus, input from both eyes actually affects the neuron's response. See, for example, Ohzawa I, Freemam RD. The binocular organization of simple cells in the cat's visual cortex. *Journal of Neuroscience* 56 (1986): 243–59.

Chino YM, Smith III EL, Yoshida K, Cheng H, Harmamoto J. Binocular interactions in striate cortical neurons of cats reared with discordant visual inputs. *Journal of Neuroscience* 14 (1994): 5050–67.

138 ***In 1965, they published a pivotal paper on strabismus.***

Hubel DH, Wiesel TN. Binocular interaction in striate cortex of kittens reared with artificial squint. *Journal of Neurophysiology* 28 (1965): 1041–59.

138 ***Particularly striking to the scientists was that these effects were found only in young animals.***

Yinon U. Age dependence of the effect of squint on cells in kittens' visual cortex. *Experimental Brain Research* 26 (1976): 151–57.

Wiesel TN. Nobel lecture: The postnatal development of the visual cortex and the influence of environment (1981). In Hubel DH, Wiesel TN. *Brain and Visual Perception: The Story of a 25-Year Collaboration.* Oxford: Oxford University Press, 2005.

139 ***They found that about half of the children developed some stereovision if their eyes were aligned and stayed aligned during the first year of life.***

Costenbacher FD. Infantile esotropia. *Transactions of the American Ophthalmological Society* 59 (1961): 397–429.

Taylor DM. Is congenital esotropia functionally curable? *Transactions of the American Ophthalmological Society* 70 (1972): 529–76.

Ing MR. Early surgical alignment for congenital esotropia. *Transactions of the American Ophthalmological Society* 79 (1981): 625–63.

See also the following later studies: Birch EE, Fawcett S, Stager DR. Why does early surgical alignment improve stereoacuity outcomes in infantile esotropia? *Journal of AAPOS* 4 (2000): 10–14.

Birch EE, Felius J, Stager Sr DR, Weakley Jr DR, Bosworth RG. Pre-operative stability of infantile esotropia and post-operative outcome. *American Journal of Ophthalmology* 138 (2004): 1003–9.

Birch EE, Stager Sr DR. Long-term motor and sensory outcomes after early surgery for infantile esotropia. *Journal of AAPOS* 10 (2006): 409–13.

Birch EE, Stager DR, Everett ME. Random dot stereoacuity following surgical correction of infantile esotropia. *Journal of Pediatric Ophthalmology and Strabismus* 32 (1995): 231–35.

Helveston EM, Neely DF, Stidham DB, Wallace DK, Plager DA, Spunger DT. Results of early alignment of congenital esotropia. *Ophthalmology* 106 (1999): 1716–26.

Hiles DA, Watson BA, Biglan AW. Characteristics of infantile esotropia following early bimedial rectus recession. *Archives of Ophthalmology* 98 (1980): 697–703.

Ing MR, Okino LM. Outcome study of stereopsis in relation to duration of misalignment in congenital esotropia. *Journal of AAPOS* 6 (2002): 3–8.

Kushner BJ, Fisher M. Is alignment within 8 prism diopters of orthotropia a successful outcome for infantile esotropia surgery? *Archives of Ophthalmology* 114 (1996): 176–80.

Park MM. Stereopsis in congenital esotropia. *American Orthoptic Journal* 47 (1997): 99–102.

140 ***"A missing aspect of this work is knowledge of the time course of the strabismus animals, cats or monkeys, and in the monkeys the possibilities of recovery."***

Hubel DH, Wiesel TN. *Brain and Visual Perception*. New York: Oxford University Press, 2005, 590.

As Hubel had mentioned to me, animal studies have not clearly established a critical period for strabismus. To truly delineate a critical period, you must demonstrate that the effects of strabismus on cortical wiring cannot be reversed after a certain age. As in my case, surgical repair may not be enough to promote a change in vision. To replicate my visual experience in a monkey, you would have to teach the animal to perform vision therapy, a hard and tedious task. But two years ago, a research group at the University of Houston School of Optometry performed this sort of experiment. They made infant monkeys optically strabismic with prisms. The prisms shifted the visual field of the two eyes in such a way that the animals could not fuse images. When the prisms were removed from the animals at age fourteen weeks, they were stereoblind. At the age of two years, that is, as young adults, the stereoblind monkeys were given stereovision training. Following training, the strabismic monkeys improved their stereoacuity. What's more, the number of binocular neurons in their visual cortex increased. This experiment indicates that the proper kind of training or therapy can change cortical wiring even in an adult individual who has been stereoblind since early infancy.

Nakatsuka C, Zhang B, Watanabe I, Zheng J, Bi H, Ganz L, Smith EL, Harwerth RS, Chino YM. Effects of perceptual learning on local stereopsis and neuronal responses of V1 and V2 in prism-reared monkeys. *Journal of Neurophysiology* 97 (2007): 2612–26.

140 ***For example, binocular neurons sensitive to retinal disparity are found in one-week-old macaque monkeys, the earliest age at which recordings of nerve impulses can be made.***

Chino YM, Smith III EL, Hatta S, Cheng H. Postnatal development of binocular disparity sensitivity in neurons of the primate visual cortex. *Journal of Neuroscience* 17 (1997): 296–307.

In addition, binocular, disparity-sensitive neurons have been found in newborn lambs that have not been exposed to light.

Clarke PGH, Ramachandran VS, Whitteridge FRS. The development of the binocular depth cells in the secondary visual cortex of the lamb. *Proceedings of the Royal Society of London B* 204 (1979): 455–65.

Ramachandran VS, Clarke PD, Whitteridge D. Cells selective to binocular disparity in the cortex of newborn lambs. *Nature* 268 (1977): 333–35.

Finally, binocular vision may be dependent upon the formation of ocular dominance columns in the visual cortex, and these columns complete formation shortly after birth.

Horton JC, Hocking DR. An adult-like pattern of ocular dominance columns in striate cortex of newborn monkeys prior to visual experience. *Journal of Neuroscience* 16 (1996): 1791–807.

LeVay S, Wiesel TN, Hubel DH. The development of ocular dominance columns in normal and visually deprived monkeys. *Journal of Comparative Neurology* 191 (1980): 1–51.

140 Although babies are probably born with binocular neurons, they do not demonstrate a capacity for stereovision until about four months of age.

Birch EE, Shimojo S, Held R. Preferential-looking assessment of fusion and stereopsis in infants aged 1–6 months. *Investigative Ophthalmology and Visual Science* 26 (1985): 366–70.

Fox R, Aslin RN, Shea SL, Dumais ST. Stereopsis in human infants. *Science* 207 (1980): 323–24.

Petrig B, Julesz B, Kropfl W, Baumgartner G, Anliker M. Development of stereopsis and cortical binocularity in human infants: Electrophysiological evidence. *Science* 213 (1981): 1402–5.

Thorn F, Gwiazda J, Cruz AA, Bauer JA, Held R. The development of eye alignment, convergence, and sensory binocularity in young infants. *Investigative Ophthalmology and Visual Science* 35 (1994): 544–53.

141 So, I was intrigued to read studies published in the mid-1980s by Eileen Birch and David Stager of the Retina Foundation of the Southwest.

Birch EE, Stager DR. Monocular acuity and stereopsis in infantile esotropia. *Investigative Ophthalmology and Visual Science* 26 (1985): 1624–30.

Stager DR, Birch EE. Preferential-looking acuity and stereopsis in infantile esotropia. *Journal of Pediatric Ophthalmology and Strabismus* 23 (1986): 160–65.

Also see Bechtoldt HP, Hutz CS. Stereopsis in young infants and stereopsis in an infant with congenital esotropia. *Journal of Pediatric Ophthalmology and Strabismus* 16 (1979): 49–54.

142 ***Their experiments demonstrate that strabismic individuals who flunk the standard stereopsis tests used in the eye doctor's office may be able to see in 3D when they look at large or moving targets located in their peripheral visual fields.***

Kitaoji H, Toyama K. Preservation of position and motion stereopsis in strabismic subjects. *Investigative Ophthalmology and Visual Science* 28 (1987): 1260–67.

O'Shea RP, McDonald AA, Cumming A, Pearl D, Sanderson G, Molteno AC. Interocular transfer of the movement aftereffect in central and peripheral vision of people with strabismus. *Investigative Ophthalmology and Visual Science* 35 (1994): 313–17.

Sireteanu R. Binocular vision in strabismic humans with alternating fixation. *Vision Research* 22 (1982): 889–96.

Sireteanu R, Fronius M, Singer W. Binocular interaction in the peripheral visual field of humans with strabismic and anisometropic amblyopia. *Vision Research* 21 (1981): 1065–74.

143 ***Indeed, Frederick Brock noted, "Nearly all strabismics have occasional moments when they maintain binocular vision. The only reason this is not generally known is that most of us [eye doctors] have never taken the trouble to discover the fact."***

Brock FW. *Lecture Notes on Strabismus*. Meadville, PA: Keystone View Co., n.d.

143 ***One way that Dr. Brock and other optometrists promoted this latent stereovision in their patients was to project large stereo targets onto the wall.***

Brock FW. Pitfalls in orthoptic training of squints. *Optometric Weekly* 32 (1941): 1185–89.

143 ***The vast majority of these experiments have involved recordings of neurons that respond to only the central 5° of the visual field.***

One study did report recordings made from noncentral neurons in a strabismic animal, and these neurons remained binocular.

Sengpiel F, Blakemore C. The neural basis of suppression and amblyopia in strabismus. *Eye* 10 (1996): 250–58.

144 ***Optometrist Paul Harris calls this spectrum the binocular continuum.***

Harris P. The binocular continuum. *Journal of Behavioral Optometry* 13 (2002): 99–103.

144 ***How far a person can move along this spectrum depends in large part upon how he has adapted to his visual disorder.***

In general, strabismics who have a very large eye turn or who demonstrate an entrenched anomalous correspondence will have a more difficult time gaining normal binocular vision.

Etting GL. Strabismus therapy in private practice: Cure rates after three months of therapy. *Journal of the American Optometric Association* 49 (1978): 1367–73.

Flax N, Duckman RH. Orthoptic treatment of strabismus. *Journal of the American Optometric Association* 49 (1978): 1353–61.

Ludlam WM. Orthoptic treatment of strabismus: A study of one hundred forty-nine non-operated, unselected, concomitant strabismus patients completing orthoptic training at the Optometric Center of New York. *American Journal of Optometry and Archives of the American Academy of Optometry* 38 (1961): 369–88.

Ludlam WM, Kleinman BI. The long range results of orthoptic treatment of strabismus. *American Journal of Optometry and Archives of the American Academy of Optometry* 42 (1965): 647–84.

Is it possible, however, that some people are simply born with deficient binocular wiring, and that is why they develop strabismus and never see in 3D? Do people with a family history of strabismus inherit a deficient number of binocular neurons and a poor binocular system? Surprisingly, patients with a family history of strabismus achieve as much or more success with optometric vision therapy than those with no family history. So, even these patients probably begin life with binocular neurons and have the potential to develop stable binocular vision with stereopsis.

Flom MC. Issues in the clinical management of binocular anomalies. In Rosenbloom AA, Morgan MW (eds.), *Principles and Practice of Pediatric Optometry*. Philadelphia: JB Lippincot, 1990.

Press, LJ. *Applied Concepts in Vision Therapy*. St. Louis, MO: Mosby, 1997, 96.

146 ***The best way to test this was to simulate congenital cataracts in an animal and then make recordings from visual neurons.***

Wiesel TN, Hubel DH. Single-cell responses in striate cortex of kittens deprived of vision in one eye. *Journal of Neurophysiology* 26 (1963): 1003–17.

Hubel DH, Wiesel TN, LeVay S. Plasticity of ocular dominance columns in monkey striate cortex. *Philosophical Transactions of the Royal Society of London B* 278 (1977): 377–409.

LeVay S, Wiesel TN, Hubel DH. The development of ocular dominance columns in normal and visually deprived monkeys. *Journal of Comparative Neurology* 191 (1980): 1–51.

Hubel and Wiesel's experiments indicate that a child born with a cataract should have surgery to remove the cataract within the first months of life, a practice now commonly followed.

Birch EE, Stager DR. Prevalence of good visual acuity following surgery for congenital unilateral cataract. *Archives of Ophthalmology* 106 (1988): 40–43.

146 ***If, while the animals were still very young, the situation was reversed so that the covered eye was opened and the open eye was occluded, then a change occurred in the cortical neurons.***

Blakemore C, Van Sluyters RC. Reversal of the physiological effects of monocular deprivation in kittens: Further evidence of a sensitive period. *Journal of Physiology* 237 (1974): 195–216.

LeVay S, Wiesel TN, Hubel DH. The development of ocular dominance columns in normal and visually deprived monkeys. *Journal of Comparative Neurology* 191 (1980): 1–51.

147 ***They mistakenly assume that the "critical period" for the development of amblyopia is the same as the "critical period" for its rehabilitation.***

There are different critical periods for the development of various neuronal properties, such as direction selectivity and binocularity, and for the development of different perceptual properties, such as acuity and stereopsis. In addition, the critical period for the development of a particular property may be different from the critical period for the disruption of that property or for recovery from disruption.

Daw NW. *Visual Development.* 2nd ed. New York: Springer, 2006, ch. 9.

147 ***Amblyopia can be caused by strabismus when only one eye does the looking.***

Daw NW. *Visual Development*. New York: Springer, 2006, ch. 8.

Ciuffreda KJ, Levi DM, Selenow A. *Amblyopia: Basic and Clinical Aspects.* Boston: Butterworth-Heinemann, 1991.

148 ***So, unlike the animals in the monocular deprivation experiments, children with strabismic amblyopia have not been deprived of all vision in one eye since the first days of life.***

In Hubel and Wiesel's studies, kittens that had been made strabismic did not develop amblyopia but alternated fixation between the two eyes instead. Thus, Hubel and Wiesel were not able to develop a cat model for strabismic amblyopia. In a later study, they were able to produce one monkey with strabismic amblyopia.

Hubel DH, Wiesel TN. Binocular interaction in striate cortex of kittens reared with artificial squint. *Journal of Neurophysiology* 28 (1965): 1041–59.

Wiesel TN. The postnatal development of the visual cortex and the influence of environment. *Nature* 299 (1982): 583–91. (This Nobel lecture was delivered on December 8, 1981, and is also reprinted in Hubel DH, Wiesel TN. *Brain and Visual Perception: The Story of a 25-Year Collaboration.* Oxford: Oxford University Press, 2005, 686–704; see also 591.)

148 ***Under these conditions, a condition called anisometropic amblyopia may develop in the more farsighted eye.***

Daw NW. *Visual Development*. New York: Springer, 2006, ch. 8.

Ciuffreda KJ, Levi DM, Selenow A. *Amblyopia: Basic and Clinical Aspects.* Boston: Butterworth-Heinemann, 1991.

148 ***Not surprisingly, these investigators found that the changes in circuitry in the visual cortex were not as severe as in the cortex of the monocularly deprived animals.***

Kiorpes L, Boothe RG, Hendrickson AE, Movshon JA, Eggers HM, Gizzi MS. Effects of early unilateral blur on the macaques' visual system. I. Behavioral observations. *Journal of Neuroscience* 7 (1987): 1318–26.

Hendrickson AE, Movshon JA, Eggers HM, Gizzi MS, Boothe RG, Kiorpes L. Effects of early unilateral blur on the macaque's visual system. II. Anatomical observations. *Journal of Neuroscience* 7 (1987): 1327–39.

Movshon JA, Eggers HM, Gizzi MS, Hendrickson AE, Kiorpes L, Boothe RG. Effects of early unilateral blur on the macaques' visual system. III. Physiological observations. *Journal of Neuroscience* 7 (1987): 1340–51.

Kiorpes L, Kiper D, O'Keefe L, Cavanaugh J, Movshon J. Neuronal correlates of amblyopia in the visual cortex of macaque monkeys with experimental strabismus and anisometropia. *Journal of Neuroscience* 18 (1998): 6411–24.

See also Eggers HM, Blakemore C. Physiological basis of anisometropic amblyopia. *Science* 201 (1978): 264–67.

Horton JC, Stryker MP. Amblyopia induced by anisometropia without shrinkage of ocular dominance columns in human striate cortex.

Proceedings of the National Academy of Sciences 90 (1993): 5494–98.

149 ***One drawback of occlusion therapies is that the open eye may improve its acuity at the expense of the occluded, or "good," eye.***

Birch EE, Stager DR, Berry P, Everett ME. Prospective assessment of acuity and stereopsis in amblyopic infantile esotropes following early surgery. *Investigative Ophthalmology and Visual Science* 31 (1990): 758–65.

149 ***Indeed, in his address upon winning the Nobel Prize for his research on vision, Torsten Wiesel expressed these concerns.***

Wiesel TN. The postnatal development of the visual cortex and the influence of environment. *Nature* 299 (1982): 583–91. (This Nobel lecture was delivered on December 8, 1981, and is also reprinted in Hubel DH, Wiesel TN. *Brain and Visual Perception: The Story of a 25-Year Collaboration.* Oxford: Oxford University Press, 2005, 686–704.)

In addition, a study of 427 amblyopic adults suggests that a lack of normal binocular function and stereovision is correlated with a poor ability to identify letters on eye charts (optotype, or Snellen, acuity), a task that requires interpretation of complex visual patterns.

McKee SP, Levi DM, Movshon JA. The pattern of visual deficits in amblyopia. *Journal of Vision* 3 (2003): 380–405.

Furthermore, in formerly monocular-deprived kittens, just brief periods of normal binocular vision are sufficient to promote the recovery of normal visual acuity in the deprived eye. These periods of normal vision provide correlated binocular input onto visual cortical neurons.

Mitchell DE. A special role for binocular visual input during development and as a component of occlusion therapy for treatment of amblyopia. *Restorative Neurology and Neuroscience* 26 (2008): 425–34.

Kind PC, Mitchell DE, Ahmed B, Blakemore C, Bonhoeffer T, Sengpiel F. Correlated binocular activity guides recovery from monocular deprivation. *Nature* 416 (2002): 430–33.

Mitchell DE, Kind PC, Sengpiel F, Murphy K. Short periods of concordant binocular vision prevent the development of deprivation amblyopia. *European Journal of Neuroscience* 23 (2006): 2458–66.

Schwarzkopf DS, Vorbyov V, Mitchell DE, Sengpiel F. Brief daily binocular vision prevents monocular deprivation effects in visual cortex. *European Journal of Neuroscience* 25 (2007): 270–80.

149 ***Scientific studies have revealed that the amblyopic eye not only has reduced acuity but provides a distorted sense of space, tracks objects less accurately, and is the poorer eye for directing hand movements.***

Bedell HE, Flom MC. Monocular spatial distortion in strabismic amblyopia. *Investigative Ophthalmology and Visual Science* 20 (1981): 263–68.

Bedell HE, Flom MC. Normal and abnormal space perception. *American Journal of Optometry and Physiological Optics* 60 (1983): 426–35.

Daw NW. *Visual Development*. New York: Springer, 2006, ch. 8.

Hess RF, Campbell FW, Greenhalgh T. On the nature of the neural abnormality in human amblyopia: Neural aberrations and neural sensitivity loss. *Pflugers Archives* 377 (1978): 201–7.

Hess RF, Wang Y-Z, Demanins R, Wilkinson F, Wilson HR. A deficit in strabismic amblyopia for global shape detection. *Vision Research* 39 (1999): 901–14.

Howard IP, Rogers BJ. *Seeing in Depth*. Ontario: I. Porteus, 2002, ch. 13.

Levi DM, Song S, Pelli DG. Amblyopic reading is crowded. *Journal of Vision* 7 (2007): article 21, 1–17.

McKee SP, Levi DM, Movshon JA. The pattern of visual deficits in amblyopia. *Journal of Vision* 3 (2003): article 5, 380–405.

Simmers AJ, Ledgeway T, Mansouri B, Hutchisnon CV, Hess RF. The extent of the dorsal extra-striate deficit in amblyopia. *Vision Research* 46 (2006): 2571–80.

Sireteanu R, Baumer CC, Iftime A. Temporal instability in amblyopic vision: Relationship to a displacement map of visual space. *Investigative Ophthalmology and Visual Science* 49 (2008): 3940–54.

149 To reduce amblyopia, you must train the eye and brain in many different tasks.

Ciuffreda KJ, Levi DM, Selenow A. *Amblyopia: Basic and Clinical Aspects.* Boston: Butterworth-Heinemann, 1991.

Griffin JR, Grisham JD. *Binocular Anomalies: Diagnosis and Vision Therapy*. New York: Butterworth-Heinemann, 2002.

Krumholtz I, Fitzgerald D. Efficacy of treatment modalities in refractive amblyopia. *Journal of the American Optometric Association* 70 (1999): 399–404.

Press, LJ. *Applied Concepts in Vision Therapy*. St. Louis, MO: Mosby, 1997.

Wick B, Wingard M, Cotter S, Scheiman M. Anisometropic amblyopia: Is the patient ever too old to treat? *Optometry and Vision Science* 69 (1992): 866–78.

149 In 2007, Robert Hess and his colleagues at McGill University published a study demonstrating that people with amblyopia do not discount all information from the amblyopic eye.

Baker, DH, Meese TS, Mansouri B, Hess RF. Binocular summation of contrast remains intact in strabismic amblyopia. *Investigative Ophthalmology and Visual Science* 48 (2007): 5332–38.

150 They have developed a class of procedures called "monocular fixation in a binocular field" (MFBF).

Brock FW. New methods for testing binocular control. *Journal of the American Optometric Association* 34 (1963): 443–50.

Cohen AH. Monocular fixation in a binocular field. *Journal of the American Optometric Association* 52 (1981): 801–6.

Press LJ. *Applied Concepts in Vision Therapy*. St. Louis, MO: Mosby, 1997.

Schapero M. *Amblyopia.* Philadelphia: Clinton Book Co., 1971, 253–54.

151 In one published study, one-third of the 203 amblyopes examined, many of whom were older adults, experienced significantly improved eyesight in their amblyopic eye after vision was lost in the fellow eye.

Vereecken EP, Brabant P. Prognosis for vision in amblyopia after the loss of the good eye. *Archives of Ophthalmology* 102 (1984): 220–24.

Daw NW. Critical periods in the visual system. In Hopkins B, Johnson SP (eds.), *Neurobiology of Infant Vision.* Westport, CT: Praeger Pub., 2003, 64–67.

151 As early as 1957, Carl Kupfer published a study in which he showed dramatic improvements in adult amblyopes after a four-week period of patching combined with vision therapy.

Kupfer C. Treatment of amblyopia ex anopsia in adults: A preliminary report of seven cases. *American Journal of Ophthalmology* 43 (1957): 918–22.

152 In a 1977 study, Martin Birnbaum and his colleagues reviewed twenty-three published studies on amblyopia and reported that improvements in eyesight were found for all ages.

Birnbaum MH, Koslowe K, Sanet R. Success in amblyopia therapy as a function of age: A literature survey. *American Journal of Optometry and Physiological Optics* 54 (1977): 269–75.

In 1992, Bruce Wick and colleagues published a study in which dramatic improvements in acuity of the amblyopic eye as well as binocular vision were obtained in anisometropic amblyopes with the proper glasses, part-time occlusion, and vision therapy. This study contrasted with published results by Meyer and colleagues, who found that occlusion treatment alone produced dramatic improvements only in patients under ten years of age. The difference between these two studies was the use of vision therapy.

Wick B, Wingard M, Cotter S, Scheiman M. Anisometropic amblyopia: Is the patient ever too old to treat? *Optometry and Vision Science* 69 (1992): 866–78.

Meyer E, Mizrahi E, Perlman I. Amblyopia success index: A new method of quantitative assessment of treatment efficacy application in a study of 473 anisometropic amblyopic patients. *Binocular Vision Quarterly* 6 (1991): 75–82.

Other studies demonstrating successful treatment of older amblyopes are listed below:

Pediatric Eye Disease Investigator Group. Randomized trial of treatment of amblyopia in children aged 7 to 17 years. *Archives Ophthalmology* 123 (2005): 437–47.

Rutstein RP, Fuhr PS. Efficacy and stability of amblyopia therapy. *Optometry and Vision Science* 69 (1992): 747–54.

Saulles H. Treatment of refractive amblyopia in adults. *Journal of the American Optometric Association* 58 (1987): 959–60.

Selenow A, Cuiffreda KJ. Vision function recovery during orthoptic therapy in an adult esotropic amblyope. *Journal of the American Optometric Association* 57 (1986): 132–40.

152 For example, exposing adult rats to enriched environments reverses the amblyopia produced by monocular deprivation occurring in infancy.

Sale A, Maya Vetencourt JF, Medini P, Cenni MC, Baroncelli L, De Pasquale R, Maffei L. Environmental enrichment in adulthood promotes amblyopia recovery through a reduction of intracortical inhibition. *Nature Neuroscience* 10 (2007): 679–81.

152 Placing adult rats in the dark for three to ten days can also reverse the effects of monocular deprivation.

He H-Y, Hodos W, Quinlan EM. Visual deprivation reactivates rapid ocular dominance plasticity in adult visual cortex. *Journal of Neuroscience* 261 (2006): 2951–55.

He H-Y, Ray B, Dennis K, Quinlan EM. Experience-dependent recovery of vision following chronic deprivation amblyopia. *Nature Neuroscience* 10 (2007): 1134–36.

152 Studies of "perceptual learning" in human amblyopes pioneered by Dennis Levi and Uri Polat in the mid-1990s demonstrate improvements in eyesight in the amblyopic eye even in adult patients.

Fronius M, Cirina L, Kuhli C, Cordy A, Ohrloff C. Training the adult amblyopic eye with "perceptual learning" after vision loss in the non-amblyopic eye. *Strabismus* 14 (2006): 75–79.

Huang C-B, Zhou Y, Lu, Z-L. Broad bandwidth of perceptual learning in the visual system of adults with anisometropic amblyopia. *Proceedings of the National Academy of Sciences* 105 (2008): 4068–73.

Levi DM. Perceptual learning in adults with amblyopia: A reevaluation of critical periods in human vision. *Developmental Psychobiology* 46 (2005): 222–32.

Li RW, Klein SA, Levi DM. Prolonged perceptual learning of positional acuity in adult amblyopia: Perceptual template retuning dynamics. *Journal of Neuroscience* 28 (2008): 14223–29.

Polat U, Levi DM. Neural plasticity in adults with amblyopia. *Proceedings of the National Academy of Sciences* 93 (1996): 6830–34.

Polat U, Ma-Naim T, Belkin M, Sagi D. Improving vision in adult amblyopia by perceptual learning. *Proceedings of the National Academy of Sciences* 101 (2004): 6692–97.

Zhou Y, Huang C, Xu P, Tao L, Qiu Z, Li X, Lu Z-L. Perceptual learning improves contrast sensitivity and visual acuity in adults with anisometropic amblyopia. *Vision Research* 46 (2006): 739–50.

153 In contrast, 38 to 50 percent of patients with infantile strabismus and 70 percent of patients whose strabismus develops after the first year acquire stereopsis through optometric vision therapy.

Etting GL. Strabismus therapy in private practice: Cure rates after three months of therapy. *Journal of the American Optometric Association* 49 (1978): 1367–73.

Flax N, Duckman RH. Orthoptic treatment of strabismus. *Journal of the American Optometric Association* 49 (1978): 1353–61.

Ludlam WM. Orthoptic treatment of strabismus: A study of one hundred forty-nine non-operated, unselected, concomitant strabismus patients completing orthoptic training at the Optometric Center of New York. *American Journal of Optometry and Archives of the American Academy of Optometry* 38 (1961): 369–88.

Ludlam WM, Kleinman BI. The long range results of orthoptic treatment of strabismus. *American Journal of Optometry and Archives of the American Academy of Optometry* 42 (1965): 647–84.

Chapter 9: Vision and Revision

156 ***In his fascinating book* Rebuilt: How Becoming Part Computer Made Me More Human, *Michael Chorost, who was hard of hearing as a young child and profoundly deaf in adulthood, describes how he learned to hear again using a cochlear implant.***

Chorost M. *Rebuilt: How Becoming Part Computer Made Me More Human*. New York: Houghton Mifflin Co., 2005, 126.

157 ***Edward Taub and his colleagues at the University of Alabama discovered that the patients most actively involved in their own rehabilitation recovered best from strokes.***

Taub E, Uswatte G, Mark VW, Morris DM. The learned nonuse phenomenon: Implications for rehabilitation. *Europa Medicophysica* 42 (2006): 241–56.

Morris DM, Taub E, Mark VW. Constraint-induced movement therapy: Characterizing the intervention protocol. *Europa Medicophysica* 42 (2006): 257–68.

When a person suffers a stroke, he may lose the use of one of his limbs. Right after the stroke, the amount of brain area used to control, let's say, the affected arm has contracted. The person may have to exert great effort to move the arm, and the resulting movements are clumsy. So, he avoids use of the affected arm and finds other ways to move in order to compensate. With time and healing, he may actually regain better control of the weak arm, but it is too late. He has already learned to discount its use. Taub and his colleagues call this behavior "learned nonuse," and without intervention, this way of moving becomes permanent.

To counteract learned nonuse, Taub and his colleagues developed constraint-induced movement therapy (CI therapy) in which patients wear a restraining device, such as a mitt on the good arm, to force the use of the affected limb. During an intense two-week period, the patients also work in an office with a trained therapist or interventionist and practice arm-movement exercises of increasing difficulty. Taub and his colleagues assumed that these interventions would be the most important in helping their patients use the arm again. So, they were surprised to discover that the patients' ability to use their affected arm in everyday life did not correlate with their ability on motor performance tests. Instead, the most critical component of the therapy was a set of procedures called the transfer package, so named because it involved transferring the skills learned in therapy sessions to the real world. As part of the transfer package, the patients created a list of "activities of daily living" that involved the affected arm, such as tying shoes or eating with a spoon and fork. They then drew up a contract with their interventionist in which they stated how much they would use their affected arm in these activities. They kept a diary of how they were using their weakened limb and discussed with the interventionist how they solved problems involving the use of the arm. Taub writes, "A major difference in CI therapy is *the involvement of the patient as an active participant in all requirements of the therapy* not only during the treatment period but also (and especially) after laboratory therapy has been completed" (emphasis added).

158 ***Indeed, as early as the mid-1900s, Frederick Brock stressed these ideas when he noted that to train strabismics to see with normal binocular vision and stereopsis, you have to challenge them with tasks that are close to, but just beyond, their current skills and with exercises that resemble actions experienced in real life.***

Brock FW. Visual Training—part III. *Optometric Weekly* 46–50 (1955–59).

158 ***If, however, these adults are forced to hunt, then they realign their brain's auditory spatial maps with the prism-altered visual maps.***

Bergan JF, Ro P, Ro D, Knudsen EI. Hunting increases adaptive auditory map plasticity in adult barn owls. *Journal of Neuroscience* 25 (2005): 9816–20.

158 ***The critical period encompasses the developmental stage when the brain changes in response to most strong stimuli, not just to behaviorally relevant ones.***

This idea has been expressed by several investigators: Bao S, Chang EF, Davis JD, Gobeske KT, Merzenich MM. Progressive degradation and subsequent refinement of acoustic representations in the adult auditory cortex. *Journal of Neuroscience* 26 (2003): 10765–75.

Keuroghlian AS, Knudsen EI. Adaptive auditory plasticity in developing and adult animals. *Progress in Neurobiology* 82 (2007): 109–21.

159 ***As I suggest in chapter 6, some of the changes in my brain involved modifications of synaptic connections in the visual cortex, an area of the brain that is highly evolved in humans but much less developed in our distant vertebrate cousins.***

All vertebrate animals have a cerebral cortex, which is an outgrowth of the roof of the forebrain. The cortex, however, takes on a whole new dimension in mammals. Many people learn in school that mammals can be distinguished from nonmammalian vertebrates by the presence of fur or hair for regulating body temperature and mammary glands for suckling the young. As John Allman points out in *Evolving Brains* (New York: Scientific American Library, 2000), another very important distinguishing characteristic of mammals is our many-layered cerebral cortex.

In nonmammalian vertebrates, including fish, amphibians, and reptiles, the cerebral cortex contains one to three layers of cells and is called the dorsal cortex. In contrast, in mammals, the cerebral cortex is made up of six principal layers, some with sublayers, and is called the neocortex.

159 In fact, the wiring in the cerebral cortex reflects the history of our actions and is constantly reshaped by them.

Polley DB, Steinberg EE, Merzenich MM. Perceptual learning directs auditory cortical map reorganization through top-down influences. *Journal of Neuroscience* 26 (2006): 4970–82.

The primary visual, primary auditory, and primary somatosensory cortices are the first areas of the cerebral cortex to receive input from the eyes, ears, and body, respectively. The circuitry of the primary sensory areas was once thought to develop early in life and then remain relatively immune to change. Recent research, however, indicates that this is not the case. For example, in experiments performed in the above-cited paper, adult rats were played a series of tones of different pitches and intensities. One group of rats was rewarded for correctly identifying a tone of a certain (five kilohertz) pitch. The loudness or softness of the five-kilohertz tone did not matter. In contrast, another group was rewarded for correctly identifying a tone of a certain intensity or loudness (twenty-five decibels), but the pitch of the tone did not matter.

Rats who were rewarded if they identified the five-kilohertz tone showed enhanced neuronal responses in their primary auditory cortices to tones of five kilohertz. As a result of their training, their auditory cortex was modified so that more neurons were responsive to the five-kilohertz tone. However, no changes in neuronal responses were seen to tones of different loudness levels. In contrast, rats who were trained to discriminate tones by their loudness showed enhanced neuronal responses to tones of the trained intensity but did not show changes in neuronal responses to pitch.

Particularly striking about these results is that both groups of rats were presented throughout the experiment with the *same* tones. The tones varied in pitch and intensity, and it was up to the rats to pick out the right ones for their reward. The tones themselves provided the external sensory input. The demands of the tasks shaped the relative importance of the input. So, the response of neurons in the brain did not change as a result of simply hearing the tones but instead according to what was important to the rat—to what the rats had to learn to get the reward.

Pleger B, Blankenburg F, Ruff CC, Driver J, Dolan RJ. Reward facilitates tactile judgments and modulates hemodynamic responses in human primary somatosensory cortex. *Journal of Neuroscience* 28 (2008): 8161–68.

In the above-cited study, changes with learning in the human primary somatosensory cortex were observed using functional MRI. Vibrations of two different frequencies were applied to the index finger of human volunteers, and the volunteers then reported which of the two stimuli was at the higher frequency. Prior to this test, the volunteers were shown on a computer screen how much money they would receive for the right answer. Their performance on this task improved with an increase in the size of the monetary reward. After each choice, the volunteers were given visual (but not somatosensory) feedback as to whether or not they had given the right answer and how much money they had earned. Not surprisingly, their somatosensory cortex, the part of the cortex that responds to touch, was active as the volunteers' fingers were vibrated. Intriguing was the fact that the somatosensory cortex reactivated when the volunteers received a visual signal indicating their reward. The investigators postulated that upon receipt of the reward, the somatosensory cortex was reactivated because it was reorganizing itself in a way that made it more sensitive to the relevant vibrations.

160 ***In several different experiments, adult guinea pigs or rats were played a sound of a particular pitch, while neuronal activity was monitored in their auditory cortex.***

Bakin JS, Weinberger NM. Induction of a physiological memory in the cerebral cortex by stimulation of the nucleus basalis. *Proceedings of the National Academy of Sciences* 93 (1996): 11219–24.

Kilgard MP, Merzenich MM. Cortical map reorganization enabled by nucleus basalis activity. *Science* 279 (1998): 1714–18.

160 ***Similar results have also been seen when presentation of a particular stimulus is paired with activation of other neuromodulatory areas of the brain.***

Bao S, Chan VT, Merzenich NM. Cortical remodeling induced by activity of ventral tegmental dopamine neurons. *Nature* 412 (2001): 79–83.

Bear MF, Singer W. Modulation of visual cortical plasticity by acetylcholine and noradrenaline. *Nature* 320 (1986): 172–76.

Gu Q. Neuromodulatory transmitter systems in the cortex and their role in cortical plasticity. *Neuroscience* 111 (2002): 815–35.

Kasamatsu T, Watabe K, Heggelund P, Scholler E. Plasticity in cat visual cortex restored by electrical stimulation of the locus coeruleus. *Neuroscience Research* 2 (1985): 365–86.

Kentros CG, Agnihotri NT, Streater S, Hawkins RD, Kandel ER. Increased attention to spatial context increases both place field stability and spatial memory. *Neuron* 42 (2004): 283–95.

Kojic L, Gu Q, Douglas RM, Cynader MS. Serotonin facilitates synaptic plasticity in kitten visual cortex: An in vitro study. *Developmental Brain Research* 101 (1997): 299–304.

Li S, Cullen WK, Anwyl R, Rowan MJ. Dopamine-dependent facilitation of LTP induction in hippocampal CA1 by exposure to spatial novelty. *Nature Neuroscience* 6 (2003): 526–31.

Weinberger NM. Associative representational plasticity in the auditory cortex: A synthesis of two disciplines. *Learning and Memory* 14 (2007): 1–16.

161 The neuromodulators may have helped to unmask and strengthen connections that had been ineffective but were never entirely lost.

Brocher S, Artola A, Singer W. Agonists of cholinergic and noradrenergic receptors facilitate synergistically the induction of long-term potentiation in slices of rat visual cortex. *Brain Research* 573 (1992): 27–36.

Kasamatsu T, Pettigrew JD. Depletion of brain catecholamines: Failure of ocular dominance shift after monocular occlusion in kittens. *Science* 194 (1976): 206–9.

Kirkwood A, Rozas C, Kirkwood J, Perez F, Bear MF. Modulation of long-term synaptic depression in visual cortex by acetylcholine and norepinephrine. *Journal of Neuroscience* 19 (1999): 1599–609.

161 In addition, the same neuromodulators that triggered and facilitated synaptic changes may have made these changes long-lasting.

Bailey CH, Giustetto M, Huang Y-Y, Hawkins RD, Kandel ER. Is heterosynaptic modulation essential for stabilizing Hebbian plasticity and memory? *Nature Reviews. Neuroscience* 1 (2000): 11–20.

Ma X, Suga N. Long-term cortical plasticity evoked by electric stimulation and acetylcholine applied to the auditory cortex. *Proceedings of the National Academy of Sciences* 102 (2005): 9335–40.

161 ***High levels of neuronal activity in the brainstem and basal forebrain are seen in animals when they are alert and exploring their environment, when they are learning about novel stimuli, and when they anticipate a reward for their actions.***

Aston-Jones G, Rajkowski J, Kubiak P. Conditioned responses of monkey locus coeruleus neurons anticipate acquisition of discriminative behavior in a vigilance task. *Neuroscience* 80 (1997): 697–715.

Corbetta M, Patel G, Shulman GL. The reorienting system of the human brain: From environment to theory of mind. *Neuron* 58 (2008): 306–24.

Richardson RT, DeLong MR. Context-dependent responses of primate nucleus basalis neurons in a go/no-go task. *Journal of Neuroscience* 10 (1990): 2528–40.

162 ***My surprising and delightful views sent me on hunts for new sights.***

Beverly Biderman expresses the same feelings in her book *Wired for Sound: A Journey into Hearing* (Toronto: Trifolium Books, 1998) when she describes going on "sound hunts" after receiving a cochlear implant.

162 ***After training, neurons in the uninjured areas of the somatosensory cortex respond to touch from the affected fingers.***

Xerri C, Merzenich MM, Peterson BE, Jenkins W. Plasticity of primary somatosensory cortex paralleling sensorimotor skill recovery from stroke in adult monkeys. *Journal of Neurophysiology* 79 (1998): 2119–48.

163 ***Not surprisingly, then, neurons have been found in the brain that are sensitive to both tactile and visual input and are involved in our ability to reach for and grasp objects.***

Colby CL, Goldberg ME. Space and attention in parietal cortex. *Annual Review of Neuroscience* 22 (1999): 319–49.

163 ***The responses of some neurons in the visual cortex are modulated by sounds.***

Allman BL, Meredith MA. Multisensory processing in "unimodal" neurons: Cross-modal subthreshold auditory effects in cat extrastriate visual cortex. *Journal of Neurophysiology* 98 (2007): 545–49.]

Capp C, Barone P. Heteromodal connections supporting multisensory integration at low levels of cortical processing in the monkey. *European Journal of Neuroscience* 22 (2005): 2886–902.

Clemo HR, Sharma GK, Allman BL, Meredith MA. Auditory projections to extrastriate visual cortex: Connectional basis for multisensory processing in "unimodal" visual neurons. *Experimental Brain Research* 191 (2008): 37–47.

Wang Y, Simona C, Trotter Y, Barone P. Visuo-auditory interactions in the primary visual cortex of the behaving monkey: Electrophysiological evidence. *BMC Neuroscience* 9 (2008): 79. Available online at www.biomedcentral.com/1471-2202/9/79.

163 The books **Privileged Hands** *and* **Touching the Rock** *both highlight in fascinating detail what it is like to be blind.*

Vermeij G. *Privileged Hands: A Scientific Life*. New York: W. H. Freeman and Co., 1997.

Hull JM. *Touching the Rock: An Experience of Blindness*. New York: Pantheon Books, 1990.

163 Indeed, imaging studies of the brains of individuals who are born blind or become blind in early life indicate that they use their visual cortex for nonvisual activities.

Pascual-Leone A, Amedi A, Fregni F, Merabet LB. The plastic human brain cortex. *Annual Review of Neuroscience* 28 (2005): 377–401.

164 However, the National Federation of the Blind has reported that audible traffic signals can actually compromise safety.

Available online at http://access-board.gov/PROWAC/comments/comments-10–28/mccarthy-j.htm.

164 In Spain, future teachers of the blind must spend a week with blindfolds on in an attempt to experience firsthand what it is like not to see.

Pascual-Leone A, Amedi A, Fregni F, Merabet LB. The plastic human brain cortex. *Annual Review of Neuroscience* 28 (2005): 377–401.

164 Alavaro Pascual-Leone and his colleagues at Harvard University blindfolded sighted individuals for one week and imaged their brains while the participants attempted to identify braille letters or the pitch of a sound.

Pascual-Leone A, Amedi A, Fregni F, Merabet LB. The plastic human brain cortex. *Annual Review of Neuroscience* 28 (2005): 377–401.

Saito DN, Okada T, Honda M, Yonekura Y, Sadato N. Practice makes perfect: The neural substrates of tactile discrimination by Mah-Jong experts include the primary visual cortex. *BBMC Neuroscience* 7 (2006): 79. Available online at http://biomedcentral.com/1471–2202/7/79.

Saito and colleagues have also shown that tactile stimulation can activate the primary visual cortex in normally sighted people. Their study involved participants who were experts at the game Mah-Jong and could readily identify by feel the carved marks in a Mah-Jong tile. When these players felt the tiles with their eyes closed, their primary visual cortex and lateral occipital cortex were activated. Visual cortical areas were not activated by the same task in control observers who did not play Mah-Jong.

165 ***When I consider the extraordinary changes produced in the blindfold study described above, the alterations that may have occurred in my brain do not seem so surprising.***

The visual cortex and neuromodulatory areas may not be the only brain areas involved in my vision changes. The visual cortex has a continual back-and-forth dialogue with a brain region called the thalamus and indirectly the retina, and changes may have occurred in these pathways as well. To learn to see in stereo, I had to concentrate hard on the therapy tasks at hand, and focused attention requires input from nonvisual parts of my cerebral cortex. In fact, imaging studies on humans reveal that a different pattern of whole-brain activity is seen when we focus on a demanding task than when we perform an automatic action.

Corbetta M, Patel G, Shulman GL. The reorienting system of the human brain: From environment to theory of mind. *Neuron* 58 (2008): 306–24.

Fox MD, Corbetta M, Snyder AZ, Vincent JL, Raichle ME. Spontaneous neuronal activity distinguishes human dorsal and ventral attention systems. *Proceedings of the National Academy of Sciences* 103 (2006): 10046–51.

Fox MD, Snyder AZ, Vincent JL, Corbetta M, Van Essen DC, Raichle ME. The human brain is intrinsically organized into dynamic, anticorrelated functional networks. *Proceedings of the National Academy of Sciences* 102 (2005): 9673–78.

For me, stereovision came on gradually, allowing me to see objects close to me, then more distant objects, in three dimensions. For Tracy Gray, the woman with torticollis described in chapter 4, both stereovision and an increase in peripheral vision appeared abruptly and in full measure.

Tracy states, “I was sitting on the sofa in my living room about midnight, and I immediately saw the whole room and all the objects in it in 3D. The breadth of it was not just the 3D vision, but the fact that I was able to take in so much more of the room than I did before.” Jennifer Clark, who wrote to me from England, described a very similar experience. Accounts like Tracy’s and Jennifer’s suggest a sudden and global change in brain state, a change in the activity of whole populations of neurons.