

A Neurobiologist's Notebook

STEREO SUE

Why two eyes are better than one

by Oliver Sacks

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see also Stereo Sue's website: <http://www.stereosue.com/>

In nature, binocular vision -- stereoscoby -- is anything but a gimmick. It makes possible our three-dimensional world.



When Galen, in the second century, and Leonardo, thirteen centuries later, observed that the images received by the two eyes were slightly different, neither of them appreciated the full significance of these differences. It was not until the early eighteen-thirties that the English scientist and inventor Charles Wheatstone began to suspect that the disparities between the two retinal images were in fact crucial to the brain's mysterious ability to generate a sensation of depth -- and that the brain somehow fused these images automatically and unconsciously.

Wheatstone confirmed the truth of his conjecture by an experimental method as simple as it was brilliant. He made pairs of drawings of a solid object as seen from the slightly different perspectives of the two eyes, and then designed an instrument that used mirrors to insure that each eye saw only its own drawing. He called it a stereoscope, from the Greek for "solid vision." If one looked into the stereoscope, the two flat drawings would fuse to produce a single three-dimensional drawing poised in space.

(One does not need a stereoscope to see stereo depth; it is relatively easy for most people to learn

how to "free-fuse" such drawings, simply by diverging or converging the eyes. So it is strange that stereopsis was not discovered centuries before: Euclid or Archimedes could have drawn stereo diagrams in the sand, as David Hubel has remarked, and discovered stereopsis in the third century B.C. But they did not, as far as we know.)

A few years after Wheatstone's discovery came the invention of photography, and stereophotographs, with their magical illusion of depth, became immensely popular. Queen Victoria herself was presented with a stereoscope after admiring one at the 1851 Great Exhibition, at the Crystal Palace, and soon no Victorian drawing room was complete without one. With the development of smaller, cheaper stereoscopes, easier photographic printing, and even stereo parlors, there were few people in Europe or America who did not have access to stereo viewers by the end of the nineteenth century.

With stereo-photographs, viewers could see the monuments of Paris and London, or great sights of nature like Niagara Falls or the Alps, in all their majesty and depth -- with an uncanny verisimilitude that made them feel as if they were hovering over the actual scenes. (By the mid-eighteen-fifties, a subspecialty of stereophotography, stereopornography, was already well established, though this was of a rather static type, because the photographic processes used at the time required lengthy exposures.)

In 1861, Oliver Wendell Holmes (who invented the popular handheld Holmes Stereo Viewer), in one of several *Atlantic Monthly* articles on stereoscopes, remarked on the special pleasure people seemed to derive from this magical illusion of depth:

The shutting out of surrounding objects, and the concentration of the whole attention ... produces a dream-like exaltation ... in which we seem to leave the body behind us and sail into one strange scene after another, like disembodied spirits.

There are, of course, many other ways of judging depth: occlusion of distant objects by closer objects, perspective (the fact that distant objects appear smaller), shading (which delineates the shape of objects), "aerial" perspective (the blurring and bluing of more distant objects by the intervening air), and, most important, motion parallax -- the change of spatial relationships as we move our heads. All these cues, acting in tandem, can give a vivid sense of reality and space and depth. But the only way to actually *perceive* depth rather than judge it is with binocular stereoscopy.

In my boyhood home, in London, during the nineteen-thirties, we had two stereoscopes: a large, old-fashioned wooden one, which took glass slides, and a smaller, handheld one, which took cardboard stereophotographs. We also had books of bicolor anaglyphs -- stereophotographs printed in different colors, which had to be viewed with a pair of red-and-green glasses that effectively restricted each eye to seeing only one of the images.

So when I developed a passion for photography, at the age of ten, I wanted, of course, to make my own pairs of stereophotos. This was easy to do, by moving the camera horizontally about two and a half inches between exposures, mimicking the distance between the two eyes. (I did not yet have a double-lens stereo-camera, which would take simultaneous stereo pairs.)

I started taking pictures with greater and greater separations between them, and then, using a cardboard tube about a yard long and four little mirrors, I made a hyperstereoscope -- turning myself, in effect, into a creature with eyes a yard apart. With this, I could look at even a very distant object, like the dome of St. Paul's Cathedral, which normally appeared as a flat semicircle on the horizon, and see it in its full rotundity, projecting toward me. I also experimented with the opposite of this by making a pseudoscope (another device invented by Wheatstone), which transposed the views of the two eyes. This reversed the stereo effect to some extent, making distant objects appear closer than near ones, and turning faces into hollow masks, even though this contradicted common sense, and contradicted all the other depth cues of perspective and occlusion -- a bizarre and disorienting experience as the brain struggled to reconcile two opposite conclusions, and alternated rapidly between rival hypotheses.

After the Second World War, new techniques and forms of stereoscopy became popular. The View-Master, a little stereoscope made of plastic, took reels of tiny Kodachrome transparencies that one flicked through by pressing a lever. I fell in love with faraway America at this time, partly through such View-Master reels of the grand scenery of the West and the Southwest.

One could also get Polaroid Vectographs, in which the stereo images were polarized at right angles to one another; these were viewed through a special pair of Polaroid glasses, with the polarization of the lenses also at right angles, insuring that each eye saw only its own image. Such Vectographs, unlike the red-and-green anaglyphs, could be in full color, which gave them a special appeal.

Then there were lenticular stereograms, in which the two images were printed in alternating narrow vertical bands covered by clear ridged plastic. The ridges served to transmit each set of images to the proper eye, eliminating the need for any special glasses. I first saw a lenticular stereogram just after the war, in the London Tube -- an advertisement, as it happened, for Maidenform bras. I wrote to Maidenform, asking if I could have one of their advertisements, but got no reply, they must have imagined I was a sex-obsessed teen-ager, rather than a simple stereophile.

Finally, there was a slew of 3-D films (like the Madame Tussaud's horror film, "House of Wax"), which one would look at through red-and-green or Polaroid glasses. As cinema, most of these were awful -- but some, like "Inferno," were very beautiful, and used stereophotography in an exquisite, delicate, unintrusive way.

Over the years, I amassed a collection of stereograms and books about stereoscopy. I am an active member of the New York Stereoscopic Society, and at their meetings I encounter other stereo buffs. Unlike most, we do not take stereoscopy for granted but revel in it. While most people may not notice any great change if they close one eye, we stereophiles are sharply conscious of the change, as our world suddenly loses its spaciousness and depth. Perhaps we rely more on stereoscopy, or perhaps we are simply more aware of it. We want to understand how it works. The problem is not a trivial one, for if one can understand stereoscopy, one can understand not only a simple and brilliant visual stratagem but something of the nature of visual awareness, and of consciousness itself.

Some people, losing binocular vision for a long period, find the experience very disturbing. In a recent issue of *Binocular Vision & Strabismus Quarterly*, Paul Romano, a sixty-eight-year-old retired pediatric ophthalmologist, recounted his own story of losing nearly A sight in one eye, following a massive ocular hemorrhage. After one day of monocular vision, he noted, "I see items but I often don't recognize them: I have lost my physical localization memory My office is a mess Now that I have been reduced to a two-dimensional world I don't know where anything is."

The next day, he wrote, "Things are not the same object at all monocularly as they were binocularly Cutting meat on the plate -- it is difficult to see fat and gristle that you want to cut away I just don't recognize it as fat and gristle when it only has two dimensions."

After almost a month, though Dr. Romano was becoming less clumsy, he still had a sense of great loss:

Although driving at normal speed replaces the loss of depth perception with motion stereopsis, I have lost my spatial orientation. There is no longer the feeling I used to have of knowing exactly where I am in space and the world. North was over here before now I don't know where it is I am sure my dead reckoning is gone.

His conclusion, after thirty-five days, was that "even though I adapt better to monocularly every day, I can't see spending the rest of my life in this way.... Binocular stereoscopic depth perception is not just a visual phenomenon. It is a way of life Life in a two-dimensional world is very different from that in a three-dimensional world and very inferior." As the weeks passed, Dr. Romano became more at home in his monocular world, but it was with enormous relief that, after nine months, he finally recovered his stereo vision.

In the nineteen-seventies, I had my own experience with losing stereoscopy when, following surgery for a ruptured quadriceps, I was put in a tiny windowless room in a London hospital. The room was scarcely bigger than a prison cell, and visitors complained of it, but I soon accommodated, and even enjoyed it. The effects of its limited horizon did not become apparent to me until later, as I described in "A Leg to Stand On":

I was moved into a new room, a new spacious room, after twenty days in my tiny cell. I was settling myself, with delight, when I suddenly noticed something most strange. Everything close to me had its proper solidity, spaciousness, depth -- but everything farther away was totally flat. Beyond my open door was the door of the ward opposite; beyond this a patient seated in a wheelchair; beyond him, on the windowsill, a vase of flowers; and beyond this, over the road, the gabled windows of the house opposite-and all this, two hundred feet perhaps ... seemed to lie like a giant Kodachrome in the air, exquisitely colored and detailed, but perfectly flat.

I had never realized that stereoscopy and spatial judgment could be so changed after a mere three weeks in a small space. My own stereoscopy had returned, jerkily, after about two hours, but I wondered what happened to prisoners, confined for much longer periods. I had heard stories of

people living in rain forests so dense that their far point was only six or seven feet away. If they were taken out of the forest, it was said, they might have so little idea or perception of space and distance beyond a few feet that they would try to touch distant mountaintops with their outstretched hands.

When I was a neurology resident, in the early nineteen-sixties, I read the papers of David Hubel and Torsten Wiesel, who later received a Nobel Prize for their work. They revolutionized our understanding of how mammals learn to see, in particular of how early visual experience is critical for the development of special cells or mechanisms in the brain needed for normal vision. Among these are the binocular cells in the visual cortex that are necessary to construct a sense of depth from retinal disparities. Hubel and Wiesel showed that if normal binocular vision was rendered impossible by a congenital condition (as in Siamese cats, often born cross-eyed) or by experiment (cutting one of the muscles to the eyeballs, so that the subjects became wall-eyed), these binocular cells would fail to develop, and the animals would permanently lack stereoscopy. A significant number of people are born with similar conditions -- collectively known as strabismus, or squint -- a misalignment sometimes too subtle to attract notice but sufficient to interfere with the development of stereo vision.

Yet there are many accounts of stereo-blind people who achieve remarkable feats of visuomotor coordination. Wiley Post, the first person to fly solo around the world, as famous in the nineteen-thirties as Charles Lindbergh, did so after losing an eye in his mid-twenties (he went on to become a pioneer of high-altitude flight, and invented a pressurized flight suit). A number of professional athletes have been blind in one eye, and so was at least one eminent ophthalmic surgeon.

There are many others -- perhaps five or ten per cent of the population -- who, for one reason or another, have little or no stereo vision, though often they are not aware of this, and may learn it only after careful examination by an ophthalmologist or optometrist. They may not all be pilots or world-class athletes, but many of them have no sense of visual impairment, either. Most manage to get along very well using only monocular cues, though some do have difficulty judging depth, threading needles, or playing sports.

There may even be certain advantages to monocular vision, as when photographers and cinematographers deliberately renounce their binocularity and stereoscopy by confining themselves to a oneeye, one-lens view, the better to frame and compose their pictures. And those who have never had stereopsis but manage well without it may be hard put to understand why anyone should pay much attention to it. Errol Morris, the filmmaker, was born with strabismus, and subsequently lost almost all the vision in one eye, but feels he gets along perfectly well. "I see things in 3-D," he said. "I move my head when I need to -- parallax is enough. I don't see the world as a plane." He joked that he considered stereopsis no more than a "gimmick" and found my interest in it "bizarre."

I tried to argue with him, to expatiate on the special character and beauty of stereopsis. But one cannot convey to the stereo-blind what stereopsis is *like*; the subjective quality, the *quale*, of stereopsis is unique and no less remarkable than that of color. However brilliantly a person with monocular vision may function, he or she is, in this one sense, totally lacking.

And stereopsis, as a biological strategy, is crucial to a diverse array of animals. Predators, in general, have forward-facing eyes, with much overlap of the two visual fields and, presumably, stereoscopic vision; prey animals, by contrast, tend to have eyes at the sides of their heads, which gives them panoramic vision, helping them spot danger even if it comes from behind. An astonishing strategy is found in cuttlefish, whose wide-set eyes normally permit a large degree of panoramic vision but can be rotated forward by a special muscular mechanism when the animal is about to attack, giving it the binocular vision it needs for shooting out its tentacles with deadly aim.

In primates like ourselves, forward-facing eyes have other functions. The huge, close-set eyes of many types of lemurs serve to clarify the complexity of dark, dense close-up foliage, which, if the head is kept still, is almost impossible to sort out without stereoscopic vision -- and in a jungle full of illusion and deceit, stereopsis is indispensable in breaking camouflage. On the more exuberant side, aerial acrobats like gibbons might find it very difficult to swing from branch to branch without the special powers conferred by stereoscopy. A one-eyed gibbon might not fare too well -- and the same might be true of a oneeyed lemur or cuttlefish.

Stereoscopy is highly conserved in such animals, despite its costs -- the sacrifice of panoramic vision, the need for special neural and muscular mechanisms for coordinating and aligning the eyes, and, not least, for special brain mechanisms to compute depth from the disparities of the two visual images. Thus, in nature, stereoscopy is anything but a gimmick, even if some human beings manage, and may even do better, without it.

In December of 2004, I received an unexpected letter from a woman named Sue Barry. She reminded me how we had met, in 1996, at a shuttle-launch party in Cape Canaveral (her husband, Dan, was then an astronaut). We had been talking about different ways of experiencing the world -- how, for example, Dan and other astronauts lost their sense of "up" and "down" in the near-zero-gravity conditions of outer space and had to find ways of adapting. Sue had then told me of her own visual world: she had been born cross-eyed, and so viewed the world with one eye at a time, her eyes rapidly and unconsciously alternating. I had asked if this was any disadvantage to her. No, she said, she got along perfectly well -- she drove a car, she could play softball, she could do whatever anyone else could. She might not be able to see depth directly, as other people could, but she could judge it as well as anybody, using other cues.

I had asked Sue if she could *imagine* what the world would look like if viewed stereoscopically. Sue said she thought she could -- after all, she was a professor of neurobiology, and she had read plenty of papers on visual processing, binocular vision, and stereopsis. She felt this knowledge had given her some special insight into what she was missing -- she knew what stereopsis must be like, even if she had never experienced it.

But now, nine years after our initial conversation, she felt compelled to write to me about this question:

You asked me if I could imagine what the world would look like when viewed with two eyes. I told you that I thought I could But I was wrong.

She went on to give me details of her visual history, starting with her parents noticing that she was cross-eyed a few months after she was born.

The doctors told them that I would probably outgrow the condition. This may have been the best advice at the time. The year was 1954, eleven years before David Hubel and Torsten Wiesel published their pivotal papers on visual development, critical periods, and cross-eyed kittens. Today, a surgeon would realign the eyes of a cross-eyed child during the "critical period" ...in order to preserve binocular vision and stereopsis. Binocular vision depends on good alignment between the two eyes. The general dogma states that the eyes must be realigned in the first year or two. If surgery is performed later than that, the brain will have already rewired itself in a way that prevents binocular vision.

Sue did have operations to correct her strabismus, first on the muscles of the right eye, when she was two, and then of the left eye, and finally of both eyes, when she was seven. When she was nine, her surgeon told her that she could now "do anything a person with normal vision could do except fly an airplane." (Wiley Post, apparently, had already been forgotten by the nineteen-sixties.)

She no longer looked cross-eyed to a casual observer, but she was half aware that her eyes were still not working together, that there was still something amiss, though she could not specify what it was. "No one mentioned to me that I lacked binocular vision, and I remained happily ignorant of the fact until I was a junior in college," she wrote. Then she took a course in neurophysiology:

The professor described the development of the visual cortex, ocular dominance columns, monocular and binocular vision, and experiments done on kittens reared with artificial strabismus. He mentioned that these cats probably lacked binocular vision and stereopsis. I was completely floored. I had no idea that there was a way of seeing the world that I lacked.

After her initial astonishment, Sue began to investigate her own stereo vision:

I went to the library and struggled through the scientific papers. I tried every stereo vision test that I could find and flunked them all. I even learned that one was supposed to see a three-dimensional image through the View-Master, the toy stereo viewer that I had been given after my third operation. I found the old toy in my parents' home, but could not see a three-dimensional image with it. Everyone else who tried the toy could.

At this point, Sue wondered whether there might be any therapy by which she could acquire binocular vision, but "the doctors told me that it would be a waste of my time and money to attempt vision therapy. It was simply too late. I could only have developed binocular vision if my eyes had been properly aligned by age two. Since I had read Hubel and Wiesel's work on visual development and early critical periods, I accepted their advice."

Twenty-five years passed -- years in which Sue married and raised a family while pursuing an

academic career in neurobiology. She had not tried to fly an airplane, but she had found she could do almost everything else, with her other, monocular ways of judging space and distance. Occasionally, she enjoyed showing off these special abilities:

I took some tennis lessons with an accomplished pro. One day, I asked him to wear an eye patch so that he had to hit the ball using only one eye. I hit a ball to him high in the air and watched this superb athlete miss the ball entirely. Frustrated, he ripped off the eye patch and threw it away. I am ashamed to admit it, but I enjoyed watching him flounder, a sort of revenge against all two-eyed athletes.

But when Sue was in her late forties new problems began:

It became increasingly difficult to see things at a distance. Not only did my eye muscles fatigue more quickly, but the world appeared to shimmer when I looked in the distance. It was hard to focus on the letters on street signs or distinguish whether a person was walking toward or away from me At the same time, my glasses, used for distance vision, made me far-sighted. In the classroom, I could not read my lecture notes and see the students at the same time I decided it was time to get bifocals or progressive lenses. I was determined to find an eye doctor who would give me both progressive lenses to improve my visual acuity and eye exercises to strengthen my eye muscles.

She consulted Dr. Theresa Ruggiero, an optometrist, who found that Sue's eyes were developing various forms of imbalance -- this sometimes happens after surgery for strabismus -- and that the reasonable vision she had enjoyed for decades was now being undermined.

Dr. Ruggiero confirmed that I saw the world monocularly. I only used two eyes together when looking within two inches of my face. She told me that I consistently misjudged the location of objects when viewing them solely with my left eye. She explained that the shimmering, the difficulty in focusing on distant objects, resulted from binocular rivalry. I was constantly switching eyes. Most importantly, she discovered that my two eyes were misaligned vertically. The visual field of my left eye was about three degrees above that of my right. Dr. Ruggiero placed a prism in front of my right lens that shifted the entire visual field of the right eye upward Without the prism, I had trouble reading the eye chart on a computer screen across the room because the letters appeared to shimmer.

With the prism, the shimmer was greatly reduced.

("Shimmer," Sue later explained, was perhaps too mild a term, for it was not like the shimmer one might see with a heat haze on a summer day -- it was, rather, a rapid alternation of the misaligned images from each eye, so that whatever she was seeing seemed to jump up and down eight or ten times a second, in a dizzying way.)

Sue got her new eyeglasses, complete with the prism, on February 12, 2002. Two days later, she had her first vision-therapy session with Dr. Ruggiero -- a long session in which, using Polaroid glasses to allow a different image to be presented to each eye, she attempted to fuse the two pictures. At first, she did not understand what "fusion" meant -- how it was possible to bring the two images together -- but after trying for several minutes she found she was able to do this,

though only for a second at a time. Although she was looking at a pair of stereo images, she had no perception of depth -- but nevertheless she had made the first step, achieving "flat fusion," as Dr. Ruggiero called it.

Sue wondered whether, if she could hold the eyes aligned for longer, this would allow not just flat fusion but stereo fusion, too. Dr. Ruggiero gave her further exercises to stabilize her tracking and hold her gaze, and she worked on these exercises diligently at home. Three days later, something odd occurred:

I noticed today that the light fixture that hangs down from our kitchen ceiling looks different. It seems to occupy some space between myself and the ceiling. The edges are also more rounded. It's a subtle effect but noticeable.

In her second session with Dr. Ruggiero, on February 21st, Sue repeated the Polaroid exercise and tried a new one, using colored beads at different distances on a string. This exercise, known as the Brock string, taught Sue to fixate both eyes on the same point in space, so that her visual system would not suppress the images from one eye or the other but would fuse them together. The effect of this session was immediate:

I went back to my car and happened to glance at the steering wheel. It had "popped out" from the dashboard. I closed one eye, then the other, then looked with both eyes again, and the steering wheel looked different. I decided that the light from the setting sun was playing tricks on me and drove home. But the next day I got up, did the eye exercises, and got into the car to drive to work. When I looked at the rear-view mirror, it had popped out from the windshield.

Her new vision was "absolutely delightful," Sue wrote. "I had no idea what I had been missing." As she put it, "Ordinary things looked extraordinary. Light fixtures floated and water faucets stuck way out into space." But it was "also a bit confusing. I don't know how far one object should 'pop out' in front of another for a given distance between the two objects It is ... a bit like I am in a fun house or high on drugs. I keep staring at things The world really does look different." She included some excerpts from her diary:

February 22: I noticed the edge of the open door to my office seemed to stick out toward me. Now, I always knew that the door was sticking out toward me when it was open because of the shape of the door, perspective and other monocular cues, but I had never seen it in depth. It made me do a double take and look at it with one eye and then the other in order to convince myself that it looked different. It was definitely out there.

When I was eating lunch, I looked down at my fork over the bowl of rice and the fork was poised in the air in front of the bowl. There was space between the fork and the bowl. I had never seen that before.... I kept looking at a grape poised at the edge of my fork. I could see it in depth.

March 1: Today, I was walking by the complete horse skeleton in the basement of the building where I work, when I saw the horse's skull sticking out so much, that I actually

jumped back and cried out.

March 4: While I was running this morning with the dog, I noticed that the bushes looked different. Every leaf seemed to stand out in its own little 3-D space. The leaves didn't just overlap with each other as I used to see them. I could see the SPACE between the leaves. The same is true for twigs on trees, pebbles on the road, stones in a stone wall. Everything has more texture.

Sue's letter continued in this lyrical vein, describing experiences utterly novel for her, beyond anything she could have imagined or inferred before. She had discovered for herself that there is no substitute for experience, that there is an unbridgeable gulf between what Bertrand Russell called "knowledge by description" and actual "knowledge by acquaintance," and no way of going from one to the other.

One would think that the sudden appearance of an entirely new quality of sensation or perception might be confusing or frightening, but Sue seemed to adapt to her new world with remarkable ease. She was startled and disoriented at first, but for the most part she felt entirely, and increasingly, at home with stereoscopy. Though she continues to be conscious of the novelty of stereo vision, and indeed rejoices in it, she also feels now that it is "natural" -- that she is seeing the world as it really is, as it should be. Flowers, she says, seem "intensely real, inflated," where they were "flat" before.

Sue's acquisition of stereoscopy after almost half a century of being stereo-blind has been a constant source of delight, and a great practical benefit. Driving is easier, threading a needle, too, and when she looks down into her binocular microscope at work she can see paramecia swimming at different levels, and see this directly, rather than inferring it by refocussing the microscope up or down.

At seminars ... my attention is completely captivated by the way an empty chair displays itself in space, and a whole row of empty chairs occupies my attention for minutes. I would like to take a whole day just to walk around and LOOK. I did escape today for an hour to the college greenhouse just to look at the plants and flowers from all angles.

Most of the phone calls and letters I receive are about mishaps, problems, losses of various sorts. Sue's letter, though, was a story not of loss and lamentation but of the sudden gaining of a new sense and sensibility, and, with this, a sense of delight and jubilation. Yet her letter also sounded a note of bewilderment and reservation: she did not know of any experience or story like her own, and was perplexed to find, in all that she had read, that the achievement of stereoscopy in adult life was "impossible." Had she always had binocular cells in her visual cortex, she wondered, just waiting for the right input? Was it possible that the critical period in early life was less critical than generally thought? What did I make of all this?

I mulled over Sue's letter for a few days, and discussed it with several colleagues, including Bob Wasserman, an ophthalmologist, and Ralph Siegel, a vision physiologist. A few weeks later, in February of 2005, the three of us went to see Sue at her home in Massachusetts, bringing along ophthalmological equipment and various stereoscopes and stereograms.

Sue welcomed us and, as we chatted, showed us some childhood photos, since we were interested in trying to reconstruct her early visual history. Her childhood strabismus, prior to surgery, was quite clear in the photographs. Had she ever been able to see in three dimensions, we asked? Sue thought for a moment, and answered yes, perhaps -- very occasionally, as a child, lying in the grass, she might suddenly see a blade of grass stand out from its background. The grass would have to be very close to her eyes, within inches, to do this, and the standing out would last just a second or two -- she had almost forgotten about this until we quizzed her. So there was a suggestion (if her memory was not playing her false) that Sue may have had a few brief and rare stereo experiences in early life, but there was no way to be certain of this.

Sue had written, in her letter, "I think, all my life, I have desired to see things in greater depth, even before I knew I had poor depth perception." Was it possible that the intensity of this wish had made her believe that she was seeing in stereo when she actually was not? It was important to test her with special stereograms that had no cues or clues as to depth -- no perspective or occlusion, for example. I had brought one stereogram with lines, of print -- unrelated words and short phrases -- that, if viewed stereoscopically, appeared to be on seven different planes of depth, but, if viewed with one eye, or without true stereo vision, appeared to be on the same plane. Sue looked at this picture through the stereoscope and saw it as a flat plane. It was only when I prompted her by telling her that some of the print was at different levels that she looked again, and said, "Oh, now I see." After this, she was able to distinguish all seven levels and put them in the correct order.

Given enough time, Sue might have been able to see all seven levels on her own, but such "top-down" factors -- knowing or remembering or having an idea of what one should see -- are crucial in many aspects of perception. A special attention, a special searching, may be necessary to reinforce a relatively weak physiological faculty. It seems likely that such factors are strongly operative with Sue, especially in this type of test situation. Her difficulties in real life are much less, because every other factor here -- knowledge, context, and expectation no less than perspective, occlusion, and motion parallax -- helps her experience the three-dimensional reality around her.

Sue was able to see depth in the red-and-green drawings I had brought. One of these images-an impossible three-pronged tuning fork such as M. C. Escher might have drawn, with three tines of increasing heights -- Sue found "spectacular"; she saw the top of the uppermost prong as three or four centimetres above the plane of the paper. Bob and Ralph, by comparison, saw it as twelve centimetres above, and I saw it as fifteen centimetres above.

I found this surprising, because we were all the same distance from the drawing, and I had imagined that a given disparity would be perceived, invariantly, as a constant depth. Puzzled by this, I wrote to several neuroscientists, including Shinsuke Shimojo, at Caltech, an expert in many aspects of visual perception. He brought out, in his reply, that when one looks at a stereogram the computational process in the brain is based not solely on the binocular cue of disparity but also on monocular cues such as size, occlusion, and motion parallax. With a stereoscopic illusion, these cues conflict, the monocular ones working against the binocular ones. The brain must therefore balance one set of cues against the other, and arrive at a weighted

average. This final result will be different in different individuals, because there is huge variation, even in the normal population: some people rely predominantly on binocular cues, others on monocular cues, and still others use both. In looking at a stereo illusion such as the tuning fork, a strongly binocular person will see unusual stereo depth; a monocularly oriented person will see much less depth; and others, relying more equally on both binocular and monocular cues, will see something in between.

Later in the day, we paid a visit to Sue's optometrist, Dr. Theresa Ruggiero, who described how Sue had first consulted her, in 2001. Sue had complained then of eyestrain, especially when driving, impaired clarity, and a disconcerting jumping or flickering of images -- but had not mentioned her lack of stereoscopy.

Dr. Ruggiero herself was greatly surprised, she said, when, immediately after achieving flat fusion, Sue experienced stereoscopy. She speculated that Sue must have had some binocular vision and stereoscopy, even if very briefly, during the critical childhood period, or it would not have been possible for her to have stereo vision now. What was so remarkable about Sue, Ruggiero said, over and above the initial achievement of stereoscopy, was her adventurous and positive reaction to it, and her fierce determination to hold on to it and enhance it, however much work this might entail.

And it did indeed entail, and still entails, a great deal of work -- taxing fusion exercises for at least twenty minutes every day. With these exercises, Sue found that she was starting to perceive depth at greater and greater distances, where at first she had seen depth only close up, as with the steering wheel. She continued to have jumps of improvement in her stereo acuity, so that she was able to see depth with smaller and smaller disparities -- but when she stopped therapy for six months she quickly regressed. This upset her deeply, and she resumed the eye exercises by herself, working on them every day. Three years later, she still does them, "religiously."

Sue has continued to work very hard on her stereo perception and stereo acuity in the months since our visit, and her perception of stereo depth has continued to increase measurably. Moreover, she has developed a skill she did not have when we initially visited her: the ability to see random-dot stereograms. Unlike conventional stereo pictures, these are constellations of dots with no images that can be seen monocularly, but which reveal images or shapes when viewed with both eyes. This illusion may take some practice, and many people, even with normal binocular vision, are not able to get it. But often, as one continues to gaze, a strange sort of turbulence appears among the dots, and then a startling illusion -- an image, a shape, whatever -- will suddenly appear far above, or far below, the plane of the paper. Getting these illusions is the purest test of stereoscopic vision. It is unfakable, for there are no monocular cues whatever; it is only by stereoscopically fusing thousands of seemingly random points as seen by the two different eyes that the brain can construct a three-dimensional image.

Though a theoretical understanding of random-dot stereograms came only in the nineteen-sixties, they are akin to the stereo illusions described by David Brewster, the inventor of another early stereo viewer, as early as 1844. Gazing at wallpaper with small repetitive motifs, he observed that the patterns might quiver or shift, and then jump into startling stereoscopic relief, especially if these patterns were offset in relation to one another. Such "autostereograms" have probably

been experienced for millennia, with the repetitive patterns of Islamic art, Celtic art, the art of many other cultures. Medieval manuscripts such as the Book of Kells or the Lindisfarne Gospels, for example, contain exquisitely intricate designs done so exactly that whole pages can be seen, with the unaided eye, as stereoscopic illusions. John Cisne, a paleobiologist at Cornell, has suggested that such stereograms may have been "something of a trade secret among the educated elite of the seventh and eighth century British Isles.")

In the past decade and a half, elaborate autostereograms have been widely published as "Magic Eye" books. These have added another dimension to Sue's newfound stereoscopic powers: "I find these wallpaper autostereograms easy (and quite thrilling)," she recently wrote, "probably because I practice convergent and divergent fusion regularly."

In the summer of 2005, Bob and I paid Sue another visit, in Woods Hole, Massachusetts, where she was running a fellowship program in neurobiology. She had mentioned to me that the bay there was sometimes full of luminous organisms, mostly tiny dinoflagellates, and that she enjoyed swimming among them. When we arrived, in the middle of August, we found that our timing was perfect -- the water was aflame with the luminous creatures ("*Noctiluca scintillans* -- I love the name," said Sue). After dark, we went down to the beach, armed with masks and snorkels. We could see the water sparkling from the shore, as if fireflies were in it, and when we immersed ourselves and moved our arms and legs in the water, clouds of miniature fireworks lit up around our limbs. When we swam, the night lights rushed past our eyes like the stars streaking past the Enterprise as it reaches warp speed. In one area, where the noctiluca were particularly dense, Bob said, "It's like swimming into a galaxy, a globular cluster."

Sue, overhearing this, said, "Now I see them in 3-D -- they all seemed to twinkle in a flat plane before." Here there were no contours, no boundaries, no large objects to occlude or give perspective. There was no context whatsoever -- it was like being immersed in a giant random-dot stereogram, and yet Sue now saw the noctiluca at different depths and distances, in three-dimensional space. If she could do this, we mused, perhaps she could now do even better on the random-dot stereogram tests. But Sue, normally eager to talk about stereo vision, was mesmerized by the beauty of the scintillating organisms. "Enough thinking!" she said. "Give yourself to the noctiluca."

Struggling to find an analogy for her experience, Sue had suggested, in her original letter to me, that her experience might be akin to that of someone born totally color-blind, able to see only in shades of gray, who is suddenly given the ability to see in full color. Such a person, she wrote, "would probably be overwhelmed by the beauty of the world. Could they stop looking?" While I liked the poetry of Sue's analogy, I disagreed with the thought, for I suspect that someone who has grown up in a completely colorless world would find it confusing, or even impossible, to integrate a new "sense" such as color with an already complete visual world. Color, for such a person, would have no associations, no meaning. But Sue's experience of stereoscopy was clearly not a gratuitous or meaningless addition to her visual world. After a brief confusion, she embraced the new experience, and felt it not as an arbitrary add-on but as an enrichment, a natural and delicious deepening of her existing vision. Perhaps this was because a three-dimensional world was already a perceptual reality for her, even though she had relied on non-stereoscopic means to achieve it. With color, there is no precursor -- we either see a world of

color or we do not -- but all of us live and move in a three-dimensional world.

David Hubel has followed Sue's case with interest, and has corresponded with her and with me about it. He has pointed out that we are still quite ignorant of the cellular basis of stereoscopy. We do not know, even in animals, whether disparity-sensitive cells (the binocular cells specialized for stereoscopy) are present at birth (though Hubel suspects they are); what happens to these cells if there is strabismus and lack of binocular experience in early life; and, most crucially, whether they can recover if the strabismus is repaired. With regard to Sue, he wrote, "It seems to me that [her regaining of stereopsis] occurred too quickly for it to be due to a reestablishment of connections, and I rather would guess that the apparatus was there all along, and just required reestablishment of fusion to be brought out." But, he added, "that's just a guess!"

Whether the cells and mechanisms that enable binocular stereoscopy are present at birth or form soon thereafter, the notion of a critical period of maximum sensitivity to environmental stimuli still stands fast. Without early binocular experiences, these cellular mechanisms either die out or fail to develop. But if there is any binocular vision at all during the critical period -- and with strabismus there may still be some overlap of the visual fields of each eye and thus a small area of fusion -- then the essential apparatus for stereopsis may be established.

What emerges from Sue's experience is that there seems to be sufficient plasticity in the adult brain for these binocular cells and circuits, if some have survived the critical period, to be reactivated later. In such a situation, though a person may have had little or no stereo vision that she can remember, the potential for stereopsis is nonetheless present and may spring to life -- most unexpectedly -- if good alignment of the eyes can be obtained. That this seems to have happened with Sue after a dormant period of almost fifty years is very striking.

Though Sue originally thought her own case unique, she has found, on the Internet, accounts by a number of other people with strabismus and related problems who have unexpectedly achieved stereo vision through vision therapy.

And a report that has just been published in the journal *Nature* described the case of S.K., a twenty-nine-year-old man who was born without lenses in his eyes. Though functionally blind for his entire life (he could sense little more than light and dark), he was able to acquire competent vision after being given a pair of glasses. Such an acquisition, long after the critical period, would traditionally have been considered extremely improbable. But S.K.'s case, like Sue's, suggests that if there are even small islands of function in the visual cortex, there may be a fair chance of reactivating and expanding them in later life, even after a lapse of decades, if vision can be made optically possible. Cases like these may offer new hope for those once considered incorrigibly blind or stereo-blind.

Whatever its neurological basis, the augmentation of Sue's visual world has effectively granted her an added sense, a circumstance that the rest of us can scarcely imagine. For her, stereopsis continues to have a quality of revelation.

"After almost three years," she wrote, my new vision continues to surprise and delight me. One

winter day, I was racing from the classroom to the deli for a quick lunch. After taking only a few steps from the classroom building, I stopped short. The snow was falling lazily around me in large, wet flakes. I could see the space between each flake, and all the flakes together produced a beautiful three-dimensional dance. In the past, the snow would have appeared to fall in a flat sheet in one plane slightly in front of me. I would have felt like I was looking in on the snowfall. But now, I felt myself within the snowfall, among the snowflakes. Lunch forgotten, I watched the snow fall for several minutes, and, as I watched, I was overcome with a deep sense of joy. A snowfall can be quite beautiful -- especially when you see it for the first time."