Bela Julesz

1928–2003

BIOGRAPHICAL *Memoirs*

A Biographical Memoir by
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NATIONAL ACADEMY OF SCIENCES

BELA **JULESZ**

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By Christopher Tyler

Bela Julesz is a revered figure in the history of perception. A founder of the field of computer vision, the inventor of the random-dot stereogram and its brethren, he was a pioneer in the application of complexity theory to the brain. He was also among the first computer artists, an early recipient of the McArthur genius award, and a raconteur extraordinaire.

The formal details of Bela's full life are available in Papathomas (2005). Other tributes to him were published by Frisby, (2004) Siegel, (2004) and the New York Times. In brief, he was born in Budapest, Hungary, in 1928, was married devotedly to Margit Fásy until his death in 2003, emigrated to the United States in 1956, and worked at Bell Laboratories for most of his career, although he maintained worldwide scientific collaborations. He was chosen for a McArthur "Genius Award" in 1983, was elected to the National Academy of Sciences in 1995, and received numerous other awards.

At various times, Bela had visiting research professorships at the Massachusetts Institute of Technology, the University of Western Australia, the Swiss Federal Institute of Technology, the California Institute of Technology, the University of California at Berkeley, and the Hungarian Academy of Sciences. Though he had no children, he mentored a flourishing array of postdoctoral fellows with whom he and Margit kept in close touch throughout his life.

Bela attended the same Budapest gimnázium that had fostered so many great Hungarian scientists. He also studied privately under the celebrated mathematician Rózsa Péter, founder of recursive function theory and author of the elegant *Playing with Infinity*. He did his graduate work at the Telecommunications Research Institute of Budapest in the early 1950s, completing a Ph.D. dissertation on advanced radar methodology.

Unfortunately for him, this paper was classified by the military as soon as it was accepted, requiring him to do a second dissertation—on the topic of TV bandwidth compression—in order to receive his Ph.D. from the Hungarian Academy of Sciences.

Here I will focus on the more personal aspects that made Bela the unique individual that he was, and on my own interactions with him. In my eulogy on his retirement from Bell Laboratories, I pointed to his place in the pantheon of Hungarian exponents of complexity theory across the domains of science—John von Neumann, Leó Szilárd, Eugene Wigner, Dennis Gabor, Erdös, Albert Szent-Györgi, Georg von Békésy, and János Szentágothai. He knew them all and deserves to be honored in their company. Bela investigated principles of globality, cooperativity and entropy in the human brain through the medium of complex visual perception. In this, he was far ahead of the predominantly atomistic approach of his time, and in many respects his work remains far ahead to this day. He was seriously impacted by an unfortunate car accident in his prime, never fully to recover, and should have had many more decades to inspire us with his global insights.

When the Soviets invaded Hungary in 1956, Bela and his colleagues decided to head for the West and developed a plan to escape Hungary by swimming across a river (perhaps the Hansági-föcsatorna canal which runs along the Austro-Hungarian border near Andau) with their most precious possessions. Bela and Margit were to be the first of the 12 couples to try the route, and once across were to make their way to a radio station and broadcast a coded message that the escape route was safe—something along the lines of "The teddy bear is tucked up in bed." When they arrived on the opposite bank, however, Bela realized that he had left his glasses behind, and he modified the message to say "The teddy bear is tucked up in bed with his glasses on the nightstand." This modification caused consternation among the 11 remaining couples gathered around the radio to hear the message, puzzling whether this was a coded warning that their escape route had been spotted, until finally his father said "His glasses! They must still be in his bedroom!" The assembled company were reassured, and all managed to use the escape route successfully.

On arriving in New York, Bela needed only a week to head to Bell Laboratories where he was welcomed by the community of engineers, which included a number of Hungarian expatriates, and where he worked until his formal retirement, when he was offered a State of New Jersey Professorship and founding directorship of the Laboratory of Vision Research at Rutgers University. He retained a deep appreciation for the Bell Labs philosophy of not only fostering great science in all fields relating to communications, but in allowing its employees to follow their untrammeled research paths, which in his case took him from communications theory to human visual perception in as little as three years.

There was, however, a requirement to work on specific problems of telephony when they arose, and in Bela's case this included a most unusual one. Honeybees were being attracted to the hum of the wind in some telephone wires and were building their hives at the tops of the telephone poles. These in turn were attracting bears, who climbed the poles and damaged the wires in their attempts to extract the honey from the hives. Bela's response to this exigency was to ask, "What is the eigenfrequency of the telephone wires?" On obtaining the answer, he designed a system of clips that would alter this resonant frequency out of the range of attraction of the bees, and saved Ma Bell what he characterized as "a million dollars."

Having solved such problems, Bela could turn his attention to the issue for which he became most famous, which was the visual perception of the three-dimensional (3D) world from a combination of the two retinal images. As a radar engineer, he was familiar with the issue of decoding the presence of objects from the mismatches between the reference beam that had been transmitted and the reflected beam from the objects in its path. He generalized this approach to the problem of how the brain decodes the 3D structure of the world from the mismatch between the images received from two different vantage points by the two eyes, adding the brilliant stroke of using random noise fields—scrambled dot arrays—to mask the perception of the objects by each eye separately. He used the advanced computer resources of Bell Labs to depict virtual objects as if they were sprayed with random dots against a random-dot background, effectively camouflaging them from visibility except through their 3D structure.

From the viewpoint of human perception, this design meant that observers could not guess the form of the virtual objects by viewing with either eye alone, but had to derive their form from the pattern of binocular disparities arising between the two eyes' images in the form of a perceived depth structure. Julesz termed this capability "cyclopean vision," deriving this term from Hering's 1868 concept of a metaphorical single eye (the "eye of the Cyclops") representing the combined information in the two eyes. This depth structure could only be derived by processing in the visual cortex, a fact that allowed Bela to develop a form of "perceptual microelectrode" to study the processing in the brain, bypassing that in the retina and the monocular visual pathways. This was just one of the many pathbreaking ideas that Julesz introduced into human neuroscience.

Bela's early papers were published in the *Bell Labs Technical Journal*, but a series of his papers in *Science* soon led to international celebrity. He was invited for a year's sabbatical in the Cognitive Sciences Department at the Massachusetts Institute of Technology. This opportunity not only exposed him to a hotbed of new ideas in what is now known as cognitive neuroscience, it also brought him into contact with the computational vision community, scientists who took the challenge to explain the amazing properties of cyclopean vision through computational modeling (notably Marr and Poggio, 1976, 1979).

This sabbatical year also gave Bela the chance to write his expansive book, *Foundations of Cyclopean Vision*, which was the inspiration for a generation of perceptual investigators to enter the field of perceptual research. It is a mistake to think of this work as solely about binocular vision, however, since he gave as much space to issues of the perception of visual symmetry. This is a particularly interesting form of pattern perception, because it does not involve specific patterns, but abstract properties of pattern perception that have to be identified "on the fly."

Working at the intersection between communication engineering and neuroscience seemed to give Bela a golden touch for identifying hot-button issues that became fields of study in their own right. One of these was the distinction between attentive and pre-attentive—which is another way of saying conscious versus unconscious—perceptual processes. He was one of the first to focus on this distinction and to explore the complexity of the pre-attentive aspects of visual processing before the neural signals reached consciousness. He regarded this level as the true *visual* processing—before cognitive and linguistic processes had had the opportunity to intervene in the perceptual process.

It was his formulation of this level of processing that would later give rise to *texton theory*, which Bela regarded as his greatest contribution to science. The concept of textons grew out of his theory of the higher-order statistics of textures in the world. Such statistics to second-order are completely defined by the Fourier spectrum of the image, which was a popular image descriptor at the time. In 1962 he took a virtually unique step in the field by publishing a formal conjecture that pre-attentive vision would be limited to such second-order statistical descriptions—i.e., that textures differing only in their higher-order statistics would not be discriminable within the time scale of pre-attentive processing, which he took to be 50 milliseconds (Julesz, 1962; Julesz, et al., 1973).

The Julesz Conjecture stood until 1975, when Bela published the first textures that contradicted the conjecture (spearheaded by some that I contributed myself, in fact). This breakthrough led to his concept of *textons*, which were originally formulated as local elements that were visible beyond the second-order constraint. That concept has since been largely diluted to apply to any local texture element for which specialized neural processing can be identified, of which most are in fact only second order. The interesting field of higher-order textons that he proposed thus remains to be explored.

My year at Bell Labs was one of the most rewarding of my career, in which we spent several hours a day interacting on wide range of issues, discussing our respective publications, developing ideas and exploring the latest scientific developments.

It was Bela's explorations of human texture processing that led to his participation, together with Mike Knoll of Bell Labs, in the first U.S. exhibition of digital computer art, at the Howard Wise Gallery in New York City in 1965. His computer-generated textures were blown up to large scale for exhibition, though they were greeted as soulless abstractions by many critics (somewhat surprisingly in view of the widespread currency of minimalist art at the time) and led to something of a reaction against computer art. He always eschewed any claim to them as artistic creations, however, maintaining that they were exhibited solely as examples of scientific interest. In another art-science endeavor, Bela collaborated with Leon Harmon to generate the block-Lincoln portrait (Harmon and Julesz, 1973), which was a blown-up digitization of the Mathew Brady photograph of Abraham Lincoln. The scientific interest was that blurring the picture, which removed information from the high spatial frequencies, was found, paradoxically, to enhance its visibility as a portrait, as though information had in fact been added to the picture. This enhancement could be understood as removing the masking effect of the block artifacts on the visibility of the face.

This perceptual paradox excited the interest of the art community, and in particular Salvador Dali, who soon produced his own version of the Lincoln portrait featuring on overlay of his wife/model Gala looking through the blocks to a view behind. Dali subsequently invited Bela to dinner at his two-floor apartment at the St. Regis Hotel in downtown Manhattan, surrounded by what Bela described as the full panoply of the New York demimonde at the time—including a tame leopard that liked to be stroked by the guests. At the close of the meal, Dali rose and said "I now invite you to my inner sanctum," where he unveiled his latest creation. To Bela's discomfort, Dali had incorporated his random-dot stereogram of a torus as the halo of a saint in image of high religiosity. Bela was outraged at this adoption of a scientific tool as a device for conveying miracles to impressionable Spanish peasants!

Bela had an endless fund of such stories, as part of his persona as a true polymath. His model of mentorship was to have postdoctoral fellows for one year at a time, in order to work closely with each one in turn. My year at Bell Labs was one of the most rewarding of my career, in which we spent several hours a day interacting on wide range of issues, discussing our respective publications, developing ideas and exploring the latest scientific developments.

Bela also had an immense storehouse of jokes, but, true to his character, they could not be just ordinary jokes, they had to be "basic jokes," each one conceived as a type specimen of its genre of jokes. They further had to be *a propos* of the conversation. The only one I still recall was from his time at MIT and had to do with mathematics professor Norbert Weiner, who was notoriously absentminded. One morning his wife says, "Norbert, don't forget that today is the day we are moving to that house on the neighboring street, so don't come back here this evening but remember to go to the new house." Weiner inevitably forgets these instructions, returning to find his house unexpectedly empty of furniture. Spotting a little girl playing on the street, he says, "Hello, little girl, I wonder if you happen to know why my house is empty?" She answers, "Yes, Daddy, Mommy left me here to remind you that we moved today!" (The joke being, of course, that he did not even remember his own daughter.) I myself could never divine the criterion that elevated particular jokes to "basic" status, but they were certainly very amusing.

Later in life Bela was awarded a Fairchild Distinguished Scholarship to Caltech in Pasadena, where he spent three winters interacting with a community of Nobel laureates and other eminent biologists and physicists on the faculty, exploring a wealth of computational and biological approaches to the brain and its workings.

This memoir is not intended to cover in detail the vast range of contributions that Bela Julesz made to the science of visual and auditory neuroscience. He collaborated with many great scientists to advance our knowledge of form and pattern vision, local feature detection and spatial frequency analysis, higher-order texture and motion processing, binocular depth perception and global stereopsis, pre-attentive and attentive perceptual processing, neurophysiological and evoked potential methodologies, and many other related topics. He originated many concepts that were ahead of their time, such as mental holography, the cyclopean retina, the use of visual noise as a tool for vision research, visual cooperativity, neurontropy, stereoattention, and texton theory. Thanks to him, our view of the perceptual processes is both immeasurably richer and also more accessible to investigation. His combination of global perspective and analytic rigor will have a lasting impact on the field.

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