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AN ILLUSTRATION

IMAGINE that you are sitting in an opera house. The orchestra is playing; on stage, actors in resplendent costumes are singing. Luciano Pavarotti makes his entrance and strikes his initial notes, and you say to yourself, what a velvety voice!

How did you come to think that? What processes took place in your head to give you this impression? Why *velvety*? The word means "feeling like velvet when touched." How can sound evoke an impression that properly belongs to the sense of touch?

All these questions are part of sensory research, an interdisciplinary scientific study of our senses–vision, hearing, and touch, but also taste, smell, and others. Yes, there are others. Pain is one of them. Where there are no pain receptors, there is no pain. A surgeon can cut into your brain as much as he wants, and you will feel no pain; the brain has no pain receptors. And how about the internal senses of balance and kinesthesia, which allow us to walk upright and to monitor our movements? It is not clear how many senses there are: we may not know all of them. For instance, what senses do birds use to direct their course on their long biannual voyages when the sun by day and the stars by night hide behind clouds?

Sensory research does deal with possible discoveries of new senses as well as with the phenomenon of evoking a sensation belonging to one sense modality when stimulating another–the so-called synesthesia–but its main thrust is currently directed toward more essential phenomena: what the known senses do and how they do it. Perhaps surprisingly, what we know about these basic functions is very little compared with what we should know.

Let us take an example. What does it take to produce the sensation of a sound–a mundane everyday affair? You must think, well, first of all, somebody or something must produce a sound. In more technical terms, there must be physical sound waves produced by a vibrating body. Isn't it interesting that we use the same word for the physical event and its subjective impression? This undoubtedly has come about because, in our history, we heard sounds before we realized their physical nature. We do the same with light.

The physical sound and the subjective impression of sound are two very distinct events, however. Sometimes one hears a rather loud sound without there being any external sound at all–the well-known phenomenon of ear ringing, which the otologists call *tinnitus*. In some people, the tinnitus is so strong that they are willing to undergo surgery making them deaf in the operated ear, just to get rid of it. Tinnitus usually stems from aberrant neural activity and doesn't require any mechanical vibration.

However, tinnitus may also result from a spontaneous biomechanical vibration in the inner ear. Then, the subjective impression of hearing a sound does originate in a physical vibration, although not an external one. On rare occasions, the vibration may be so powerful that it can be heard by others standing nearby. What is its mechanism? It is not certain, but vigorous research is being pursued on the subject. Are you beginning to gain the impression that the mundane affair of hearing a sound may not be a trivially simple one? There is more.

GIVEN AN EXTERNAL physical sound, how does it become audible? It has to pass several stations in our bodies and undergo several transformations. At every one of these stations, a malfunction can produce a hearing loss or even total deafness.

First, the sound waves must penetrate the ear canal and reach the eardrum, more properly called the *tympanic membrane.* If the ear canal is impacted with ear wax, a transmission loss occurs, causing what ear specialists call a conductive hearing loss. Once at the tympanic membrane, the sound waves induce it to vibrate, and the vibration is transmitted to the inner ear by three little bones connected in series, called ossicles, and contained in the middle ear. Middle-ear diseases are well-known, especially in childhood. Infection may fill the middle ear with fluid and impede the vibration of the tympanic membrane. The chain of the ossicles may be broken. The last and smallest bone in the chain, called the *stirrup* because of its shape, may become fixed to the surrounding skull bone so that it cannot vibrate.

The mechanical vibration produced by sound is converted into nerve impulses in the inner ear, an inaccessible labyrinth of fluid-filled canals that contain the sensory cells for hearing as well as for the sense of balance. The auditory cells, or receptors, transduce mechanical vibration into electrical current, acting like miniature microphones. How they do it is only now beginning to become known. They are smaller and more efficient than any manmade microphones, being only two ten thousandths of an inch in diameter and allowing us to hear vibrations on the atomic scale.

The auditory receptors occupy only one of the inner ear canals, which is spirally wound like the shell of some snails and is called *cochlea,* from the Greek word meaning 'snail'. It is divided longitudinally by an elastic partition to which the receptors are attached. Sound produces waves on the partition which resemble waves on the surface of water. They increase in amplitude up to a maximum as they travel along the canal, and then decay rapidly. The location of the maximum amplitude depends on sound frequency. It is near the beginning of the canal at high frequencies, and moves further away as the frequency decreases. It determines which group of sensory cells is excited the most. The famous nineteenth century physicist and physiologist, Hermann Helmholtz, suggested that it determines the subjective musical pitch we hear. Considerable experimental evidence has been amassed in favor of his hypothesis, perhaps the most important being the work of another physicist and physiologist, Georg von Bekesy. He received the 1961 Nobel Prize in Physiology or Medicine, mainly for his discovery of the cochlear waves.

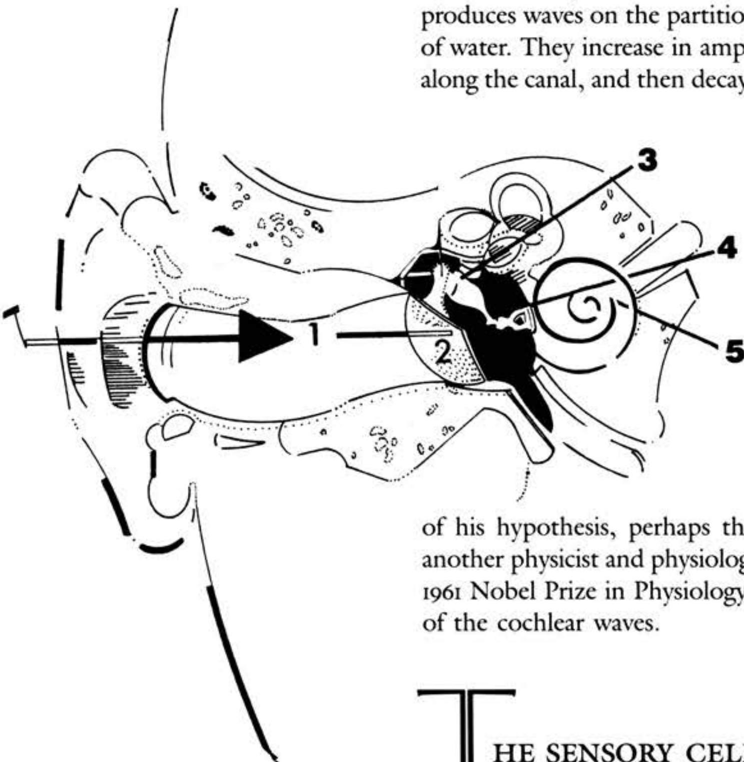

Figure 1. The hearing sequence.
1. Ear canal
2. Tympanic membrane
3. Chain of ossicles
4. Stirrup
5. Cochlea

Illustration: T. Sparks

THE SENSORY CELLS of the cochlea are extremely fragile. In humans, their number already begins to dwindle at 18 years of age, and the capacity for hearing the very high sound frequencies diminishes. Excessive noise and some pharmaceuticals accelerate this loss, which is irreversible at present. Much sensory research is devoted to a better understanding of cochlear mechanisms, partly in the hope that better understanding will allow us to decrease the damage and remedy it when it occurs. Surgical attempts are being made to replace the absent sensory cells with tiny electrodes and to excite the nerve fibers that normally innervate the cells by direct electrical stimulation. Thus far, success has been very modest, in part because of our lack of understanding of cochlear mechanisms.

The electrical currents produced by the sensory cells excite the fibers of the auditory nerve to produce short electrical impulses that run toward the brain. They pass through several nerve centers of the brain stem, called *nuclei,* before reaching the primary auditory projection area of the cortex. It is not possible to hear sounds consciously without it. There are several secondary auditory projection areas, but their significance is not known. The one thing we do know about them is that they are all organized spatially like the cochlea, and every sound frequency has its own place of maximum response. Conforming to Helmholtz's hypothesis, musical pitch appears to depend on the location of this response.

There is now growing evidence that the loudness of sounds may also be coded in the cortex according to the location of maximum response, but in a different plane. Perhaps all the auditory sound attributes depend on such a spatial code. Perhaps the same kind of code is used for all the attributes of all the subjective impressions in all the other sense modalities as well. Perhaps the brain knows only one kind of code, the spatial code.

Cortical neural activity produced by sound is not limited to the auditory areas that respond to sound alone. It invades, among others, association areas that also respond to other sensory stimuli. Do these areas produce synesthesia? Do they account for the fact that words have the same meaning whether heard, or seen, or even felt, as in reading Braille? We don't know for sure. More research is needed.

Other sensory systems consist essentially of the same parts–the peripheral organs, the sensory cells, the sensory nerves, the brain-stem nuclei, and the cortical projection areas–although their structures and functions may be very different. Their modes of operation are still partially veiled in mystery, just like those of the auditory system.

SENSORY RESEARCH

SENSORY RESEARCH is currently conducted on practically all the parts of the known sensory systems. Perhaps because of the accessibility of the eye, or because of the importance of vision to humans, or both, visual research is the most advanced. Auditory research holds second place, probably because hearing plays a crucial role in communication. Research on the remaining senses follows somewhat at a distance, although recently, tactile research has made great strides.

What motivates sensory research? Is it the fact that it belongs in part to brain research? The brain contains all the sensory systems, except their peripheral organs and nerves. Brain research has been accelerating at the highest possible pace allowed by the developments in such new technologies as electron microscopy, biochemical and immunological tracer techniques, solid-state electronics, and computers.

Why do we want to know how our brains work? Is it idle curiosity? I think not. The brain controls human behavior in all its facets. Since it is by far the most complicated system we know, the likelihood of anybody's brain functioning perfectly is practically nil. The better we understand its structures and functions, the better we are equipped to deal with its aberrations and lesions, and the more we can maximize its useful performance.

To understand how the brain functions, we must understand how the sensory systems function, not only because they constitute a substantial part of the brain but also because they control all the information it receives from our environment. This information is at the base of our memories, concepts, and thought processes.

There are other, more practical reasons for sensory research. We are virtually surrounded by its results. The lighting of our homes, offices, and streets is based on it. Both light intensity and color spectrum are adapted to the requirements of our visual systems. The same is true of our television sets and movies, which, in addition, utilize our visual capacity for fusing still pictures that follow each other in rapid succession. The sound systems that go with these media are adapted to the demands of human hearing, as is the telephone. How could one devise eyeglasses or contact lenses without knowing the optics of the eye and its malfunctions? How could one devise hearing aids without being able to measure the various types of hearing loss and match the hearing-aid performance to them? A good part of medical diagnostics is based on our sensory responses. The ophthalmologist wants you to read letters of diminishing size until you can no longer discriminate them. The otologist, or audiologist, wants you to listen to tones of various sound frequencies while decreasing their loudness until you can hardly hear them. The neurologist hits you with a little hammer on your knees and elbows and watches the reflexes of the corresponding limbs. Various physicians want to know if you feel pain anywhere and how much and what kind. Sensory tests are usually applied before and after brain surgery and, sometimes, during it. The widely reported high tech developments in robotics also rely on sensory research. Robots often contain artificial visual systems and, increasingly, tactile systems, both mimicking to some extent the corresponding human senses. Some have artificial auditory systems allowing them to obey oral commands. It would take a large book, or several, to describe adequately the existing applications of sensory research.

IN GENERAL, research on every sensory system is conducted separately. There are visual laboratories and auditory laboratories, and still other laboratories for the senses of touch and balance and taste and smell. Is such specialization desirable? I don't think so. All our senses belong to one brain which combines their inputs to give us an integrated image of the world around us. When we attend an opera, we both hear it and see it. Or should I reverse this order of priority? Even when we go to a concert hall, we rarely just listen to music. We probably observe the conductor, or the soloist, or perhaps some of the players in the orchestra. In sports, one must integrate the simultaneous inputs of several senses. Take, for instance, a football quarterback attempting to throw a pass. He has to keep his balance while being pursued by would-be tacklers, see his receiver, feel the ball in his hand, and monitor the motion of his throwing arm. And how about lovemaking? Do you realize how many senses are involved? If you think about it, you will arrive at an unexpectedly high number.

The specialization in sensory research is the result of both tradition and practical requirements. It is dictated in part by the specificity of the peripheral sense organs and the associated specificity of the sensory stimuli, and in part by the huge amount of knowledge we already have about our senses, no matter how inadequate it may be. The visual sense, of course, requires light stimuli; the auditory, sound stimuli. For the sense of touch, we need mechanical stimulators that produce patterns of skin indentation; for olfaction, controlled gas mixtures; and for taste, liquid solutions. All these stimuli have to be varied along all their physical or chemical parameters and carefully monitored. In vision, for instance, it is necessary to control the light spectrum and intensity, their temporal and spatial patterns, and the location of the retina on which the light is projected. The numbers of stimulus variables for every other sense are similar. Their control requires knowledge of relevant parts of applied physics, different for nearly every sense modality: optics for vision, acoustics for hearing, mechanics for touch and some other senses, chemistry for the control of olfactory and taste stimuli. The necessary sophisticated and often highly specialized equipment calls for advanced technical know-how. In addition, a sensory scientist should know the parts of anatomy, physiology, biochemistry, biophysics, and sensory psychology that apply to the sense modality he studies. I dare say very few, if any, have all this knowledge, and whole laboratories specialize in only one of these disciplines.

This specialization, often excessive, sometimes slows down sensory research by feeding it enormous amounts of redundant experimental data that illuminate only narrow aspects of one or another sensory system. The research often lacks the integration necessary for a complete conceptual representation of our sensory functions and the physiological mechanisms underlying them.

A MULTISENSORY APPROACH

IN CONTRAST TO the traditional specialization, Syracuse University has an institute, called the Institute for Sensory Research, which pursues research on three senses along all the essential disciplines. Is this a worthwhile undertaking? It might be dangerous to break with established traditions; they endure because they work. On the other hand, progress means a change in traditions. I am happy to report that, in the case of the institute, the traditions were broken very cautiously, according to principles of pragmatic evolution rather than of dogmatic revolution. These principles seem to have worked again since the institute is showing all the outward signs of success. It is funded, mainly by the National Institutes of Health and the National Science Foundation, to the tune of about $1.5 million per year. Its research publications are widely cited in the scientific literature; about three hundred citations per year are acknowledged by the Science Citation Index. Because of its pioneering and successful break with the established traditions, it was named as a unique national resource by a past president of the National Academy of Sciences and is regarded as such by the administrators of the National Institutes of Health.

I could attempt to analyze for you the institute's structure and activities, which are seemingly responsible for its success. But it may be more illustrative to consider its beginnings and some of its evolution. How did the institute come about?

It all started with a series of experiments in hearing. I had been appointed to the Division of Special Education of the School of Education with the expectation that I would organize a research laboratory in the Gordon D. Hoople Hearing and Speech Center. This was promptly accomplished in 1958, and the new laboratory was called the Bioacoustic Laboratory. The experiments were performed there. They concerned the nature of a well-established auditory phenomenon according to which faint sounds become more audible as their duration increases. The phenomenon had suggested to many scientists that the auditory system integrates sound energy over a certain short span of time. Our experiments indicated that this interpretation was incorrect, and that the system integrates the neural response to sound rather than sound energy. They also indicated that the integration takes place in the brain rather than in the peripheral organ. However, some of the experiments were running into a snag due to an exclusive and difficult-to-comprehend property of the auditory system, its ability to convert very short sounds into their spectral frequency components having longer durations.

If the integration takes place in the brain and not in the specialized peripheral organ, we reasoned, perhaps it also applies to other sensory systems. If this were true, we could use another sense modality for some of the experiments we could not perform on hearing. Practical considerations led us to the sense of touch; it had the advantage of responding to vibratory stimuli related in nature to sound waves. The tactile experiments confirmed our expectations, extending the generality of temporal integration to the sense of touch. The phenomenon had already been observed in vision.

The tactile experiments also gave us an insight of a very different nature: certain complementary key experiments can be performed on two different sense modalities and reveal directly related similarities and dissimilarities between them. Both are crucial for our understanding of general sensory performance, but the similarities are of particular interest since they allow us to find general sensory principles, or laws. Such laws form the basic structure of our most developed and fundamental science–physics.

Having discovered some of the advantages of intersensory research, we have continued to pursue it, undertaking many parallel experiments on hearing and touch. These experiments have shown more functional similarities between the two senses than we expected–an outcome of substantial evolutionary significance in view of the fact that the sensory systems involved are structurally quite different. Of course, many functional differences have been found also.

In the process of performing the tactile experiments, our tactile enterprise grew and prospered under the leadership of the current director of the Institute for Sensory Research, Ronald T. Verrillo. It is now one of the two leading tactile laboratories in this country.

The addition of tactile research to the original auditory research made the name "Bioacoustic Laboratory" appear inappropriate, and we changed it to the "Laboratory of Sensory Communication," acknowledging that our senses serve for communication with our environment. We kept that name for about ten years, but it became awkward when the Newhouse Communications Center was established; its faculty received some of our mail and we received some of theirs. In 1973, therefore, we took the present name of the "Institute for Sensory Research." It really was more than just a name change, however. We also advanced to independent departmental status.

ALL THE EXPERIMENTS at the Bioacoustic Laboratory were performed within one discipline–sensory psychology. Human observers received various auditory or tactile stimuli and had to tell us if they perceived them, either by pressing a key that activated a signal light, or by other means. Sometimes they had to assign numbers to the loudness of sounds to indicate how great it appeared to them. Such methods allow the investigators to determine what the senses do–their overall characteristics–but not how they do it and which anatomical parts are involved. For that, it is necessary to use neurophysiology and record neural responses from various anatomical parts of a sensory system. Since a complete understanding of our sensory systems entails knowing both what they do and how they do it, we added two neurophysiological units, first an auditory, then a visual one.

It may appear surprising to you that we added visual rather than tactile neurophysiology. After all, visual neurophysiology could not explain how the tactile system works. Again, pragmatic considerations prevailed. On the one hand, a laboratory at Johns Hopkins University was performing tactile neurophysiological experiments that, by unusually good fortune, closely dovetailed with our psychological ones. On the other hand, we thought that our Laboratory of Sensory Communication, as it was then called, was incomplete without research on vision, our dominant sense.

Why didn't we add both tactile and visual neurophysiology? I am sure you can guess the answer–space and money. Our aim was to cover as much territory as possible with as few people as possible. We expected that the highly advanced methods of visual neurophysiology would update our methods of research on the other senses, and reciprocally, that the psychological methods we used for this research would influence our visual investigations. Both expectations were fulfilled.

As key positions have been added, and research groups have grown around them, the structure of the institute has evolved into a system of several laboratories, each pursuing its own research but interacting with one another informally on a daily basis. The interaction is greatly facilitated by physical proximity. Thus, in its young maturity, the institute represents a compromise between the specialization required for expertise, and intersensory and interdisciplinary integration. What are the advantages of such a structure?

The importance of expertise should be obvious–no state-of-the-art research is possible without it. But what role does integration play? I have already mentioned the intersensory comparisons that can and have lead to intersensory generalizations, principles, or laws. Next comes the intersensory interaction—How does seeing a light pattern affect hearing a sound pattern? You don't normally listen to an opera with your eyes closed, but, if you want to concentrate on the quality of a singer's voice, you may close your eyes for a while.

The integration also brings significant methodological benefits. Sensory specificity has led to the development of different methods for investigating different senses within the same disciplines. It often happens that a method developed for analyzing one sense modality becomes helpful in investigating another. For instance, a well-known method for measuring the ability to detect a signal in the presence of noise, originally developed for hearing, was adapted at the institute for tactile research. You will probably be very surprised to learn that the method had its roots in radar technology.

In spite of their essential specificity, some sensory systems have features in common with some other sensory systems. Take the example of spatial patterns. Their resolution is important not only in vision, but also for the sense of touch, which allows us to discriminate among surface qualities—sandpaper feels different from silk. A doctoral student at the institute is currently pioneering studies on spatial tactile patterns under the joint supervision of two faculty members, one a specialist in research on touch, and the other, on vision.

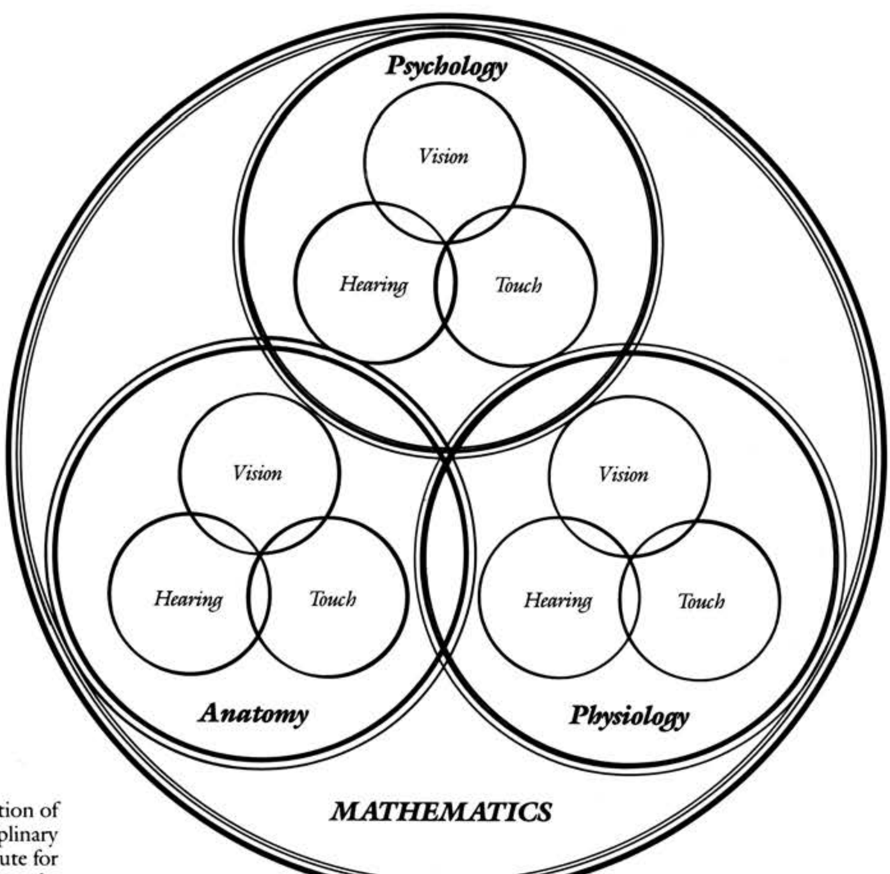

Figure 2. Graphic representation of intersensory and interdisciplinary interactions at the Institute for Sensory Research.

PROBABLY THE MOST important integration takes place among the disciplines. It is the quintessence of our interdisciplinary research. A personal experience has underscored for me the advantages of having the essential disciplines under the same roof and within the same organization. Until three years ago, my work was in auditory psychology and acoustics, and in mathematical theory as applied to these subjects. But one of my theories concerning the cochlea of the inner ear stirred up some controversy and urgently needed experimental testing. Instead of patiently waiting for someone else to do it, I decided to undertake the task myself. The experiments required neurophysiological and neuroanatomical expertise. I didn't have either, but some of my colleagues at the institute did. They graciously taught me what I had to know, and within a few months I was able to perform the necesasry experiments. I doubt that this could have been accomplished so quickly anywhere else.

The essence of the intersensory and interdisciplinary interactions at the Institute for Sensory Research is illustrated graphically on page 51. The smallest circles represent the sense modalities we are currently investigating, the larger ones the main disciplines involved. The overlaps among the circles symbolize the intersensory and interdisciplinary interactions. The largest circle encircling all the others symbolizes mathematics–the universal language of all the natural sciences.

The institute is far from having reached the peak of its development. The addition of research expertise in such areas as biochemistry, auditory and tactile anatomy, and tactile neurophysiology is planned to complement the ongoing research on the three senses of vision, hearing, and touch. We also hope to expand our activities to additional senses, including taste, smell, and some others, to steer the institute toward becoming a true world center for sensory research. The goal seems to be within reach.