In the Realm

hear

nof the Senses

Scientists are using advanced computer technologies to increase, enhance and extend the power of the senses

By James Geary

THE FIVE SENSES—VISION, HEARING, smell, taste and touch—are our only ways of knowing the world. Nothing enters our awareness, nothing affects our emotions, without first passing through one of these five portals. The senses are so essential to our knowledge of reality that language is steeped in their metaphors. A sensitive person is described as "in touch" with his feelings; an unpleasant experience leaves a "bad taste" in your mouth; we understand someone when we "see" what she means. It seems we only comprehend the world when it's phrased in the body's own vocabulary. That vocabulary is now being extended by wedding advanced computing technology to the human senses, a marriage that holds forth the promise of talking, smelling computers and devices that can restore sight to the blind. In the process we are taking one small step forward in the evolution of the man/machine.

smell

touch

taste

Touch

HIROSHI ISHII, ASSOCIATE PROFESSOR AT the Massachusetts Institute of Technology (M.I.T.) Media Lab in Cambridge, Mass., discovered his first personal digital assistant at the age of two: an abacus. He liked its texture, its smooth feel, the clear "clink" sound it made when the beads were moved. Inspired by that childhood experience, Ishii has been devising ways to make the wealth of digital information inside computers as tangible and pleasant to the touch as the abacus of his youth. "Now we experience the digital world through typing and clicking on cheap plastic boxes," he laments. "I want to use objects that we can touch to manipulate digital information, to join the richness of the physical world with digital technology." To this end, Ishii's Tangible Media Group at M.I.T. is developing haptic (which means pertaining to the sense of touch) interfaces: programs that allow you to reach out and touch someone through a computer.

One such interface is inTouch, a computer program that creates a direct link between two people separated by physical distance. Using "force feedback" technology, which allows users to physically interact with computers, the inTouch system brings people together through the manipulation of two identical objects. The current inTouch prototype consists of twin sets of cylindrical wooden rollers connected to a computer. When a user rotates one set of rollers, the computer rotates the corresponding set in exactly the same manner. In this way someone operating the inTouch system actually "feels" the movements of his or her counterpart, even though they may be located in different cities. Ishii's goal is not to recreate the physical form of the user at the other end—though that may be possible—but to create a physical link that transmits that person's gestures. "To actually physically feel something enriches our perception of it," he says, "and allows us to interact with the environment as we were meant to."

Elsewhere at m.i.t., in 1993 Kenneth Salisbury and Thomas Massie of the Institute's Artificial Intelligence Laboratory invented the PHANToM Haptic Interface: a high-tech thimble on the end of a jointed arm that lets people "feel" the information inside their computers. Massie is now chairman and chief technology officer of SensAble Technologies, the company he set up to market PHANToM. To operate PHANToM, you insert your finger into the thimble, which reproduces your finger

"I WANT ... TO JOIN THE RICHNESS OF THE PHYSICAL WORLD WITH DIGITAL TECHNOLOGY"
Hiroshi Ishii, M.I.T. Media Lab

The Revolving Doors of Perception

The mystery of synesthesia suggests that there are many ways to perceive the world

"IT'S KIND OF LIKE FIGURING OUT THAT YOU HAVE A BELLY-BUTTON," says Karen Chenausky, a 30-year-old speech researcher who lives in Somerville, Mass. "At some point you just notice and start playing with it. Then you get really into it. And after a while you get bored, because you realize everyone has one. Except not everyone has this."

Karen is talking about synesthesia, an unusual and little studied condition in which a stimulus received in one sense organ causes an experience in another. Karen, for example, has one of the most common forms of synesthesia: colored hearing. For her, sound and vision mingle: the different tones of words and letters involuntarily evoke distinct and vivid colors in her mind. Russian novelist Vladimir Nabokov was similarly gifted. In his memoir *Speak, Memory*, he lovingly recites his own private alphabetic palette of sounds: "In the green group, there are alder-leaf *f*, the unripe apple of *p*, and pistachio *t*. In the brown group, there are the rich rubbery tones of soft *g*, paler *j*, and the drab shoelace of *h*." Like Nabokov, Karen revels in this added perceptual dimension. "Synesthesia is an extra way of perceiving the world," she says. "The parts of the world I perceive in this way are parts I hold most dear."

Though known for roughly the past 300 years, synesthesia—derived from the Greek words *syn* (together) and *aisthesis* (to perceive)—is still very much a mystery. Scientists don't agree on what causes it, or even how widespread it is. According to neurologist Richard Cytowic, author of both scientific and popular books on the subject, only ten individuals in a million are synesthetes. Other surveys suggest that about one in every 2,000 people automatically sees colors when hearing words, letters or numbers.

Cytowic has tracked the source of the synesthetic experience back to the limbic system, one of the oldest parts of the brain and the site at which emotions and memories are processed. Cytowic calls synesthetes "living cognitive fossils" because he believes this

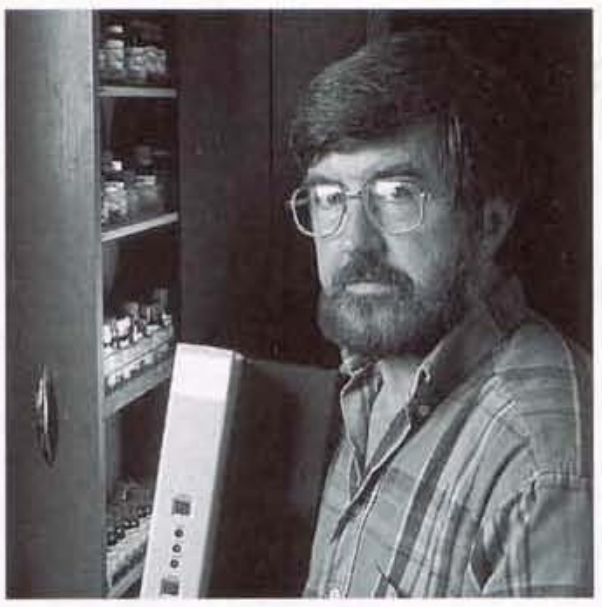
movements on a computer screen inside a virtual space filled with simple geometric shapes. When you touch something in that space—the tip of a triangle, for instance—PHANToM exerts pressure on your fingertip so that you actually feel its sharpness. By modifying the pressure and adding irregularities, even textures like rough and smooth can be reproduced. PHANToM is already finding its first commercial applications. Surgeons at Pennsylvania State College of Medicine in Hershey, Penn., are using PHANToM to train students more effectively, performing delicate virtual brain surgery on realistic virtual patients.

Though the inTouch and PHANToM systems are still a far cry from replicating, say, the subtle pressures and textures of a simple handshake, it's not hard to imagine the recreational uses to which this technology could be put once sufficient technical sophistication is achieved. Michael Dertouzos, head of M.I.T.'s Laboratory for Computer Science, foresees a new form of entertainment to complement audio and video: "bodyo." By donning virtual reality bodysuits outfitted with an array of sensors, he suggests, we will one day be able to feel everything from the roughness of computer-generated sandpaper to the pleasures of digital sex. With developments like this on the horizon, Ishii, Massie and Salisbury are proving that the beauty of the haptic interface is more than skin deep.

Smell

MEDIEVAL PHYSICIANS WERE SKILLED AT diagnosing patients by the smell of their breath. Even today it's well known that certain ailments, such as liver disease, produce very distinct odors. George Dodd, senior research fellow at the Highland Psychiatric Research Group in Inverness, Scotland, wants to reintroduce the medieval practice of breath analysis into modern medicine. But instead of a doctor's trained proboscis, an electronic nose on a computer chip will be making the diagnosis.

Primitive electronic noses—arrays of odor-sensitive electrochemical sensors attached to a high-powered computer—have been on the market for the past several years, used primarily to trace explosive residues, analyze blood alcohol levels and carry out quality control tests in the food and beverage industry. But Dodd, a native of Dublin, born within sniffing distance of the Guinness brewery, is on the scent of much more sophisticated chips.



"ONCE WE KNOW THE ODOR CODE, SMELL TECHNOLOGY WILL PROVIDE POWERFUL DIAGNOSTIC TOOLS"

George Dodd, Highlands Scientific Research Group

Dodd first began exploring the outer limits of "odor space" in the late 1960s. Back then the nature of smell was still very much the subject of scientific debate. It was only in the early 1970s that the stereochemical model of smell, which states that odors consist of molecules of different geometric shapes, eventually prevailed over rival theories. According to this theory, smells occur when an odor molecule—the disc-shaped molecule of a musky odor, for example—alights on a corresponding receptor on one of two olfactory patches ensconced high inside our nasal passages.

Dodd's work is devoted to replicating this ability on computer chips and then "training" the chips to recognize specific smells. This would lead to small, cheap hand-held diagnostic devices. A sniffer chip could even be inserted into the speaker of a telephone so that patients with, for example, liver cirrhosis could call up a computer once a month and hold a conversation with it while it analyzes their breath. Dodd imagines the day, perhaps only five years away, when there will be an electronic nose in every doctor's office and people will routinely carry credit-card-sized devices to monitor health problems like ulcers and diabetes. Such electronic

kind of multi-sensory perception is as ancient as the place from which it originates. According to his theory, synesthesia may well have been our primeval way of experiencing the world—until the more rational cortex evolved and filed the senses into their individual compartments. "Synesthesia is a normal brain function in every one of us," Cytowic says, "but its workings only reach consciousness in a handful. It may well be a memory of how early mammals saw, heard, smelled, tasted and touched."

Other researchers attribute synesthesia to a profusion of neural connections between the parts of the brain that control the five senses. Daphne Maurer of McMaster University in Ontario even suggests that this embarrassment of neurological riches makes all babies born synesthetes, who experience a rattle, for example, not just as an intriguing sound but as a barrage of colors, smells, tastes and tactile sensations. Only after about the age of four months, when the infant's cortex has sufficiently matured, does the synesthesia fade. "The brains of young babies have many more neural connections than they do in later life," explains Simon Baron-Cohen, a lecturer in the Department of Experimental Psychology at Cambridge University who is studying the theory. "Many of the links gradually get pruned back. Synesthetes may be people who retain these neural connections."

"Synesthesia is not a disease," Cytowic concludes, "but a bonus. Your senses give you more than you bargained for." Though still poorly understood, the experience of Karen Chenausky and others like her suggests there's more to the world than meets the eye, ear, nose, tongue and skin. ***—By J.G./London***

noses, however, would need to be a great deal more sensitive than the devices currently used in the food industry. Ideally they would be able to alert someone before they developed any symptoms.

And if they are to work, detailed molecular maps are needed of all the odors associated with disease. Since this entails charting the interactions of over a thousand smell molecules in the air with the hundreds of smell receptors in the human nose, immense computing power—and immense patience—is required. Dodd cautions that the ability to carry out such olfactory cartography is still a long way off. "We do not know the odor code," he admits. Accumulating the necessary data will be "a long job, but possible," he says. And once the key odor molecules for specific diseases are identified, he predicts, "a new generation of electronic noses can tune into those particular molecules" to provide powerful diagnostic tools. The only question then will be, does a rose perceived by an electronic nose really smell as sweet?

Taste

LIKE SMELL, TASTE IS NOTORIOUSLY difficult to pin down. The two senses are, in fact, intimately related: fragrance, along with flavor, texture and temperature, is crucial to determining an object's taste. Research on the subject has lagged far behind that on other senses though, largely because people seem to take their tongues for granted. But for Robert Bradley, a professor of dentistry and physiology at the University of Michigan who specializes in research on taste and the central nervous system and designed the world's first wiretap into the tongue, this type of work is to be savored.

Like a lunar landscape strewn with craters, the human tongue is pitted with around 8,000 to 10,000 taste buds, each of which is equipped with between 50 and 75 chemical taste receptors. These receptors have an extremely short shelf-life, and are replaced roughly every ten days. Bradley's device, called a sieve electrode, is made from a silicon disk only 4 mm in diameter. A series of microscopic holes—each linked to a computer—is punched into the disk, creating a miniature sieve. Researchers then sever a nerve connecting the tongue's receptor cells to

"WE'RE TAPPING INTO THE TONGUE. IT'S LIKE WATCHING AGING ... THE CELLS ARE BORN AND DIE IN DAYS"

Robert Bradley, University of Michigan

the brain and implant the sieve electrode onto the nerve. The nerve subsequently grows back through the holes in the disk to reconnect to the taste buds—and the new computerized taste receptor settles into place.

Bradley's goal in inventing this unwieldy device is to explore the reasons behind the high turnover rate of taste bud cells. "We're tapping into the tongue," he says. "It's like watching aging because the cells are born and die all within ten days." Bradley also hopes his tongue-tap will help him discover the mechanisms by which the brain is able to tell the difference between, say, the taste of salt and sugar. "One theory proposes that it's not done by a single line [from the tongue] to the brain," Bradley explains, "but by some pattern across all the [tongue's] lines to the brain. The only way to examine that is to record from multiple nerve fibers at the same time." And that is precisely what the sieve electrode is designed to do.

Though Bradley's work is still in the early stages of development, the basic technology behind his device is being used as a model for the implantation of miniature electronics in other parts of the human nervous system. According to Bradley, similar interfaces between machines and the nervous system could be used to stimulate movement in victims of paralysis or create artificial hands powered directly by nerve impulses. "The device potentially could be used as a neural interface to connect the body to anything," says Bradley. If so, treatments for a host of nervous system disorders could well lie on the tip of Bradley's artificial tongue.

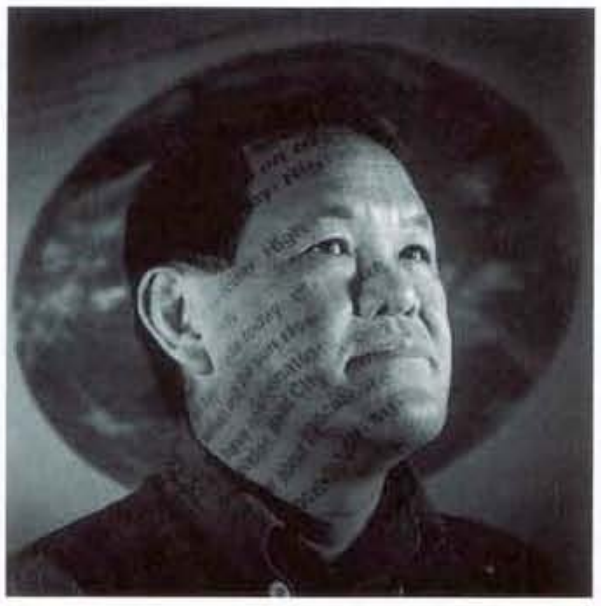
Hearing

EVERYONE LIKES TO TALK ABOUT THE weather. That's why Victor Zue, associate director of M.I.T.'s Laboratory for Computer Science, chose it as the subject with which to teach computers to hear and comprehend human speech. Ask Jupiter, a computer program designed by Zue to chat about the weather, for the temperature in New York and it will give it to you. How about Paris? Jupiter has that information too. Need to know the humidity in Tokyo or the weekend forecast in Rio? Jupiter can tell you. "You can actually carry on a conversation with this machine," Zue enthuses.

The key to Jupiter's conversational ability is that it not only hears human speech—it understands it. "To create a truly human-like conversation partner," says Zue, "the machine needs to do far more than just recognize words—it needs to understand them." Master of a vocabulary of about 1,500 weather-related terms, Jupiter doesn't understand much—just enough to hold forth about the weather. "It's a very primitive, very limited machine," says Zue, "yet it is one of a kind."

A conglomeration of four software packages, Jupiter's voice recognition program recognizes sounds and translates them into a "word hypothesis" based on a calculation of linguistic probabilities. Once the word hypothesis is reached, a second software package kicks in to determine the meaning. Then Jupiter scans U.S. National Weather Service reports on the Internet until it finds the requested information. Finally, in a robotic staccato reminiscent of Stephen Hawking's speech synthesizer, it replies. And all this within the space of a few seconds.

The technology developed for Jupiter is already making its way to market. Michael Phillips, who spent seven years helping to devise Jupiter's computer architecture, co-founded Applied Language Technologies Inc. (ALTech) in 1994 to adapt Jupiter's voice recognition software to commercial uses. Last year, ALTech released two software programs for advanced telephony-based speech recognition applications. AT&T, meanwhile, is



"YOU CAN ACTUALLY CARRY ON A CONVERSATION WITH THIS MACHINE. IT'S AMAZING"

Victor Zue, M.I.T. Lab for Computer Science

testing similar software that recognizes the digits in credit card numbers. And Zue himself soon plans to launch another system to give information about commercial airline flights. In the not-too-distant technological future, computers may be conversing about much more than just the weather.

Sight

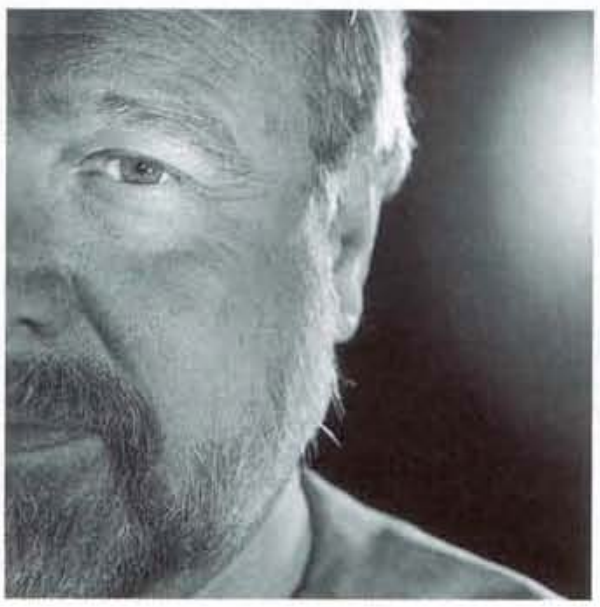
PICTURE THIS. YOU ARE WALKING DOWN A street in a foreign city, wondering how to find a particular restaurant where you've arranged to meet an old friend. After entering a few commands on a small computer attached to your belt, you see a city map appear before you in the air, with the quickest route to the restaurant outlined in yellow. Having eventually found the right street, you can just make out a sign in the distance. A light touch to your glasses magnifies the image, confirming that this is indeed the place. You enter the restaurant and recognize your friend already seated at a table. And now picture one more thing: You are legally blind.

This is the future of sight as envisioned by Tom Furness, director of the University of Washington's Human Interface Technology Laboratory in Seattle. For the past 30 years, Furness has been studying how the sense of sight can be enhanced—and, in some cases, even restored—through the use of light-emitting diodes, lasers and advanced computer technology. The result is the Virtual Retinal Display (V.R.D.), a device that paints images directly onto the human retina, the thin sheet of light-sensitive cells stretched across the back of the eye. "It's like taking a movie projector and shining it directly onto the retina," Furness explains. "Instead of creating a screen to look at, we create the light rays that emanate from that screen. When the light reaches the retina, it appears as if the image is really there—but it's not. It's a virtual image."

To all outward appearances, the V.R.D. is rather unassuming—a pair of high-tech eyeglasses attached to what looks like a simple briefcase. But feed any image into the computer within and a so-called scan converter transfers the signals to the glasses through a fiber-optic cable. Microscanners then convert the signal into color images and cast those images onto the retina using low-powered lasers. The result is a complete picture—of a map, a sign, or a face, for example—superimposed over the standard field of vision. This still-experimental version of the V.R.D. is semiportable, but not yet easily wearable. Eventually, Furness predicts, the electronics will be reduced to a unit about the size of a pack of cigarettes that can be comfortably worn on a belt, though the first commercial products, due for release in 1999, will be relatively bulky.

While the images conjured up by the V.R.D. may be virtual, the potential benefits are very real. "After we finished the first demonstration in 1993," Furness recalls, "a person came into the lab, looked into the display and said: 'I can see this image perfectly with my blind eye.' We were blown away, and started investigating." Furness' group learned that the person whose sight was restored had been in an automobile accident several years before. His injured eye was obscured by scar tissue that prevented light from reaching the retina, leaving him effectively blind in that eye. But the retina itself was still intact—and the V.R.D. image flowed right through tiny gaps in the scar tissue to strike it. This serendipitous discovery gave Furness his first hint that the V.R.D. could help people with some visual impairments, such as scar tissue and cataracts, see again.

In addition to giving sight to the blind, the V.R.D. may have other applications for those with standard vision. The "augmented vision display," what Furness describes as images of "the normal outside world



"WE MIGHT BE ABLE TO GIVE PEOPLE A SORT OF HYPERVISION ... LIKE CREATING BIONIC EYES"

Tom Furness, University of Washington

with the virtual world superimposed on top of it," is a case in point. This technology would enable architects and contractors to construct buildings around virtual images of the planned structure. Using it as an elaborate paint-by-numbers set, construction workers could assemble a building simply by filling in the virtual image with the actual materials. "You will see a virtual girder," Furness explains, "and put the real girder in the same place." But Furness has his sights set on other targets as well. He believes the V.R.D. will change the very way things are perceived. "We might be able to give people a sort of hypervision," he suggests. "It would be like creating bionic eyes ... to see things [people] would never see otherwise."

Soon new technologies like PHANToM, Jupiter and the V.R.D. will become so sophisticated that it will be difficult—if not impossible—to tell the computer-generated touch, voice or image from the real thing. But Furness, for one, is not troubled by the potential dangers of this kind of double vision. "The eye is picking up light [with the V.R.D] as it would in the real world," he says. "The only difference is that it's being scanned onto the retina. Who's to say the image is not really there?" What's "really there" will ultimately be determined by the eye of the beholder. But if seeing is indeed believing, then "virtual reality" is slowly but surely becoming just plain reality. ***—Reported by Lamia Abu-Haidar/Cambridge, Dan Cray/Los Angeles and Barry Hillenbrand/Inverness***