Remember Evelyn Cyril Gordon? No? How about Scar Gordon? Or maybe you recall Oscar Gordon better? By whatever name, the one his parents gave him, the one tacked on by his army buddies, or the one given him by that beautiful stranger, he was the hero of Heinlein's "Glory Road. His adventures made a fine tale, a fun tale, but without his "eyes behind"—one Rufo—and a certain hyper-dimensional suitcase with all of Neiman-Marcus stuffed inside it, the story would have been proverbially nasty, brutish, and short, as well as vastly less entertaining. But was it Rufo or the bag of tricks that brought him through, successful in his quest, safe, and loved?

It wasn't the bag of tricks. That disappeared almost as soon as the trouble started. But Rufo? The "eyes behind"? He helped in other ways too, but that was the way that mattered. Heinlein effectively gave Oscar Gordon eyes in the back of his head in just the way that most of history's heroes have had them, in just the way that an army patrol has them—a rear guard.

Would you believe a single hero? A one-man patrol? Maybe, but you wouldn't want to be that man. He'd be too easily ambushed and killed. Now. But soon—five years? ten?—he may be possible. Scientists now are working on vision replacements for the blind that could be used to give a man a third eye.

Perhaps most reminiscent of science fiction is what might be called the "brain-jack" approach to the problem. Put simply, nerve cells are known to communicate by electrical impulses.* (*Chemical impulses, actually. But they're always accompanied by electrical pulses so the difference needn't concern us.)

They can be activated .by electrical stimuli and their own activity may be used to electrical sensors. And, accordingly, innumerable stories have been written in which the decision-making capability of the human brain is combined with the prodigious calculating capacity of the digital computer by using electrical stimulators and sensors to read in, formation into and out of the brain. Some of those stories have actually used the notion of a plug, perhaps mounted in the forehead and looking rather like the socket of a radio tube, to link a computer directly to the cells of the brain. Others have mentioned induction fields such as might be set up between a set of small transformers implanted under the scalp and another set in a helmet. Still others have suggested tendrils or needles that would penetrate the scalp or skull and establish their connections with the nerve cells as the occasion demanded. These notions are science fiction.

A few scientists, however, are working along these lines. Not that they're trying to mate man and computer. So far they've done no more than apply small, square arrays of tiny electrodes to the surface of the visual cortex (that portion of the cerebrum which processes visual data) and provide patterned stimulation to the nerve cells there. In experiments on human beings they have been able to present letters of the alphabet and have their subjects report that they could actually "see" them. The images were not really clear—after all, the electrical stimuli were affecting vastly greater numbers of cells than are normally stimulated by similar images falling on the retina of the eye—and the sensation was not precisely that of vision, but a limited amount of information was getting through. The "brain-jack" works.

But not very well. Hook up that electrode array to a TV camera and maybe you could read. But you wouldn't be able to appreciate a *Playboy* nude. For that it takes another sort of approach. One that, although the information is still limited, can provide more visual information with less risk and fewer technological problems. A group of scientists in San Francisco has developed a system using a TV camera, some electronic circuitry, and a patch of skin on the belly or back or thigh, and though the system is being tested for use on blind (and blindfolded) subjects, there is a distinct possibility that it could be used to provide a "natural" sort of rear-view vision to a normally-sighted person.

Except for those researchers interested in implanting electrodes directly into the brain, most of the scientists working on the problem of vision replacement are focusing on ways of using the skin as a replacement or substitute for the retina. For instance, the Linville-Bliss Optacon uses photocells which, when passed over a line of print such as this, drive 144 small vibrators fastened to the fingertips and enable the blind to read. Another system uses a TV camera to drive an array of vibrators mounted on the forehead.

Even the Russians, though they approach the problem a little differently, think in terms of using the skin. At last report, they had a woman who could read with her naked fingertips, even through a sheet of glass. How she did it, they didn't know, but they were studying her and her odd talent with an eye toward training others to do the same. So far as I know, they have met with no great success.

The system I wish to discuss here is the one being developed and investigated by Professor Paul Bachy-Rita and his colleagues at the Smith-Kettlewell Institute of Visual Science in San Francisco.* (*Dr. Bach-y-Rita's recent book, "Brain Mechanisms in Sensory Substitution," Academic Press, New York, 1972, is the source of much material in this article and I acknowledge his work gratefully.)

Their *tactile vision substitution system* (TVSS) uses an ordinary television camera to drive, through appropriate circuitry, an array of either vibrators or electrical stimulators which, because of the small size of the electric pulses they deliver and their high frequency (60 pulses per second), feel like vibrators. The circuitry reduces the TV image to a dot picture, rather like a black and white mosaic, in which each dot controls one stimulator in the array (e.g., light-on, dark-off). The array, applied to an area of skin, actually permits a blind person to "see." Not color, and not yet very well, but well enough to read large letters on a wall, to locate a telephone or coffee cup, and to discover that a wife or husband doesn't really look as nice as the blind subject had thought.

Figure 1. The first tactile vision substitution system consisted of (from right to left) a modified dentist's chair with an array of mechanical stimulators (vibrators) mounted in the back, a television camera which reduced its picture to a square array of points, each point of which corresponded to one vibrator, and a slanted display board It weighed 400 pounds and was thus not portable, but it did show that such a sensory substitution system is feasible.

The original version of the TVSS, built in the late 1960's, used a standard television camera and had an array of mechanical stimulators mounted in the back of a modified dentist's chair, as shown in Figure 1. Thus, when the subject sat down in the chair and leaned back, the vibrators were in position to impress their "image" upon his skin. The system was not portable; it weighed 400 pounds and was quite bulky; but the movements of the camera could be controlled by the subject.

Later models, however, were made portable, the first such consisting of a stimulator array on the belly and a, one-pound camera slung over one shoulder like a handbag, and connected by fiber optics to a "look-out" station be side the eye. The latest differs from this principally in that the TV camera weighs only six grams and is mounted on a glasses frame, thus permitting a blind person to attain, in some respects, nearly normal vision. The stimulus array delivers small electrical pulses to the skin and, since the electrodes are much smaller than the vibrators, it is much lighter than the earliest mechanical arrays.

The exact nature of the apparatus involved, though, is not as important as the nature of the phenomena observed and the "visual" results obtained. The first TVSS, heavy, bulky, and with only an 8 x 8 array of stimulators, proved that the approach was workable, that blind persons could use senses other than their ears and hands to obtain intelligible information about the world around them. Later models showed just how much like vision the tactile substitution can be.

Most of the subjects who have cooperated in the development and study of the TVSS have been the so-called early blind, that is, people who have been blind from or nearly from birth. (Visually-guided behavior does not develop in man until about two months after birth, so it is not possible to diagnose blindness before then.) These persons have had no prior experience of vision, but with some training on the TVSS, all became "visually" sophisticated enough to be susceptible to the visual illusions.

In fact, one such person was using the set-up of Figure 1 (the slanted board is used to allow the demonstration and use of certain distance cues, such as the height of an object on the board) when the board unexpectedly fell forward onto the camera. Several days later, the experimenter recreated the incident by operating the camera's zoom lever without warning the subject. The subject threw up his arms and tried to leap backward, away from the falling "wall," even though the "visual" information upon which he was acting was being impressed upon the skin of his back. Not only did he learn the first time what a "looming" stimulus meant, but he localized it correctly in space, precisely as if he had functional eyes.

This is all the more startling when we consider the nature of the stimulus: an array of point stimuli, 20 x 20 in the latest models, only some of which are activated by the light reflected from an object and entering the camera. Figure 2 shows, schematically, what a beer stein would look like with this system. The figure is most accurate as a representation of the earlier mechanical stimulation—the dots of the image are black and white and the corresponding vibrators are either on or off. Gray-scale information is only now becoming available in those models which use electrical stimuli.

Figure 2.

A pictorial representation of a TVSS image. The large black dots are those activated by the light entering the TV camera and are felt by the subject as vibrating points.

Obviously, a 400-point array cannot convey much information, but because the subject can move the camera, either by its controls as in Figure 1, or by moving his head as when the camera is mounted in the glasses, he can carry out what astronomers call occlusion studies and get a very accurate idea of what the actual contours of an object are.

As presently designed, the system is cyclopean, or monocular, and it has a narrow (two-to-ten degrees) field of view in order to let as much detail as possible reach the dot picture of the array. But as long as the subject can control the movements of the camera, he can not only "see" the object, but, as indicated above, he can "see" it as located in front of him, even though the signals that reach his brain are originating on the skin of his back. He senses it not as a pattern of vibration, but as an externally localized object, just as sighted persons do those objects they sense through their eyes.

It helps that the subject can correlate changes in the stimulus pattern with his own motor output—if he makes a motion in connection with an object he knows is there, then stimulus changes become identified with the object. It is in just this way that infants may learn to identify external objects as external by correlating changes in appearance with eye and head movements.

But this similarity only disguises the nature of the problem to which the TVSS seems to be a solution. Sensory substitution depends on the ability of one sensory system to assume the functions of another, where "system" means the peripheral receptors, the nerves linking them to the spinal cord and/or the brain, and the central nervous system itself. The various systems differ from each other most obviously in the nature of their receptors, though there are also important differences in the neural equipment that processes the data received and passed on by them.

While no two sensory systems may do the same thing, one may be made to serve the same purposes as another. It is quite possible to transform stimuli appropriate to one receptor into stimuli appropriate to another, and that is just what the TVSS does: the TV camera absorbs light and acts as a transducer to change that stimulus to the electrical or vibratory stimulus appropriate to skin receptors.

Now, most people are surprised when they are told that the skin can be made to serve as an eye. "How?" they ask. "After all, the eye is very small and covered with millions of very sensitive light receptors and the skin is big and its receptors don't seem very sensitive at all." If they know a little more, they point out that most areas of the skin are not sensitive enough to tell the difference between one and two pinpricks unless they are relatively far apart. But the sensitivity is greater than it seems, and the skin's reaction to pinpricks is not entirely pertinent: patterns can be sensed, and a good example is the way your "insensitive" back responds to the texture of a shirt. We don't use it, but the potential is there, and the skin of a person with a sensory handicap such as blindness often becomes almost excruciatingly sensitive—the blind are sometimes said to be able to "feel" walls and other obstacles either as light or as sound.

The average individual has about two square meters of skin on his body, 90 percent of it hairy and all of it loaded, more or less heavily, depending on its location, with receptors for touch, heat, cold, and several other stimuli. The scientists don't yet know which ones transfer the information provided by the TVSS to the brain, but they do know that one or more does the job, and that, because of the rapidly changing nature of the information provided by the TVSS, it must be a receptor that adapts rapidly to changes in the stimulus to which it responds. But even so, the nature of the skin and its receptors acts to provide some preliminary processing of the TVSS data—when vibratory stimuli are used, the traveling waves set up in the skin by the vibration act to stimulate neighboring receptors and to blur the "image." Electrical stimuli, which spread much less when the electrodes are properly designed, provide a much crisper, clearer picture and hence permit more detail to be seen and more points to be usefully used in the stimulus array. Furthermore, thanks to such characteristics of the skin receptors and their nerves as lateral inhibition and varying adaptation times, the TVSS information is filtered and funneled so that the data reaching the central nervous system for analysis and "perception" are in some ways simplified.

Despite this simplification, however, the scientists responsible for the TVSS have not tried to change the characteristics of their system to reflect it and, perhaps, make it possible for the nervous system to extract more use from the data they can provide the skin. The traditional approaches to the problem of sensory substitution (such as Braille) did attempt to do something like it, producing systems which provided only data considered "meaningful" by their designers, but such approaches were not very successful. Braille, for instance, is a highly artificial construction that not only requires learning a whole new code and relies on specially prepared materials, but discards all of the nuances of typography and leaves its user isolated from handwriting, billboards, and most printed material.

Any attempt to constrain the inputs leads to a loss of usefulness; in effect, it deprives the brain of any chance to examine a whole pattern and extract its own meaning; it removes the context of a stimulus which is essential to any understanding of its significance. The designers of the TVSS have instead focused on providing as much information as possible to the brain, though it has been found that if the image of an object is processed so that only the edges appear in the dot picture the ease of recognition is increased. The only constraints on the data provided by the TVSS are those constraints inherent in the system itself, and those are severe enough. It has been said that the limitations of the system are more attributable to the lack of information in the dot picture than to any overloading of the data-handling capacities of the skin.

Nevertheless, a blind person must be taught to use the TVSS. He has to learn the visual concepts and strategies that sighted persons learn so far back in infancy that they have completely forgotten that they once did not know them. He must be taught, through the use of pedagogical aids like the slanted demonstration board of Figure 1, such cues to distance, shape, and relationship as overlap, height in a field of view, shadows, and distortion of shape with rotation. It was this last lesson, pointing out that squares and circles are never seen as such by sighted persons unless held, or approached, perpendicularly to the line of vision, that caused one girl to exclaim, "My, you sighted people certainly live in a distorted world!" To her, the shapes of things were invariant because they always felt the same to her exploring fingers, but within a few hours she learned the principle of "shape constancy" that rules our learned belief that shapes never change.

Blind persons who are given sight surgically often become so confused by the chaotic, kaleidoscopic world of shape and color that they actually *refuse* to see. The shock of the unfamiliar is too threatening and they dare to use their eyes only for such customary things as reading, for there the differences are not so great. Most of the subjects using the TVSS, however, eventually learn to "see" well enough to recognize faces and objects, to use the perspective cues, and, with the portable system, to find their way around the laboratory. The difference may be because of the simplicity of the scenes to which they were exposed in training. The novelty of the input may never have been so overpowering.

It is known that the nervous system adapts to the demands made upon it by the environment. Studies of rats raised in enriched environments—meaning that their scenery and possible activities were more varied than for the average rat—have shown increased brain weights and increased amounts of the substances involved in synaptic transmission, suggesting an increase in the ability of the brain to process information, while an environmentally deprived rat shows decreases in the same items. Kittens raised with their eyes covered by prisms which distort the world show concomitant changes in their visual cortex, changes in the "circuitry" of the brain that render it able to compensate for the distortion. Persons who have been blind or deaf from birth show, on autopsy, a shriveling or withering of those parts of the brain that serve those senses. The brain's capacity for such changes, however, is not permanent; it is only during the so-called formative stages of life that it responds so obviously to alterations in the sensory environment. Once infancy or early childhood is past, blindness or environmental enrichment results in only minor changes, though these minor changes are large enough that a person blind from birth may, if given sight, regain a large amount of function.

Peripheral changes occur too. Certain diseases (e.g., psoriasis and leprosy) are associated with proliferation or destruction of the nerve endings in the skin; amputation is accompanied by atrophy of those parts of the spinal cord that served the missing limb; but such changes are much less important than the central ones listed in the previous paragraph. When the environment insists that more data be handled by a sensory system or that it be handled more efficiently, the nervous system responds by altering its central portions. The investigators of the TVSS have been able so far to find no changes in the peripheral nervous systems of their subjects.

What changes? The cells of the normal visual cortex are known to respond to tactile as well as visual stimuli, but if the visual cortex is withered or atrophied from disuse it can not be expected to serve as the central processor for TVSS "visual" data, certainly not without showing some sign of its shortcomings. And that part of the brain which does act as the central processor for information from the skin is not normally geared to handling the complexities of visual data, though the evidence suggests that it has no difficulty in handling the TVSS data.

Do the peripheral nerves and spinal cord indeed change, adapt to reduce the complexity of the data to a point where the normal "tactile" cortex can handle it? It has been found that once a blind person has learned his visual strategies and is able to use the TVSS successfully with the stimulus array applied to one area of the skin, such as the back, the array can be moved to another site, such as the belly or thigh, with no loss of the ability to "see." The transfer of the learning to the new site is immediate and includes the ability to localize objects correctly in space. There is no confusion because of the change in the site of the input. This transferability of TVSS "vision" suggests that the adaptation probably occurs at much higher levels than the spinal cord. It probably does not involve the atrophied visual cortex, but rather a functional hypertrophy, necessarily limited in the case of the older subjects on whom the system has been tested, of the tactile cortex to allow it to do the job.

Thus, what is known of the adaptability of the nervous system suggests that, once a blind person has used the TVSS long enough, his brain will adapt to allow him to extract nearly as much information from the tactile dot picture as the normal eye can. It further suggests that the younger the subject, the more thorough this adaptation will be.

The success to date of the TVSS allows us to speculate that there will soon be such a thing as a visual prosthesis. Ultimately, this may take the form of a TV camera shaped and colored like an eyeball, installed as a replacement for the natural eyeball, hooked up to the natural eye muscles for motor control, and linked by subcutaneous wires to a stimulus array embedded in the tissues underlying the skin of the belly. A blind person would then neither look nor behave any differently from his sighted neigh bor. He would not be blind.

The only significant drawbacks that remain, the basic technical problems* (*And technological. The Optacon mentioned on page 65 is now being produced and sold by Telesensory Systems, Inc.) having already been solved, are the psychological factors. Because of the lack of emotional associations with visual perceptions and because of preconceptions based on their other senses, the blind subjects who have worked with the TVSS have not always found "vision" pleasant. As mentioned. before, when they have examined the faces of people close to them, they have not always considered them as attractive as they had previously thought. Men who examined *Playboy* nudes were not aroused. A woman who had just married could only be motivated to use the TVSS to "see" by using as practice scenes the household implements with which she was then involved. But these difficulties are due only to the past experience of the subjects. They would not arise if an infant, as soon as he was diagnosed as blind, could be fitted with a visual prosthesis. He would then develop the same emotional associations with and reliance on visual stimuli as sighted persons.

As exciting as that first commercial artificial eye will be, though, there are other possible applications of the basic idea of an artificial "tactile sense." The same researchers are testing it as a way of giving hearing to the deaf: a single vibrator modulated by the output of a microphone is an accurate enough reflection of a voice so that an otherwise deaf person can actually tell when a new voice joins a conversation. Other researchers have built a model of the basilar membrane, that elongated trapezoidal structure whose vibrations stimulate the nerve endings with which we hear. The model, like the biological original, responds to sound in such a way that only one small portion of its length resonates to a single frequency. In life, the nerve endings attached to that area respond and the mass of the separate responses to the various component frequencies of a sound are integrated by the brain to produce our aural perception. To use the model, a person, deaf or otherwise, lays his arm along it, thus allowing the receptors in his skin to act like those in his ear. The difficulty is that the tactile cortex does not seem capable of integrating this frequency break-down data into anything intelligible.

But getting back to vision, the TVSS studies have not only shown that blind persons may be made to "see" in a very real sense, but that a blindfolded sighted person may also use the equipment successfully. This raises the possibility that sensory augmentation may become as important an application as sensory substitution. The artificial eye could be used to provide military scouts, pilots, elementary school teachers, and even heroes with eyes in the backs of their heads. It could provide vertical vision (an eye for the top of the head), night vision, and remote vision. It could allow a pilot to receive altimeter and radar displays directly through the seat of his pants (and that's no metaphor here), thus releasing his eyes from instrument monitoring tasks to attend to more important things.

The basic idea of the TVSS could even be used to link a man intimately into such complex systems as computers. We don't know how many "tactile senses" a man might be able to use at once without confusion, but since we do know that he can watch TV or read while listening to music, scratching several different itches, and objecting to the prickliness of his woolen pants, we might guess at three to six, surely a large enough number to allow a man to do a much better job of keeping up with the flow of data a computer can provide.

Picture, if you will, some complex system such as a traffic control computer or a spacecraft. Ordinarily it would be controlled by its operator through buttons, levers, and switches according to the information furnished him 1.3y visual (TV screens, dials, lights, and so forth) and aural (bells, alarms, and instructions) readouts. If we replace the operator's chair with another whose sides, arms, seat, and back all contain TVSS stimulus arrays, each one providing some "visual" or symbolic display, we can replace some of those more usual signals with tactile ones . . . and add some.

But all that information is not necessarily useful. It does no good to double or triple the amount of data being fed to the operator of the system if he cannot coordinate it in his mind and act upon it. If we assume (as we must for the present) that he can coordinate it, we are left with the question of whether he can operate the additional controls the additional data make possible. One solution to that problem is the science fiction notion of plugging a man's brain directly into the computer, but that involves expensive and dangerous surgery, even supposing that a way is ever found to hook into the nerve pathways of the brain in such a way as to permit the input of information and the output of commands.

To make that information useful, we need a method of commanding the system as simple and comprehensive as the TVSS inputs. Since there now exist methods of controlling artificial arms and legs by the bioelectric pulses generated by very slight, willed muscle contractions, we might dare to speculate that the "brain-jack" notion will someday be realized by a combination of TVSS inputs with bioelectric monitoring techniques that would make every muscle twitch a command to the system.