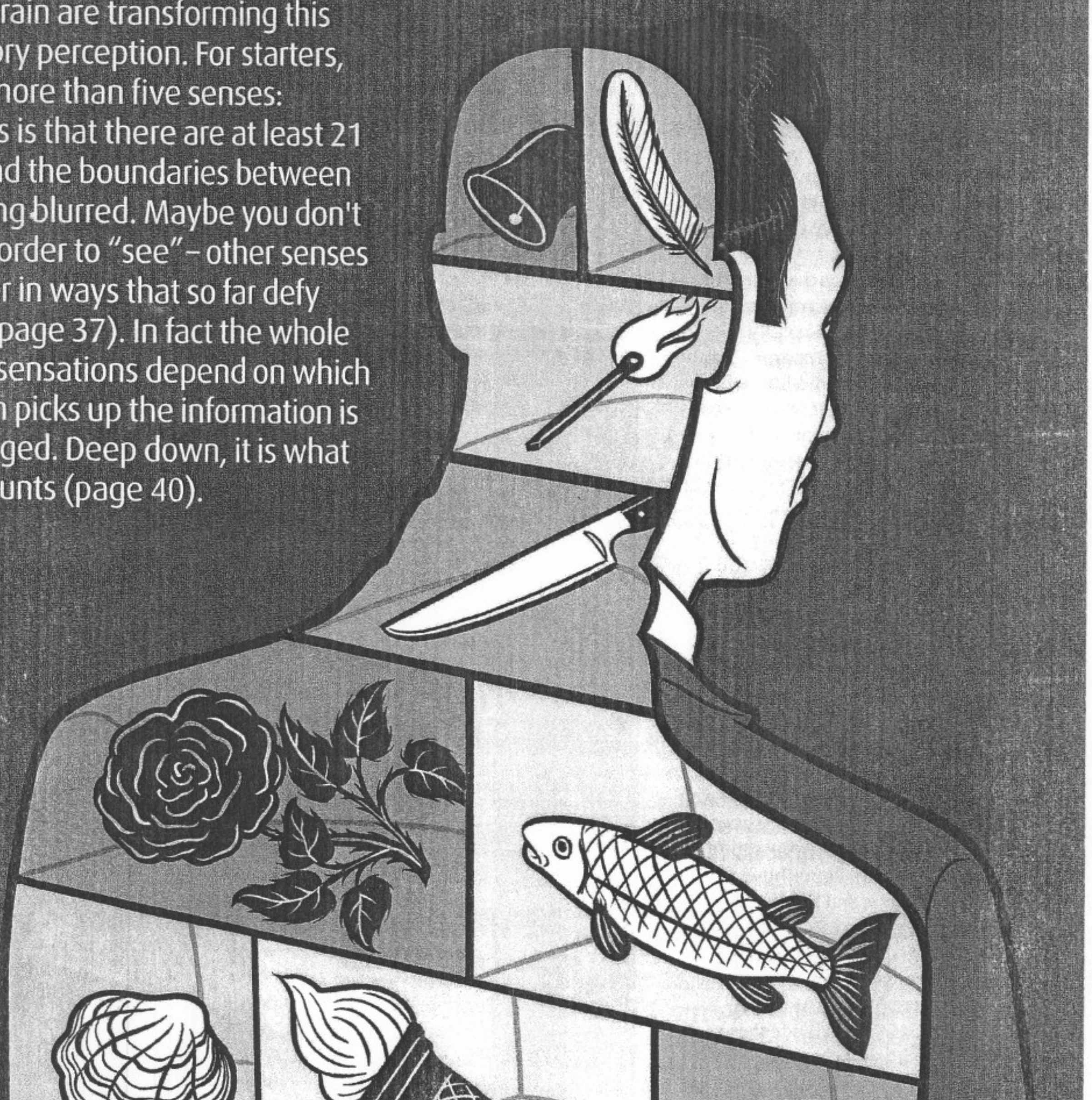
Future sense

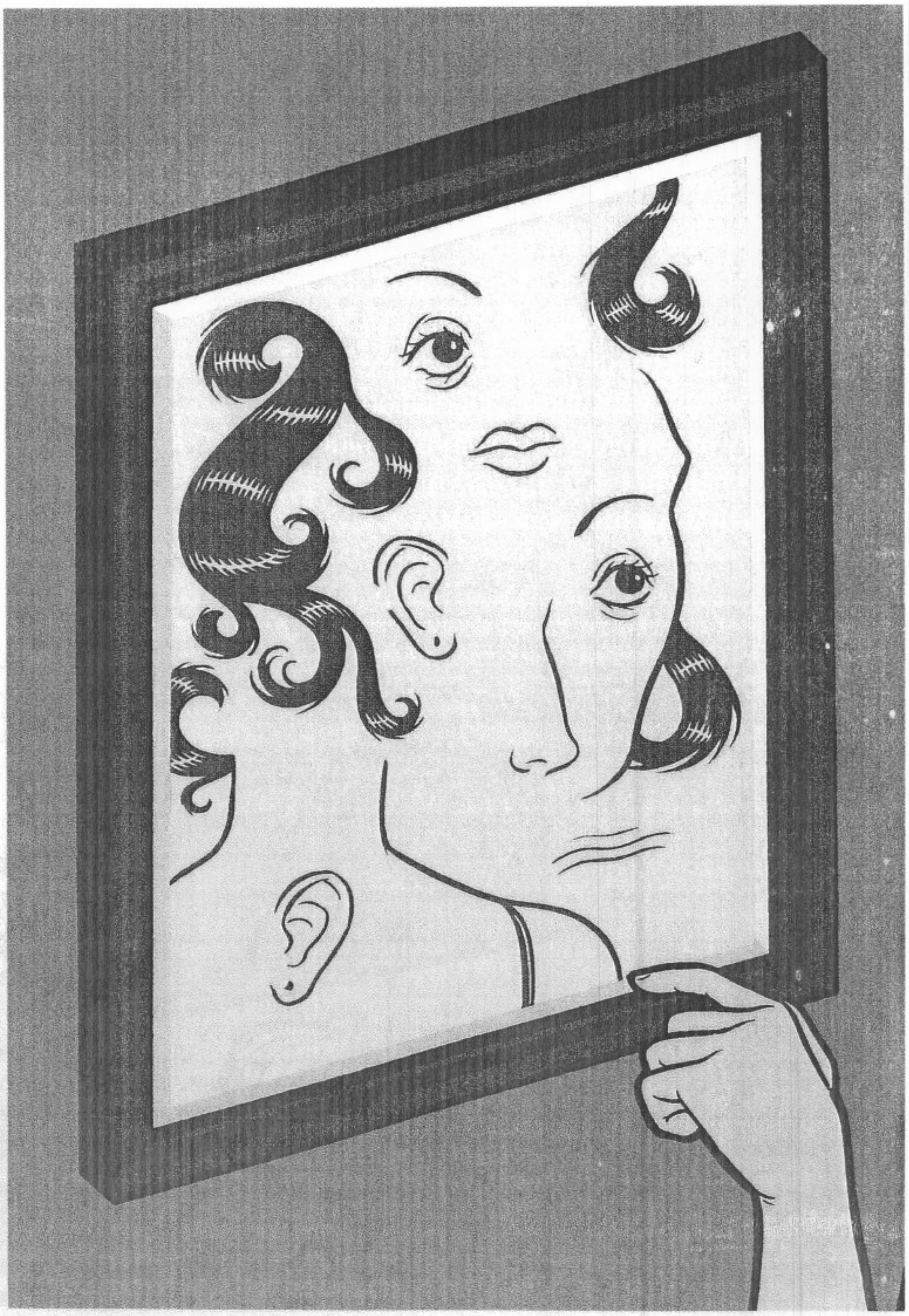
It used to be so simple. There were five senses and they created a picture of the world inside your head. But new ways of probing the brain are transforming this view of sensory perception. For starters, we have far more than five senses: the consensus is that there are at least 21 (page 34). And the boundaries between them are being blurred. Maybe you don't need eyes in order to "see" – other senses may take over in ways that so far defy explanation (page 37). In fact the whole idea that our sensations depend on which sensory organ picks up the information is being challenged. Deep down, it is what we do that counts (page 40).



NICK DEWA

Doors of perception

Taste, sight, sound, smell and touch. Is this really the only way we experience the world, asks **Bruce Durie**



NICK DEWAR

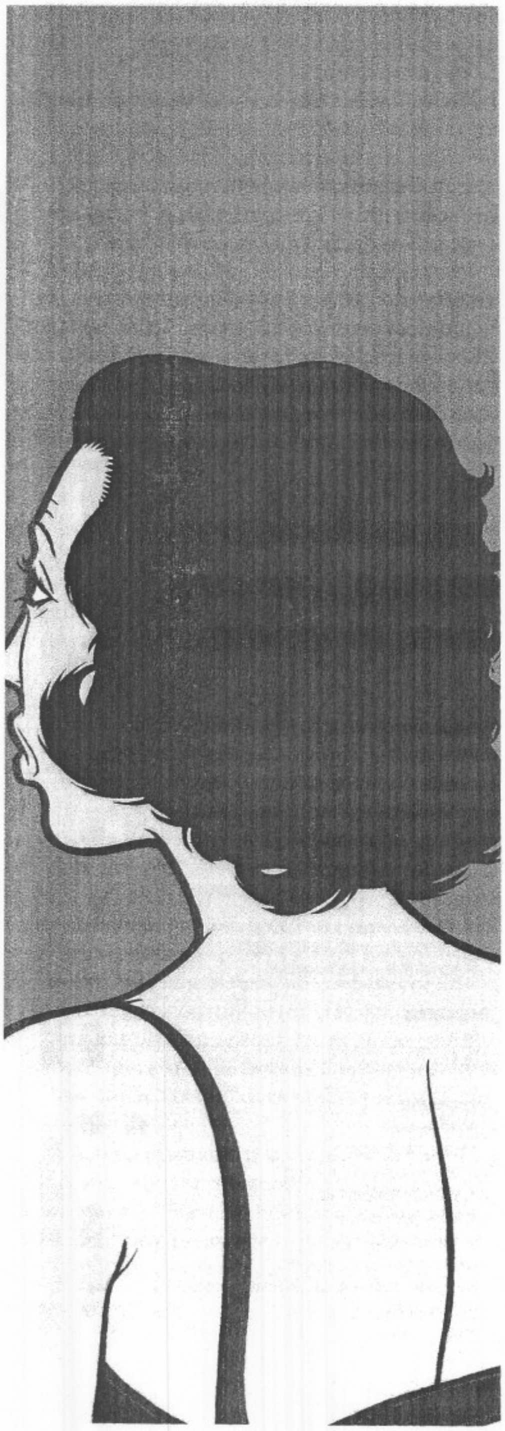
TRY something for me, will you? Close your eyes. Now stretch out your arms. How do you know where they are? Now wiggle your fingers. How do you know they are moving? Now do it all again, standing on one leg (eyes still closed, remember). Did you fall over, and if so, did it hurt?

It won't come as any surprise that you have your senses to thank for managing this feat at all. But which ones? It certainly wasn't sight, sound, taste, smell or touch.

While schools still teach us that there are five senses – an idea that came courtesy of Aristotle and permeates popular culture – the count is at odds with science. Try grabbing an ice cube with one hand and a red-hot poker with the other, and tell me that what you feel can be encompassed by the favourite five. Go on a white-knuckle ride at any theme park and convince me that everything you experienced was down to sight, sound and touch. You probably had your eyes closed anyway. There is clearly more to sensation than these five categories. So how many senses do we have?

In some ways the answer depends on how we divide our sensory systems up. For example, we could classify senses by the nature of the stimulus. In this sense (as it were) there are just three types, not five – chemical (sensed as tastes, smells or "internally", as with blood glucose), mechanical (touch and hearing) and light (vision). Some animals also have electroreception or a magnetic sense. All these groups of sensation require quite different sensory systems. Something dissolving on the tongue and producing an odour which permeates up into the nose and fits into a receptor is quite different from the mechanical movement of a hair cell in the inner ear, or a photon hitting the retina.

But we could as easily subdivide these further, and define a "sense" as a system consisting of a specialised cell type responding to a specific signal and reporting to a particular part of the brain. For instance, taste could be seen not as one sense but five – sweet, salt, sour, bitter and "umami", a Japanese word for the taste of glutamate, which gives us our sense of meaty flavours. Vision could be viewed as one sense (light),



two (light and colour) or four (light, red, green and blue). In some animals there are retinal cells which respond only to movement. Some people might consider that to be yet another sense. Neurologists classify pain as cutaneous, somatic or visceral depending on where it is felt – but does this mean they are different sensory systems or are they simply a matter of geography on and in the body?

Many people would agree that they can sense temperature, pressure, touch, joint position (proprioception), body movement (kinaesthesis), balance and feelings associated with a full bladder, an empty stomach or thirst. But there are other monitoring systems in the body that we can never be even dimly "aware of" – sensing the pH of the cerebrospinal fluid would be an example.

And take hearing. Is this one sense, or many hundreds, one per cochlear hair cell? That is probably taking things a bit too far, but it is interesting to note that we can lose high-frequency hearing without losing low-frequency acuity, and vice versa. So maybe they should be thought of separately. The more we study the structure of our sense organs, the more senses we appear to have.

But, intriguing as all this is, sensation alone isn't really all that important. When we talk of senses, what we really mean are feelings or perceptions. Otherwise we'd be operating not much above the level of an amoeba or a plant. The majority of the natural world gets by with just one or two senses – typically light and touch. A plant that grows to follow the apparent motion of the sun or the Venus fly-trap closing over an insect is merely reacting mechanically to a stimulus.

We, on the other hand, see light and shade but perceive objects, spaces and people, and their positions. We hear sounds, but we perceive voices or music or approaching traffic. We taste and smell a complex mixture of chemical signals, but we perceive the mix as ice cream or an orange or a steak. Perception is the "added value" that the organised brain gives to raw sensory data. Perception goes way beyond the palette of sensations and involves memory, early experiences and higher-level processing.

What you hear, for example, is not just a simple sum of the sounds collected by each ear, but a bigger picture. Various processes come into play, some of which allow the brain to tell the direction of the noise. Even more complex processes enable us to screen out one sound when attending to another. In the well-known "cocktail party phenomenon", for example, we ignore all extraneous sounds while taking part in a conversation, but can quickly switch focus if someone else mentions our name. The implication is that we were always "listening" to ambient sound but not always "hearing" it, except when it suddenly becomes meaningful. Our perception goes far beyond the bare sensation.

Higher animals only have to solve one general survival problem in life when encountering an object – should I eat it, run away from it or mate with it? In making this decision they get ample help from everything they gather from this new experience and previous similar ones. But more primitive animals, with more limited neural equipment, get easily fooled by brightly coloured flowers, or adversaries who can suddenly swell in size, have markings that look like eyes or smell of something unrelated, not to mention all the other tricks evolution has learned to play. A highly perceptive animal is not so much at the mercy of its primitive senses.

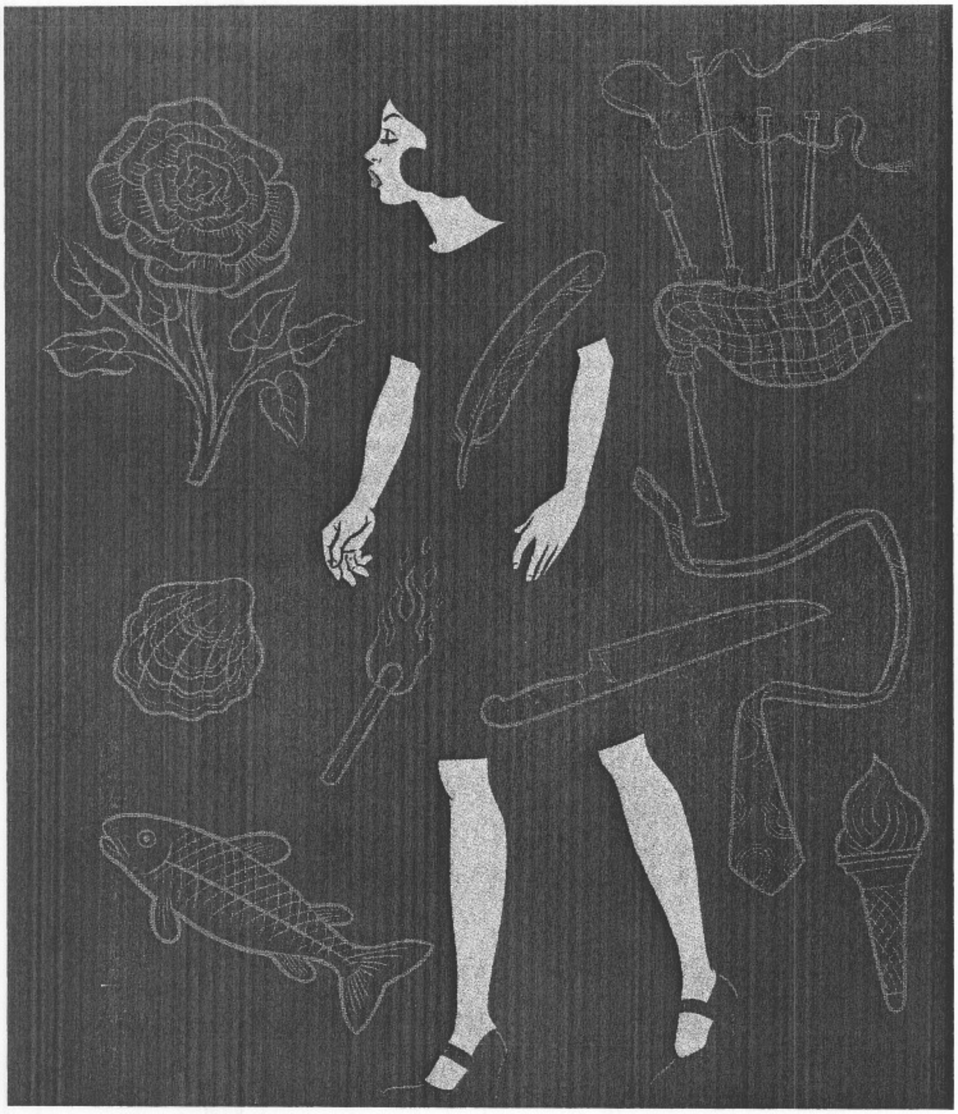
The bottom line is that we make a mistake in concentrating on senses, and even in arguing about how many there are. Perception is what matters, and sensation is what accompanies it.

For humans there are other everyday implications of all this. One is in our judgement of size. Consistency in our world view stems from the fact that objects do not usually change size over short periods of time. So for an object that we are familiar with, like a car, the larger it appears, the closer to us we perceive it to be. Though the image we sense is small, we "know" the object is big. But we can make mistakes. Clouds can be any shape and size, so their distance is hard to judge. Trains are familiar but most of us don't realise just how big they are, and so we misjudge their speed and how far away they are, which leads to around 3000 accidents annually in the US alone. We don't solve these problems by internally agonising over which senses are involved or how many senses, but by making a perceptual whole out of it. That is a higher brain function.

"Vision could be viewed as one sense, or four, or more. The more we study our sense organs, the more senses we appear to have"

Take the strange case of synaesthesia, a mixing of the senses. The most commonly reported forms are experiencing sounds, letters, numbers or words as colours. Synaesthesia is highly developed in some individuals, who were until quite recently dismissed as raving fantasists and sometimes even misdiagnosed as schizophrenic. They ▶

NICK DEWAR



may speak of an aroma's texture or the taste of different letters of the alphabet. It may be possible to "hear" the taste of a peach or "feel" a colour. What this tells us is that the senses are less than primary, and that perception is what we really get.

Quite possibly, the brain is set up to do exactly this sort of "sense-mixing" as part of the road to perception. There is growing evidence that crosstalk in the brain between different sensory areas mixes up things more than we might imagine. We may spot or recognise objects more easily if we hear a relevant sound at the same time. We may even believe we've heard something different if we are fooled into lip-reading something at odds with what is spoken. Ask any migraine sufferer about how a scent can trigger pain. Possibly we all have this facility to a greater or lesser extent, which is why minor chords are "sad" and blues music is "blue" (an interesting use of language in this context) and food can taste "sharp".

Of course, none of this is helped by confusion of nomenclature. Some things commonly labelled a "sense" are no such thing – a sense of loss, having a "sixth sense" – but perhaps the circadian rhythm system should be included. Or is that part of perception rather than a sense? The table on this page tries to bring together the cellular and other definitions of senses into some sort of framework. Doubtless it is flawed, and partial, and open to debate. If anything, it is incomplete. Though in the end, it may not matter at all.

And so, there are at least 21 senses and possibly more. But they could be a distraction. Would we do ourselves a favour by forgetting them, and concentrating on perceptions? As usual, science is fated to challenge everyday beliefs and appear counter-intuitive. We are acutely aware of our vision, smell, touch, so to say they don't matter initially seems daft. But senses may one day be consigned to the scientific dustbin, along with spontaneous generation, phlogiston and instantaneous events. It's just common sense, really. ●

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MAKING SENSE OF THE SENSES

There are many opinions about how many senses we have

SENSORY MODALITY	Conservative	Accepted	Radical
Vision	■		
Light		■	■
Colour		■	
Red			■
Green			■
Blue			■
Hearing	■	■	■
Smell	■	■	
2000 or more receptor types			■
Taste	■		
Sweet		■	■
Salt		■	■
Sour		■	■
Bitter		■	■
Umami			■
Touch	■	■	
Light touch			■
Pressure			■
Pain	■	■	
Cutaneous			■
Somatic			■
Visceral			■
Mechanoreception	■		
Balance	■	■	
Rotational acceleration			■
Linear acceleration			■
Proprioception – joint position		■	■
Kinaesthesis		■	
Muscle stretch – Golgi tendon organs			■
Muscle stretch – muscle spindles			■
Temperature	■		
Heat		■	■
Cold		■	■
Interoceptors			
Blood pressure	■	■	
Arterial blood pressure			■
Central venous blood pressure			■
Head blood temperature			■
Blood oxygen content		■	■
Cerebrospinal fluid pH		■	■
Plasma osmotic pressure (thirst?)		■	■
Artery-vein blood glucose difference (hunger?)		■	■
Lung inflation		■	■
Bladder stretch			■
Full stomach			■
TOTAL	10	21	33

Seeing without sight

Esref Armagan paints vivid, realistic pictures. How can he do this when he has always been blind, asks **Alison Motluk**

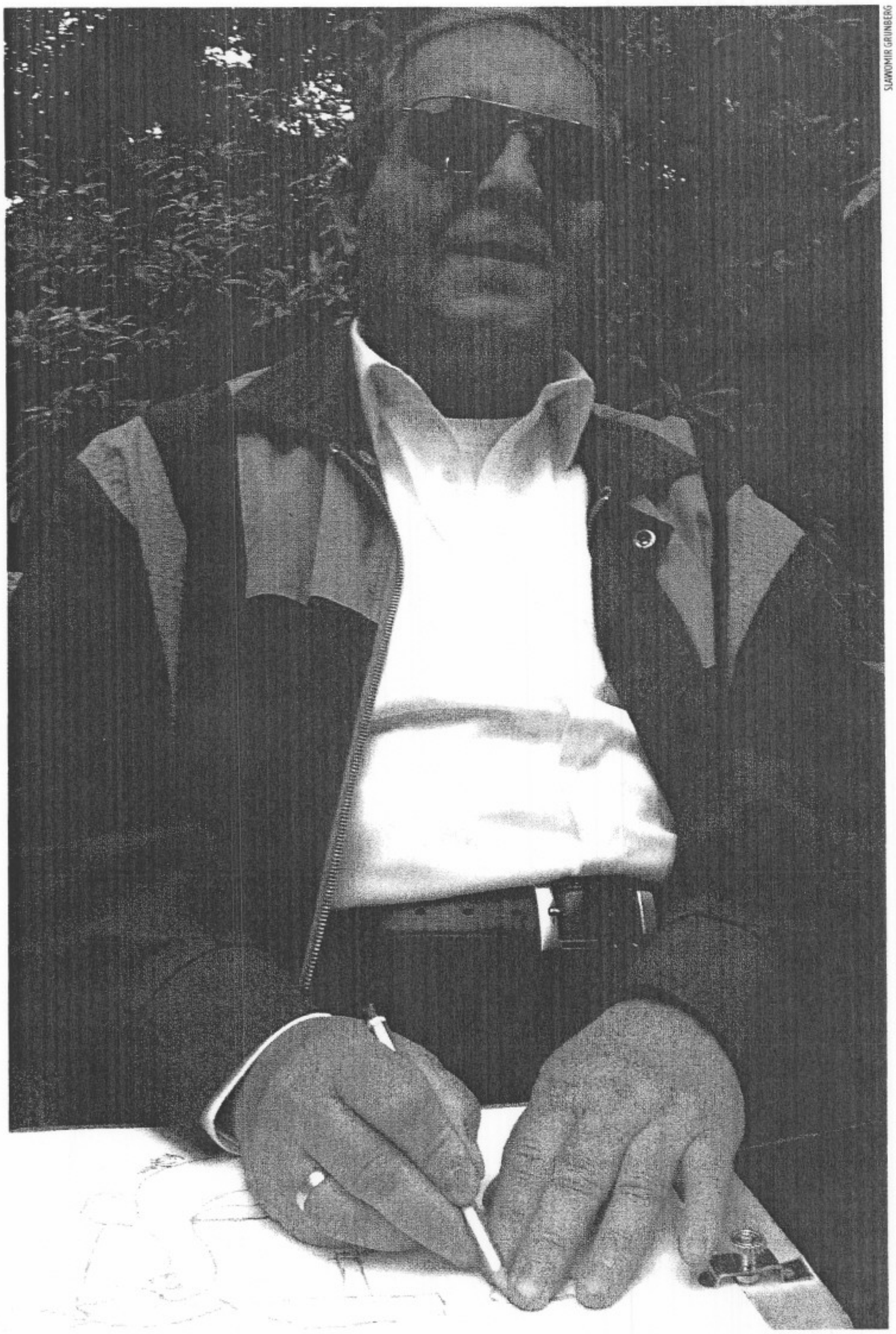
IT IS an odd sight. A middle-aged man, fully reclined, drawing pictures of hammers and mugs and animal figurines on a special clipboard, which is balanced precariously on a pillow atop his ample stomach.

A half-dozen people buzz around him. One adjusts a towel under his neck to make him more comfortable, another wields a stopwatch and chants instructions to start doing this or stop doing that, and yet another translates everything into Turkish. A small group convenes in a corner to assess the proceedings. A few of us just stand around watching, and trying not to get in the way. The elaborate ritual is a practice run for an upcoming brain scan and the researchers want to get everything just right. Meanwhile, the man at the centre of all this attention, a blind painter, cracks jokes that keep everyone tittering.

The painter is Esref Armagan. And he is here in Boston to see if a peek inside his brain can explain how a man who has never seen can paint pictures that the sighted easily recognise – and even admire. He paints houses and mountains and lakes and faces and butterflies, but he's never seen any of these things. He depicts colour, shadow and perspective, but it is not clear how he could have witnessed these things either. How does he do it?

Because if Armagan can represent images in the same way a sighted person can, it raises big questions not only about how our brains construct mental images, but also about the role those images play in seeing. Do we build up mental images using just our eyes or do other senses contribute too? How much can congenitally blind people really understand about space and the layout of objects within it? How much "seeing" does a blind person actually do?

Armagan was born 51 years ago in one of Istanbul's poorer neighbourhoods. One of his eyes failed to develop beyond a rudimentary bud, the other is stunted and scarred. It is impossible to know if he had some vision ▶



As he draws, Esref Armagan traces the outlines of the images with his fingertips

> "He paints houses and mountains and lakes and faces and butterflies, but he's never seen any of these things"

as an infant, but he certainly never saw normally and his brain detects no light now. Few of the children in his neighbourhood were formally educated, and like them, he spent his early years playing in the streets. But Armagan's blindness isolated him, and to pass the time, he turned to drawing. At first he just scratched in the dirt. But by age 6 he was using pencil and paper. At 18 he started painting with his fingers, first on paper, then on canvas with oils. At age 42 he discovered fast-drying acrylics.

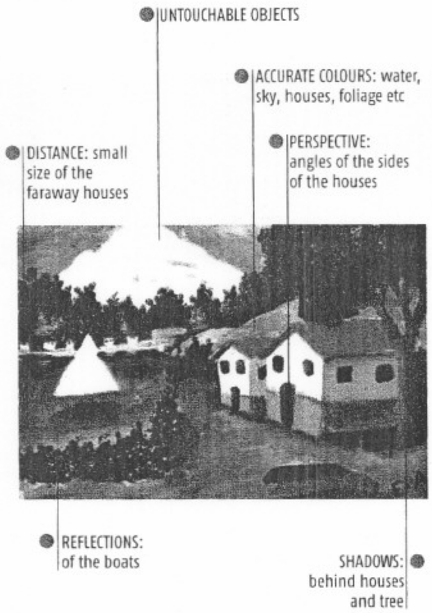
His paintings are disarmingly realistic. And his skills are formidable. "I have tested blind people for decades," says John Kennedy, a psychologist at the University of Toronto, "and I have never seen a performance like his." Kennedy's first opportunity to meet and test Armagan in person was during a visit to New York last May, for a forum organised by a group called Art Education for the Blind. Armagan, who is something of a celebrity in Turkey, has become used to touring with his canvases to the Czech Republic, China, Italy and the Netherlands. What made this visit different was the interest shown by scientists – both Kennedy and a team from Boston.

Kennedy put Armagan through a battery of tests. For instance, he presented him with solid objects that he could feel – a cube, a cone and a ball all in a row (dubbed the "three mountains task") – and asked him to draw them. He then asked him to draw them as though he was perched elsewhere at the table, across from himself, then to his right and left and hovering overhead. Kennedy asked him to draw two rows of glasses, stretching off into the distance. Representing this kind of perspective is tough even for a sighted person. And when he asked him to draw a cube, and then to rotate it to the left, and then further to the left, Armagan drew a scene with all three cubes. Astonishingly, he drew it in three-point perspective – showing a perfect grasp of how horizontal and vertical lines converge at imaginary points in the distance. "My breath was taken away," Kennedy says.

Kennedy has spent much of his career exploring art from the perspective of blind people. He has shown that people who are congenitally blind understand outline

INNER VISION

Esref Armagan is blind, yet his paintings show a remarkable understanding of the world of the sighted



drawings when they feel them just as seeing people do. They understand and can draw in three dimensions. In fact, blind children develop the ability to draw, he has found, much as sighted children do – but all too few blind children ever get the opportunity to explore this ability. Even knowledge about perspective, he has come to believe, is acquired in similar ways for both. "Where a sighted person looks out, a blind person reaches out, and they will discover the same things," says Kennedy. "The geometry of direction is common to vision and touch."

Lines and one-liners

It is the night before the Boston team's first brain scan. Armagan is sitting at a long table at an inn, entertaining everyone with one-liners, trying to explain how he does his artwork. Alvaro Pascual-Leone, the Harvard neurologist who invited him here, and Amir Amedi, his colleague, are challenging him with more and more complex tasks. Draw a road leading away, says Pascual-Leone, with poles on either side and with a source of light underneath. Armagan smiles confidently.

He uses a special rubberised tablet, called a "Sewell raised line drawing kit". This device allows him to draw lines that rise off his paper as tiny puckers, so that he can detect them with his fingertips. And so he draws the road and the poles: one hand holding the pencil, the other tracing along behind, like surrogate eyes, "observing" the image as it is being laid down. A minute or so later, the picture is done. Pascual-Leone and Amedi shake their heads in wonder.

So, we ask, how do you know how long these poles should be as they recede? I was taught, he says. Not by any formal teacher, but by casual comments by friends and acquaintances. How do you know about shadows? He learned that too. He confides that for a long time he figured that if an object was red, its shadow would be red too. "But I was told it wasn't," he says. But how do you know about red? He knows that there's an important visual quality to seen objects called "colour" and that it varies from object to object. He's memorised what has what colour and even which ones clash.

Scanning the mind's eye

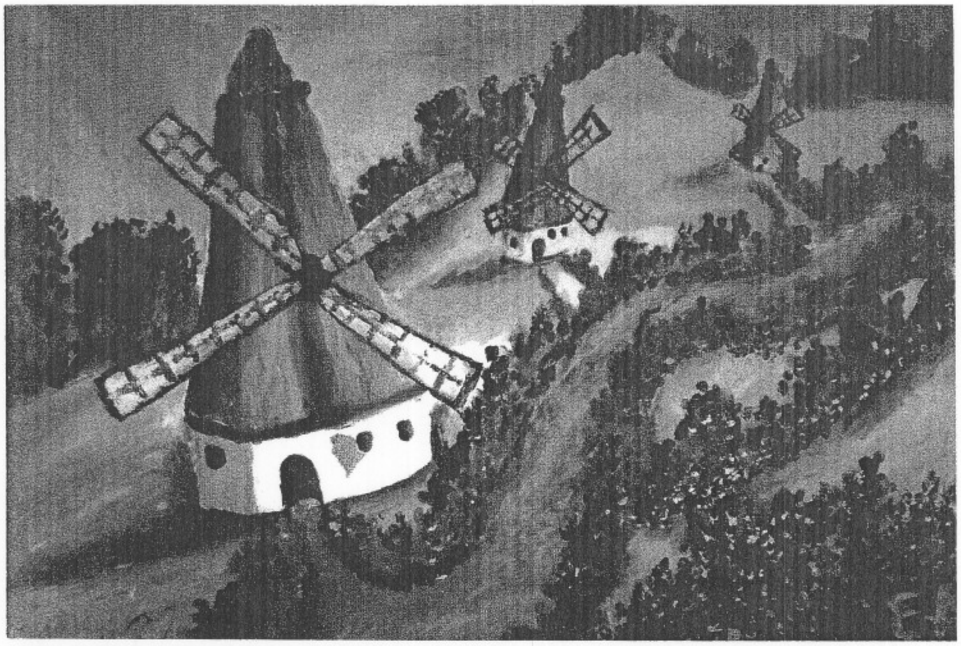
Next day, and the time has come for Armagan to get into the scanner. The Harvard scientists are collaborating with scanning experts at Boston University. In addition to taking a structural snapshot of Armagan's brain and establishing if it can perceive any light (they confirmed it cannot), this morning's experiment will have him doing some odd sequences of tasks. He'll have a set number of seconds to feel an object, imagine it and draw it. But he has also been asked to scribble, pretend to feel an object and recall a list of objects that he learned days earlier.

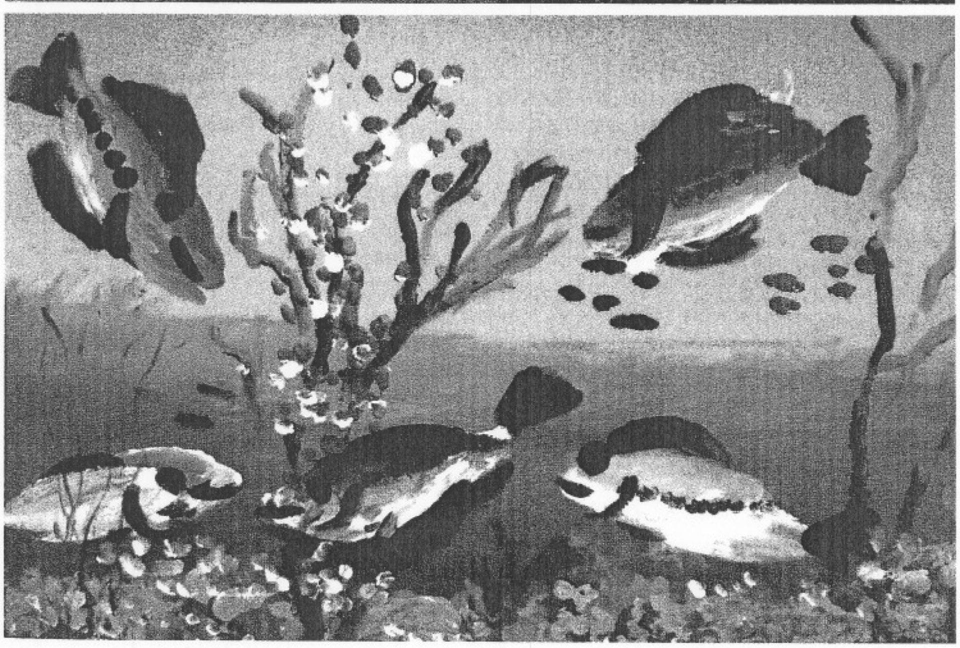
Pascual-Leone and Amedi want to see what Armagan's brain can tell them about neural plasticity. Both scientists have evidence that in the absence of vision, the "visual" cortex – the part of the brain that makes sense of the information coming from our eyes – does not lie idle. Pascual-Leone has found that proficient Braille readers recruit this area for touch. Amedi, along with Ehud Zohary at the Hebrew University in Jerusalem, found that the area is also activated in verbal memory tasks.

When Amedi analysed the results, however, he found that Armagan's visual cortex lit up during the drawing task, but hardly at all for the verbal recall. Amedi was startled by this. "To get such extraordinary plasticity for [drawing] and zero for verbal memory and language – it was such a strong result," he says. He suspects that, to a certain extent, how the unused visual areas are deployed depends on who you are and what you need from your brain.

Even more intriguing was the way in which drawing activated Armagan's visual cortex.

"We normally think of seeing as the taking in of objective reality through our eyes. But is it?"





Armagan's paintings could lead to a better understanding of how our brains build a mental picture

It is now well established that when sighted people try to imagine things – faces, scenes, colours, items they've just looked at – they engage the same parts of their visual cortex that they use to see, only to a much lesser degree. Creating these mental images is a lot like seeing, only less powerful. When Armagan imagined items he had touched, parts of his visual cortex, too, were mildly activated. But when he drew, his visual cortex lit up as though he was seeing. In fact, says Pascual-Leone, a naive viewer of his scan might assume Armagan really could see.

That result cracks open another big nut: what is "seeing" exactly? Even without the ability to detect light, Armagan is coming incredibly close to it, admits Pascual-Leone. We can't know what is actually being generated in his brain. "But whatever that thing in his mind is, he is able to transfer it to paper so that I unequivocally know it's the same object he just felt," says Pascual-Leone.

In his own life, too, Armagan seems to have a remarkable grasp of space. He seldom gets lost, says his manager Joan Eroncel. He has an uncanny sense of a room's dimensions. He once drew the layout of an apartment he had only visited briefly, she says, and remembered it perfectly nine years later.

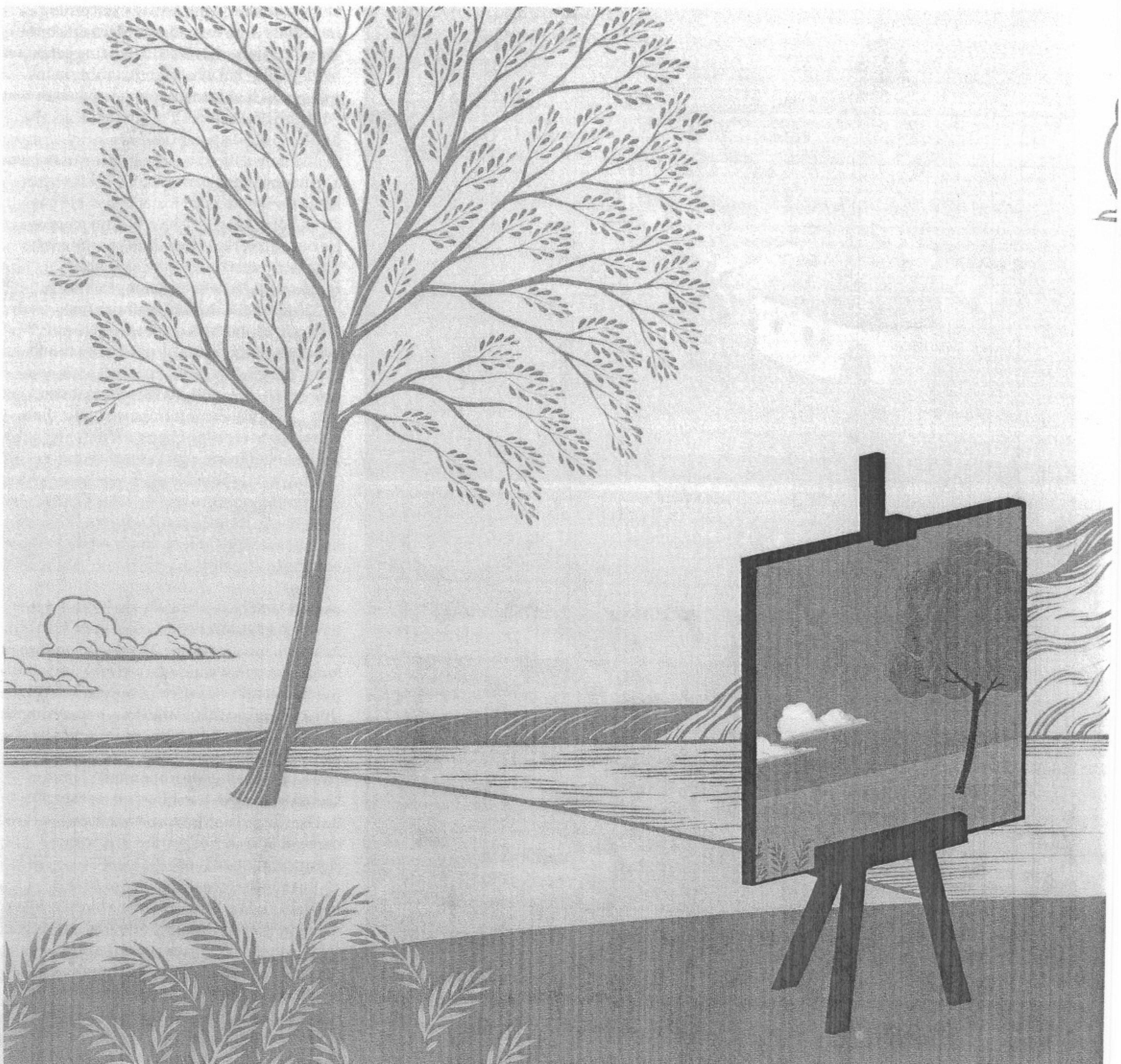
We normally think of seeing as the taking in of objective reality through our eyes. But is it? How much of what we think of as seeing really comes from without, and how much from within? The visual cortex may have a much more important role than we realise in creating expectations for what we are about to see, says Pascual-Leone. "Seeing is only possible when you know what you're going to see," he says. Perhaps in Armagan the expectation part is operational, but there is simply no data coming in visually.

Conventional wisdom suggests that a person can't have a "mind's eye" without ever having had vision. But Pascual-Leone thinks Armagan must have one. The researcher has long argued that you could arrive at the same mental picture via different senses. In fact he thinks we all do this all the time, integrating all the sensations of an object into our mental picture of it. "When we see a cup," he says, "we're also feeling with our mind's hand. Seeing is as much touching as it is seeing." But because vision is so overwhelming, we are unaware of that, he says. But in Armagan, significantly, that is not the case.

I sit across from the source of all this mystery and I ask him about the birds he loves to paint. They are brightly coloured and exotic and I wonder aloud how he knows how to depict them. He tells me about how he used to own a parakeet shop. "They come to your hand," he says. "You can easily touch them." He pauses and smiles and says: "I love being surrounded by beauty." ●

The feeling of colour

You may think there's a picture of the world in glorious technicolor inside your head. But it's an illusion, says **Helen Phillips**



NICK DEWAR

ERIK WEIHENMAYER lost his sight when he was 13. Twenty years on, in Paul Bach-y-Rita's lab at the University of Wisconsin Medical School, he caught a rolling ball, played a game of rock, paper, scissors, walked through a doorway and watched a flickering candle flame. Nothing had changed with his eyes. Instead he "saw" with his tongue.

A camera mounted on Weihenmayer's forehead fed a signal into an electronic device that turned the pattern of light and dark into electrical pulses. The pulses stimulated an array of 144 electrodes on a grid about the size of a postage stamp, which zapped the coded image onto his tongue. At first he described the sensation as being like candy pop rocks exploding, but later he experienced something more "out there" in the world – a sense of space, depth and shape.

Cheryl Schiltz danced for the first time in seven years after just 20 minutes wearing the same device. Normally she is unable to stand upright without holding onto something and concentrating on the stable things she can see around her, because her sense of balance has been destroyed by an antibiotic. If she tilts her head, the world spins and she stumbles.

But when Bach-y-Rita's device translated signals from a sort of spirit-level-in-a-hat into patterns of pulses on her tongue, she quickly learned how to read them to substitute for her missing sense of balance. The effect persisted even when she took the device off, and lingered longer each time she tried. "I was normal," she says, still emotional when she remembered the first time. "I was completely normal, and I had forgotten what it felt like."

These "sensory substitution" devices are based on a technology called the BrainPort, which Bach-y-Rita describes as a kind of USB connector into the brain. They are close to commercialisation, initially for "wobblers" like Schiltz, but eventually as devices for blind people too. The US military is interested in developing the system to guide pilots and divers through dark skies or murky waters, and others are looking at more frivolous uses in virtual reality and games. But in neuroscience and philosophy circles sensory substitution has attracted a great deal of interest because of what it is revealing about the brain and our senses.

The fact that Weihenmayer sensed something "out there" and forgot the tingling on his tongue, and the way Schiltz felt completely normal, even although she was working with a different sort of sensory feedback to keep her balance, suggests that the traditional separation of the senses – sight, hearing, touch and so on – has little bearing on how we experience the world. The sense organ that picks up the information, and the way it is delivered to the brain, seem less important than the nature of the information itself.

Some see this merely as a dramatic demonstration of the brain's flexibility. In other words, deprived of a primary source of information such as vision, the brain turns to a less prominent source, say touch, and extracts useful information from that sense. Others, however, have taken the findings much further, going to so far as to suggest that the traditional view of how the senses work is completely wrong.

The orthodox view of sensory perception is all about building internal pictures of the world. Sensory systems extract information from outside and channel it into the brain, which builds up a representation of our environment. Sensing is therefore the passive process of picking up signals; perception is the active process of turning the signals into useful information.

This model certainly chimes with our everyday experience: we talk about our mind's eye, of mental images, and so on. And there is some scientific evidence that it is correct. Brain imaging reveals that when people see, hear, feel, smell or taste, specialised parts of their brains respond, and the timing of the response coincides with the moment of conscious perception.

Another line of evidence comes from our ability to imagine things. Even in the absence of sensory information, we can generate images and sounds in our heads, and most researchers believe that the process of imagining mimics real sensory perception. When people imagine seeing something, their visual cortex lights up. Moreover, using a technique called TMS or transcranial magnetic stimulation, which temporarily knocks out activity in the brain regions it is targeting, Harvard neuroscientists Steven Kosslyn and Alvaro Pascual-Leone have shown that people can't imagine things if their visual circuits are switched off.

That's all very well, says Kevin O'Regan, a psychologist with the CNRS, France's national▶

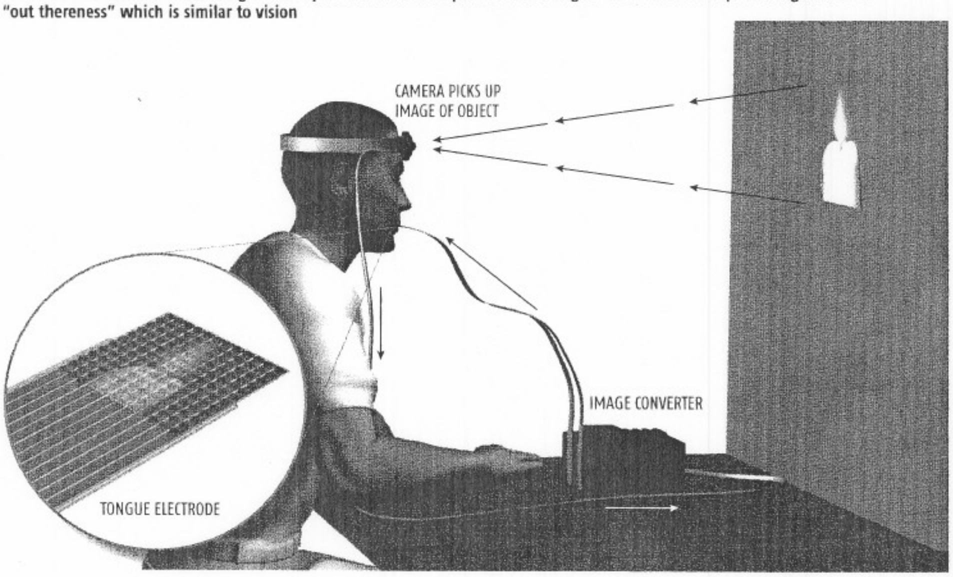
"At first it felt like candy pop rocks exploding on his tongue. But later he felt a strange sense of depth"

The BrainPort has been described as a kind of USB connector to the brain


BRAINPORT

SEEING WITH YOUR TONGUE

The BrainPort converts video images into a pattern of electrical pulses on the tongue. Users describe experiencing a sense of "out thereness" which is similar to vision



research centre at René Descartes University in Paris. But he is not convinced that this proves there is a representation of the world inside your head. In fact, he argues for a profoundly different view of sensory perception, and claims that Bach-y-Rita's sensory substitution studies support it.

O'Regan's starting point came some years back, when his interest lay mostly with eyes. He was curious as to how the world around us could feel completely stable in the face of our almost continuous eye movements, particularly large, jerky movements called saccades. O'Regan reasoned that saccades must be reported back to the brain so it could compensate for them as it built up its internal image of the world.

But he could find no evidence that this actually happens. There are neural signals associated with eye movements, but they didn't seem to be involved in building up successive visual snapshots into one big picture. Since then others have tried, and failed, to find evidence that these signals are used to compensate for eye movements in this way. But if the brain doesn't compensate for huge shifts in eye position, how can it create a stable image of the world?

Another puzzle came from a famous experiment by Dan Simons and Christopher Chabris of Harvard University. They asked volunteers to watch a recording of a basketball game and count the passes made by one of the teams. Early on in the game a man in a gorilla suit walked slowly across the court. Despite the fact that he was visible for about 45 seconds, around 40 per cent of the viewers failed to notice him. Yet when asked to watch the game with no task in mind, they all saw it immediately (*New Scientist*, 18 November 2000, p 28). To Simons, this is strong evidence that, despite the impression we have of seeing a complete and detailed image of the world, there's a lot missing. We rely on the brain to fill in the blanks.

O'Regan goes one step further. He suggests that the mental image is not only incomplete, it is completely absent. We don't reconstruct the world in our mind, we merely glimpse it in fleeting fragments. "There is no internal picture," he says. Where most researchers would argue that seeing is all about building up an internal image, O'Regan has us flitting from one visual element to the next, only becoming aware of things when we need information. In this, O'Regan departs radically from the traditional view of sensory perception: sensing becomes an active rather than a passive process, with potentially profound ramifications.

O'Regan had been struck by an earlier version of Bach-y-Rita's device, in which blind or blindfolded volunteers wore a larger array of electrodes taped onto the skin of their back or abdomen. One volunteer, with the array on his front, was "viewing" objects using a camera mounted on a tripod, but not getting anywhere. Out of frustration he grabbed the camera and started waving it around. When he started actively manipulating the camera in this way, something dramatic happened. He very quickly moved from merely feeling a tingling on his stomach to sensing the presence of external objects. Another volunteer, using a head-mounted camera, also suddenly felt the outside world become very real when he grabbed the zoom control – and almost fell over backwards as objects surged towards him.

What this suggests is that substituting touch information for visual information can produce a vision-like experience, but only when people actively control the camera in some way. Weihenmayer, for example, could almost see objects with his tongue. He didn't taste them, and after a short while he didn't feel them either. But this sensation only happened when the camera was mounted on his head, so he could move it as if he were scanning with his eyes. Similarly, blind people tapping with a cane experience open space at the end of their stick, not vibrations on their hands. They, too, are seeking information about the space around them.

Results like these have convinced O'Regan that sensory perception is not about passively collecting information but actively seeking it, and noticing how the information responds to our actions. We sense the world not by soaking up information, but by taking physical actions to interrogate it. "If the story is right, sensations are not generated in the brain," says O'Regan. "They are things we do." Sensory substitution works because it matters less to our brain where information comes from than the manner in which we gather it.

If it is right, O'Regan's theory doesn't just explain sensory substitution, it has philosophical implications too. In particular it suggests a solution to one of the "hard problems" of consciousness: why does seeing something feel different from touching it? The answer certainly doesn't seem to lie in the electrical activity of the brain. Whatever sensory stimulus triggers the activity, be it touch, taste, sight or sound, the information is translated into electrical pulses. And no one has ever been able to find anything unique about these pulses, or where they are sent to in the brain, to explain why they produce different sensations.

"Why does seeing something feel different from touching it? It doesn't seem to be down to the electrical activity of the brain"

That spongy feeling

O'Regan believes that his "sensorimotor" theory might provide an answer. Maybe, he says, touch, taste, sight and sound feel different because we have to perform different actions to collect the information.

Take, for example, the softness of a sponge. Where does the feeling of softness come from? No one has ever found a neural mechanism or specific part of the brain that exclusively lights up when you feel something soft. That, says O'Regan, is because there isn't one. Working with philosopher Erik Myin at the University of Antwerp in Belgium, he has proposed that the feeling of softness comes from how you go about seeking information about the sponge. When you press the surface, it gives way. This is a different action from touching a sharp or hard surface, or a liquid.

While the theory seems to make sense for touch, or the difference between seeing and touching, what about the hardest "hard problem" of all, the sensation of different colours? How can we explain "redness" or "greenness" in terms of different actions? To complete his theory, O'Regan needed to find unique actions or activities that are associated with perceiving different colours.

It seemed an impossible task, but O'Regan and colleague David Philipona from the Sony Computer Science Laboratory in Paris were in for a surprise. When they looked at the physical properties of coloured surfaces they found fundamental differences in the way the different colours interact with light. In classical models, reflections from surfaces are the sum of two sources: one that behaves like the reflection from a matt surface, and another that behaves like the reflection from a sheet of glass laid over the matt surface. As we move our eyes, both types of reflection change their spectral composition, and the relationship differs according to colour yoù are looking at.

O'Regan suggests that as we move our eyes over a coloured surface, we detect something of this change in relationship. And by that we experience colour. The key point as far as perception goes is what happens when we probe the environment: it's not the brain activation itself that gives the colour. The researchers have found that primary colours produce particularly distinctive changes, which may explain why they are universally recognised as special.

Already, O'Regan's ideas have doubters. Bach-y-Rita thinks the explanation for sensory substitution lies with the remarkable flexibility of the brain. There are multiple pathways from all the senses to all the different sensory areas in the brain, he says. If you lose the main input from the eyes to the visual cortex, say, weaker pathways from the skin, ears, tongue and so on take over. This is what happens in the brains of Braille readers, who recruit their visual cortex when feeling the forms of the letters.

It may not be long before we know who is right, as O'Regan and colleagues are busy thinking up testable predictions of their sensory substitution theory. One such prediction is that it should be possible to make the substitution feel more convincing by making the information-gathering action "mimic" the original as closely as possible in the new medium.

To that end, O'Regan and colleague Malika Auvray have rigged up a video camera that represents the visual world in sound. Brighter objects become louder sounds, objects high up in the visual field are represented by high pitches and object low down by low pitches, while lateral position is represented with stereo sound. It is a little hard to imagine, but say the camera was looking at a light bulb in the centre of the field of view, you would hear powerful noise made up of a limited range of pitches centred in space. With a horizontal strip light you'd hear a smaller range of pitches over a wider space. As you move the camera, the sound changes.

In preliminary tests with a similar device designed by engineer Peter Meijer from Eindhoven in the Netherlands, the signals took a little getting used to. But after a couple of hours of feedback either from touching or being told what they were viewing, people were able to recognise objects by their sound. They could tell plants from statues and crosses from circles. But they weren't fooled into thinking they were seeing. O'Regan's prediction is that the more they can make the sound information follow the rules of visual images, the more like seeing it will feel. For example, Meijer's system has a delay between moving the camera and hearing the sound. Another simple tweak would be to cut off the sound each time the subjects blink, which is exactly what happens to our visual world, though we scarcely notice it.

Perhaps one day blind people will play rock, paper, scissors in stereo surround sound. And if O'Regan is right, they could feel almost as if they are seeing. Now that really would be a sensation. ●

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