Beautiful minds

What is the human brain capable of, and what sets the most extraordinary brains apart? **Helen Phillips** investigates

EVEN the average human brain is remarkable. In adults it has perhaps 100 billion neurons, each connected to its neighbours by 5000 synapses or so. A brain can make and break a million new connections each second. It can store information for more than a century if you live that long, automatically cataloguing, re-filing and editing as needed. It can reconstruct our surroundings using a range of sensors that sample vibration, electromagnetic radiation, chemicals and pressure, and prioritise in milliseconds what might be of interest or concern. It coordinates at least 640 muscles and looks after the essentials of energy generation, reproduction and survival with little thought, freeing our minds to socialise, ponder the meaning of our existence and learn from our experiences and those of people who we may never even have met.

Yet some brains are that little bit more remarkable than others. Why do the most gifted and talented brains stand out from the crowd? Is there anything physical or physiological that sets them apart? Here we take a look at some outstanding grey matter, and ask what brains are like at the outer limits of human achievement.

High IQ

INTELLIGENCE is a slippery concept to define, so not surprisingly it has been tricky to pin it down in the brain. Several studies claim to link brain size, weight, volume or head circumference to intelligence, but no clear or consistent pattern has emerged. For example, Sandra Witelson from McMaster University in Ontario, Canada, studied the post-mortem brains of 100 people who in life had had a variety of IQ test scores. She found that while there were some positive correlations between hemisphere volume and score, the relationships varied with sex, handedness and type of test (*Brain*, vol 129, p 386). For example, verbal intelligence was positively correlated with cerebral volume in women and in right-handed men. And in women, visuospatial intelligence was positively linked with volume, but less strongly than verbal skills.

Certainly size is not the whole story. Women's brains are smaller than men's, even when corrected for body size, yet there is no consistent difference in men and women's IQs. Indeed, the *Guinness World Records* listed a woman, Marilyn vos Savant, as having the highest IQ between 1986 and 1989. Since then, incidentally, the category has not been included, partly because IQ is so hard to measure at these extreme limits – vos Savant's score varied from 186 to 228, depending on the test used, the conditions and the day.

If size does not explain all, does brain activity give any clues? In 2000, a team led by John Duncan of the MRC Cognition and Brain Sciences Unit in Cambridge, UK, identified what might be called the brain's "G spot", the area associated with general intelligence, which is what IQ tests are thought to measure (*Science*, vol 289, p 457). PET scans showed that puzzles and tasks that provide a good measure of general intelligence or "*g*" seem not to recruit vast areas of the brain as you might expect, but produce activity in a very specific region of the lateral frontal cortex. In tasks that don't measure *g* very well, activity is more diffuse. It is not clear exactly what this finding means or what this region does, but it hints that efficiency, connectivity and focused activity may be more important than size.

Intelligence may also be connected to working memory, located in the middle and inferior frontal gyrus, a region near the brain's G spot. It is sometimes possible to train working memory with practice, and doing so may benefit IQ, especially fluid intelligence – the ability to solve new problems. However, this may just be a short cut to better IQ test scores rather than an indication of brain structures that confer intelligence.

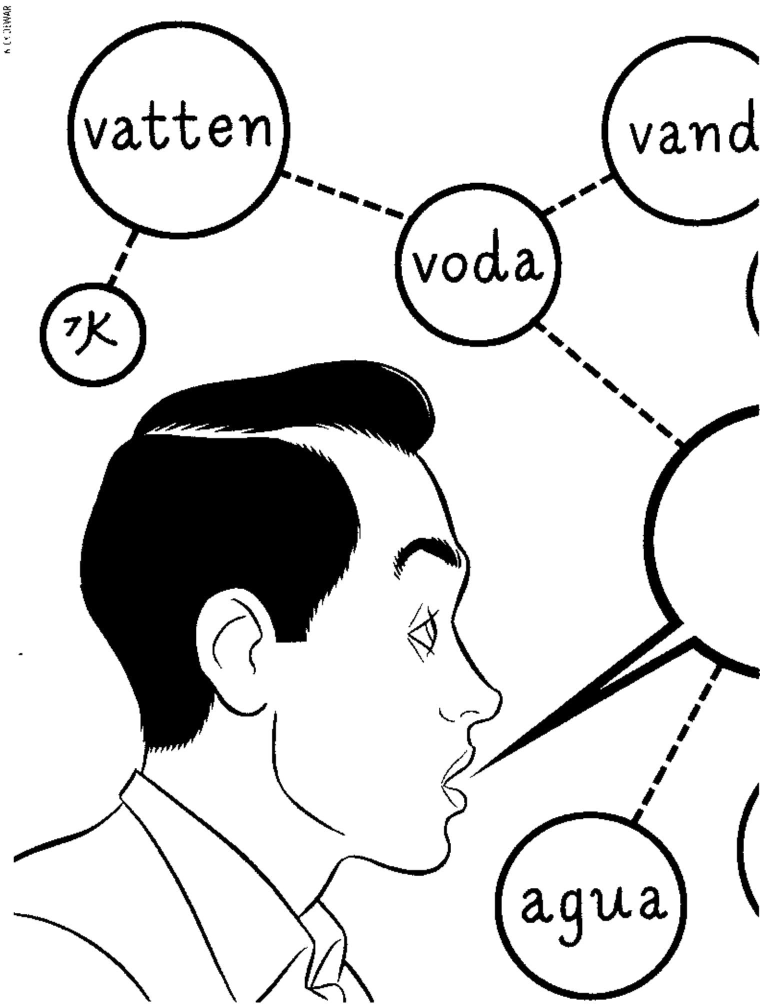
More recently, Philip Shaw from the National Institute of Mental Health in Baltimore, Maryland, found a developmental difference linked to IQ. His team studied more than 300 children aged 7 to 18, divided into groups with IQs that were average (up to 108), high (up to 120) and superior (above 120) (*Nature*, vol 440, p 676). Looking at the cerebral cortex, they found no differences in the overall thickness attained by age 18. However, children in the average group had reached peak thickness by age 8, followed by a thinning down through adolescence, whereas in the superior group, the cortex was thinner at age 7 but continued thickening until age 11 or 12 before thinning again. The high group lay in between. Shaw concludes that intelligence is a dynamic process, related to a particularly high level of plasticity during these years. ▶

A flair for language

ZIAD FAZAH claims to speak, read and write 59 languages – 10 at the tip of his tongue, and the others he reckons could be brushed up in a week. He is Lebanese, though his father was born in Colombia and he in Liberia. He moved to Lebanon as a baby, and growing up near a port, met and tried to converse with sailors of many nationalities. Fazah began learning French and English at school and decided at the age of 11 that he wanted to speak all the world's languages. So, over a three-year period during which he never left Lebanon, he studied more than 50 languages, several at a time, taking about three months to master each. Fazah had once wanted to work for the United Nations and has been approached by several intelligence agencies, but now he prefers the quiet life, working as a language teacher in Brazil.

What is the secret of such amazing linguistic talents? Fazah doesn't claim to be special, though he says his memory is "like a photographic camera", and he admits to a good deal of study. Anyone can speak a foreign language, he thinks. You need to spend 30 minutes each day listening carefully to the sounds of a native speaker, another 30 minutes studying the grammar and then 15 minutes reciting the sounds – a very important step. Recently he mastered a Caribbean creole in just a week, speaking well enough to be interviewed on local TV.

Fazah himself has never been near a brain scanner or taken part in any formal studies of his talents. Research on other polyglots, however, suggest there is no simple answer to what makes a brain linguistically gifted. The only consensus is that early exposure is a big advantage. If you don't form memories of language-specific sounds during the first year of life, the ability to recognise them may all but vanish, and learning becomes much more difficult (*Nature Neuroscience*, vol 1, p 351). Exposure to different grammars by the age of 7 also seems to leave open a window that makes it easier to learn later. On the other hand, acquiring vocabulary, say the experts, is simply down to memory and hard graft.



Scientific genius

ONE of the greatest scientific minds of all time ended up in 240 pieces, packed into a couple of jars, and was carted around for years in the trunk of Princeton pathologist Harvey Thomas's car. Einstein's brain, at the time of his autopsy in 1955 (just 7 hours after his death), was reported by Thomas to appear unremarkable – it was a little shrunken with age, and slightly smaller than average. Nevertheless, Thomas carefully photographed and dissected it, and kept it preserved in formalin until science had new ways to scrutinise this amazing grey matter.

In the early 1980s, neurologist Marian Diamond from the University of California, Berkeley, analysed some slides containing sections of Einstein's brain taken from the prefrontal and parietal lobes. These areas are part of the "association" cortex, which is involved with higher thought. Comparing the slides with similar tissue from 11 control brains, she found that Einstein's brain contained a greater than normal ratio of glial cells to neurons. Glial cells were until recently thought to be support cells for the neurons, important in providing energy and resources but not much more. They are now known to be involved in neural processing and signal transmission too. The absolute numbers were hard to measure, because of the way the tissue was preserved and sectioned, but Einstein's brain appeared to have double the normal number of glial cells in the left parietal region.

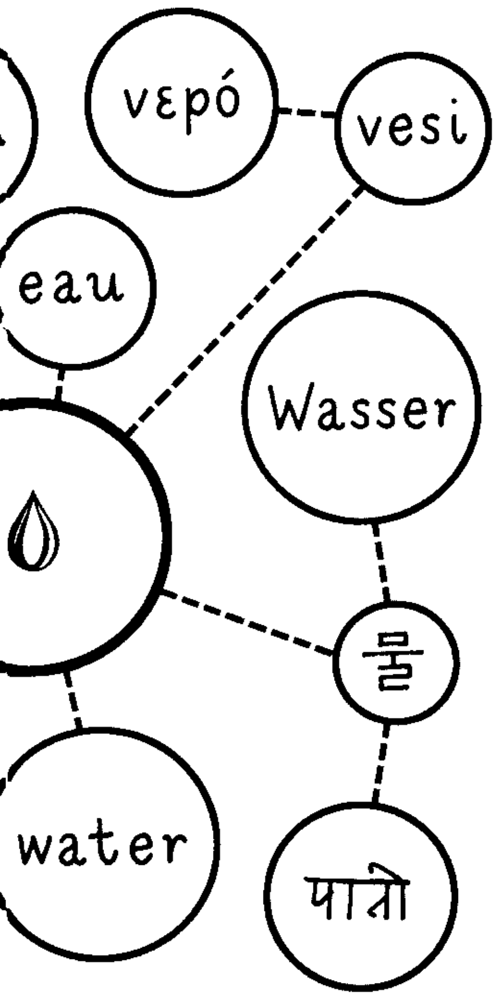
Diamond compared her findings to a case report of a mathematician whose brain was damaged in this same region so that he became unable to draw or write formulae, or to use a slide rule. Some eminent mathematicians say abstract concepts feel almost real, to the point that it is as if they exist in the brain and can be manipulated like real objects. Perhaps this region, which is known to be important for visuospatial cognition, is key. There are other possibilities, however. Einstein claimed to be dyslexic and to have a poor memory for words. Damage to this region can cause dyslexia, so maybe his low neuron-to-glia ratio was a cause or result of his verbal difficulties rather than his reasoning skills.

"Einstein's brain was 15 per cent wider than average, making it more spherical"

Another study in the mid-1990s looked at the outer millimetre of cortical tissue from Einstein's right prefrontal lobe, a region that is associated with working memory, planning, regulation of intellectual function, and motor coordination. Britt Anderson from the University of Alabama, Birmingham, reported that the number and size of neurons here appeared normal, but that the cortex was thinner than average (2.1 millimetres compared with 2.6 millimetres in five control brains) making Einstein's cortical neurons more densely packed than usual. Anderson speculates that closer packing may speed up communication between neurons.

Then in 1998, Witelson studied Einstein's brain again, this time from photos, and it appeared unremarkable except for the parietal lobes. Here the brain was 15 per cent wider than average, giving it a more spherical shape. In addition, two major grooves in this area were joined into one large furrow, which suggests the local circuitry was particularly highly integrated, Witelson speculates. What's more, while normal brains are asymmetrical, Einstein's parietal lobes were symmetrical. This all lends weight to the idea that his brain structure may have been unusual in some key areas that are important for spatial and reasoning skills.

What about other scientists? Manuel Casanova from the University of Louisville, Kentucky, studied post-mortem brain tissue from three eminent scientists and found that there were interesting patterns in the arrangement of cortical neurons (*Autism*, vol 11, p 557). The smallest processing module of neurons in the cortex is called a minicolumn – a vertical arrangement of cells that seem to work as a team. The scientists' minicolumns were smaller than those of controls, with less space between cells, meaning there were more processing units within any given cortical area. Computer modelling suggests that smaller processing units may allow for better signal detection and more focused attention. Small minicolumns are also seen in people with autism and Asperger's syndrome, says Casanova. ▶



Long-stayers

A STUDY published in August describes an autopsy of the brain of 115-year-old Hendrikje "Henny" van Andel-Schipper, a Dutch woman who was the world's oldest woman at her death (*Neurobiology of Aging*, vol 29, p 1127). Remarkably, the autopsy revealed little vascular damage, almost no build-up of the proteins linked to degenerative diseases such as Alzheimer's, and cell counts that seemed normal for an average 60 to 80 year old. The longevity of human cognition may extend far beyond most people's natural lifespan, conclude Wilfred den Dunnen and his team from the University Medical Centre Groningen in the Netherlands.

Ageing inevitably brings changes to the human brain. There is some decline in the blood vessels servicing it, and in the quantity of myelin, the fatty material that insulates the nerve fibres. The brain reduces slightly in volume, the grooves all over its surface widen, and there's a slight expansion of the cavities called ventricles. Age also brings a reduction in the speed at which nerve signals travel and there is a general decrease in coordination between different brain regions, which could explain why a person's memory can seem ever more challenged. However, while memory may start to decline as early as our 20s or 30s, according to psychologists, experience and general knowledge compensate until at least our 50s or 60s. What's more, functional imaging shows that often performance in cognitive tasks is maintained, at least to some extent, because the older brain compensates for any reduction in activity in specific regions by recruiting more areas to work on the problem.

Some researchers have suggested that dementia is almost inevitable in an aged brain. That view is being challenged as more and more sprightly centenarians have been found to have quite healthy minds and brains. There are no simple recipes for a long mental life – some risk factors for dementia run in families, others are spontaneous or build up over a lifetime – but high blood pressure, obesity and heart problems all increase the risk of stroke and dementia, while exercise and mental activity seem to reduce it. But clearly, old brains can show remarkable staying power.

"The longevity of human cognition may extend far beyond a natural lifespan"

Extraordinary talents

GLOBALLY there are around 100 "prodigious savants", who show one remarkable skill in complete isolation to their other mental functions. Savants either have autism or have suffered brain damage at birth or later in life, and their general intelligence, excepting their remarkable skill, is poorer than average. Some have photographic memories of complex scenes and can draw or sculpt unbelievably accurate representations. Others can calculate numbers, squares, primes or calendar dates. Some can remember entire books and some can rattle off a piano concerto after a single hearing. Yet others can draw perfect circles. What leads to such islands of intelligence?

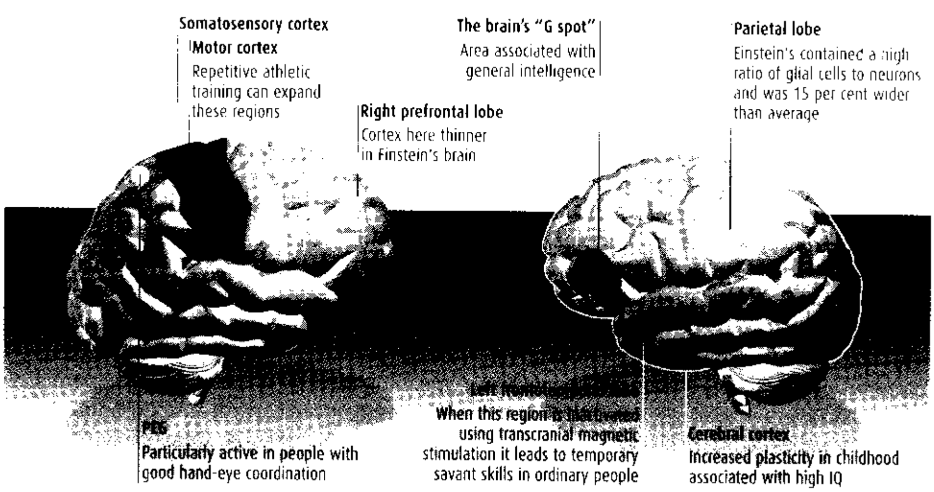
> **"Savant-like skills may result from shutting down higher-order cognition"**

There are many theories. Savants always have amazing recall in some sphere or other, though the neuropsychological basis of this is not clear. Some researchers claim that practice, which is clearly obsessive and focused in some savants, could explain their skills. Others believe that developmental errors in the brain leave a few rare people with an incredible focus on detail, while losing the more general view. This might be because of damage, or perhaps an unusual pattern of connectivity in the left hemisphere, which sees the big picture, with overcompensation by the more detail-conscious right. Certainly, injury to the left hemisphere can lead to symptoms of autism, and MRI scans of people with autism suggest differences in white matter, with hyperconnectivity in some regions but fewer connections overall.

However, research by Allan Snyder from the Centre for the Mind in Sydney, Australia, has convinced him that savant-like skills lie within us all. He believes they result from a shutting down of some of the higher-order, "rule-based" cognition, which usually makes thinking more efficient and generalisable. These higher cortical functions normally turn large amounts of basic subconscious information into useful conscious concepts. Snyder has used transcranial magnetic stimulation – a blast of magnetic pulses that temporarily and harmlessly interrupts higher brain functions – to inactivate a small area of the cortex in volunteers, who he then asks to draw, proof-read or perform difficult calculations. He claims that this improves these skills in ordinary people. If Snyder is correct, the outer limits of some of our memory and information-processing capacities may only be revealed when parts of the brain are inactivated.

CLEVER THINKING

Various brain regions are linked with exceptional talents, from athleticism to scientific genius



Athletic minds

THE bodies of athletes are clearly special – the result of good genes and lots of hard graft – but what about their brains? Is there any grey-matter advantage that helps the likes of Usain Bolt and Michael Phelps to outperform their rivals?

Many sports require specific patterns of stereotypical body movements, and these certainly leave their mark on the brain. In the somatosensory cortex, which monitors signals from different parts of the body, and the neighbouring motor cortex, which controls movements, areas corresponding to the most regularly used body parts expand with use.

Good hand-eye coordination can also be traced to a specific part of the brain. Tests in the lab using prisms that alter hand-eye relationships by shifting images to the right or left or turning them upside down, reveal that some people adapt more quickly than others. Those with more dynamic hand-eye coordination show greater activity in a region called PEG in the parietal cortex – which contains maps of space and of our bodies – on the opposite side to the movement.

Some people may also have brains that allow them to keep on going when lesser competitors give up. The sensation of tiredness we get from sporting activity seems to be generated not in the muscles but in the brain, through a signalling molecule called interleukin-6. Perhaps this signal is naturally weaker or easier to ignore in some brains. If so, this might be why some athletes can push their bodies beyond the limits that most people are able to endure.

Memory marvels

FOR anyone who goes through life forgetting where they left their keys, the outer limits of human memory are truly mind-blowing. Take AJ who is in her 40s and can remember every day of her life since her teens. Or Kim Peek, the real-life inspiration for the film *Rain Man*, who has memorised at least 7600 books and countless zip codes and telephone area codes. Then there's Ben Pridmore, an accountant from Derby, UK, who has just smashed three world records for remembering 930 binary digits in 5 minutes, 819 digits in 15 minutes and 364 playing cards in 10 minutes.

Recall like AJ's may indicate that the normal process of memory pruning has gone awry. Autobiographical memories are held temporarily in the hippocampus and then those that are not reinforced or recalled are gradually thrown away and the rest are shifted into longer-term stores in other brain regions. However, many experts believe that differences in memory owe nothing to innate structures or special neurophysiology and everything to skills that are developed. Memory marvels often use tried and tested techniques, such as mnemonics, rhymes or visualisation to help stamp memories into their grey matter. Others may use obsessive rehearsal – this can happen strategically or as a result of mental illness or brain damage. A good memory requires effort and attention not special grey matter.

"A good memory requires effort and attention not special grey matter"

NICK DEWAR

Supersenses

WHILE most of us have three types of colour receptors in our eyes, some people have four. This gives them an extra dimension to their colour perception. All these so-called tetrachromats are women, because the genes involved are on the X chromosomes. One person studied was an interior decorator, and was sensitive to colours within the range most people would see as just beige – so perhaps this supersense isn't always an advantage.

Then there are super-tasters, whose enhanced taste comes from having more than the average number of tastebuds. And acute hearing is common to most young adults, who can hear frequencies up to 20,000 hertz as compared with 8000 in the elderly. However, there is nothing special about the brains of supersensors. The human sensory cortex seems to be able to handle whatever information the sense organs can throw at it – the limits are down to the information coming in, not the grey matter that handles it.

But there is one way that the brain itself seems to stretch the boundaries of the sensors in a condition known as synaesthesia. Here the sensory experiences merge, as one sensation recruits others. Some people experience colours when they hear certain sounds or see words and numbers. Others hear sounds with touch sensations, or experience shapes with tastes. One theory for why this happens is heightened connectivity between different sensory areas in the brain (*Neuron*, vol 48, p 509).

Up to 1 in 23 people are synaesthesic and it runs in families, indicating a genetic component. However, our everyday use of mixed sensory metaphors such as "sharp tastes" or "soft sounds" indicates that this is one extraordinary mental ability that we may all experience to some extent at least. ●