Inner Sense

Also by Caroline Williams

Override

Move!

Inner Sense

How the New Science of Interoception Can Transform Your Health

Caroline Williams

Profile Books

First published in Great Britain in 2025 by
Profile Books Ltd
29 Cloth Fair
London
EC1A 7JQ

www.profilebooks.com

1 3 5 7 9 10 8 6 4 2

Typeset in Berling Nova Text by MacGuru Ltd
Printed and bound in Great Britain by
CPI Group (UK) Ltd, Croydon CR0 4YY

A CIP catalogue record for this book is
available from the British Library.

ISBN 978 1 80522 200 2
eISBN 978 1 80522 202 6

MIX
Paper | Supporting responsible forestry
FSC® C171272
FSC
www.fsc.org

For Jon and Sam, with love

Contents

Introduction

I'm lying naked (but for a pair of earplugs) in a white pod-like tank that's shaped like an avocado. Inside, a shallow bath is so packed with dissolved salts that I can float without effort, and so close to body temperature that I can't feel the water on my skin. When I close the lid and switch off the mood lighting, there is nothing to see, hear or feel. Nothing to distract me from an hour of blissful silence.

At least, that's what I thought would happen; it soon became clear that silence was not an option. Between the gurgling in my stomach and my pulse banging away in my left ear, my body had far too much to say for itself for me to enjoy what is known in my family as 'a piece of quiet'.

This was my first visit to a floatation tank – an experience that's usually sold as sensory deprivation, a way of taking a well-earned break from the outside world. What I didn't know then was that in the process of tuning out from my surroundings, I would also be tuning *in* to a sense I didn't know I had – an inner sense that is not only the centre of our personal universe but one of the most important concepts to emerge in science and medicine in decades. One that has the potential to bring better wellbeing, less stress, more energy, and new treatments for common, hard-to-treat conditions that affect mind, body or both.

Frankly, it's amazing that it's not already headline news. Perhaps that's because, despite its potential to fix pretty much everything that ails us today, its name fails to evoke just how exciting it really is. It's called interoception: the sense of our own bodies from within, and it's a catch-all term for the way the brain makes sense of signals and sensations that originate from inside our bodies, such as heartbeat, hunger, temperature, fatigue, vigour, pleasure and pain. These signals carry vital clues about our current and future wellbeing, and are so important for survival that the brain puts them at the centre of our every experience. If you can get past the name, you'll find a whole new mysterious inner world just waiting to be explored.

My hour in the tank was the start of a year-long journey into this new world. It would see me cross continents, swallow vibrating capsules, and spend an awful lot of time listening to my heart – all in a bid to understand what this has to do with how we think and feel.

The short answer is: a lot. Far from just being the inevitable clanking and whirring of a corporeal machine, the signals and sensations from our organs and tissues are increasingly seen as the foundation of the mind itself, providing a constant stream of biological mood music that colours our every thought and feeling, while also providing the impetus for our every action and desire. According to a mounting pile of research, improving our ability to sense and interpret these signals has the potential to transform our understanding of ourselves, and transform our relationships with the people close to us. It could also help us to understand what is driving some of the issues in wider society – not least the seemingly ever-increasing polarisation of political and social discourse. In recent years, calm and rational discussion has given way – especially on social media – to emotionally laden arguments and name-calling, designed to make us feel, not think. If we lack the interoceptive insight to make sense of it all, we are vulnerable to being dragged along by feelings that may not reflect reality.

When you think about it, we've always suspected that we possess something like an inner sense. The idea of listening to your heart, trusting your gut and being guided by instinct makes intuitive sense, even if it's not easy to explain why. But until recently, there was no way to measure whether this had any basis in fact.

Thanks to some ingenious experiments and the creative use of technology, scientists have now come up with ways to measure – and tweak – signals from within, and to link them with what's happening in our minds, in real time. These new approaches are revealing some important insights. First, that this 'sixth sense' is not only real, but is based on measurable bodily sensations and their conversations with the brain. Second, that some of us are better attuned to this sense than others, in ways that affect how we manage our emotions, connect to others, and make decisions. And third, that becoming attuned to this sense is a skill that is proving to be responsive to both training and targeted interventions.

It's difficult to overstate how important this is for our understanding of the mind. For one thing, it moves us away from the idea that everything to do with how we think and feel happens from the neck up – a common assumption in neuroscience and medicine.

Interoception is not about demoting the brain, however; it's about realising that the brain only makes sense in the context of the body and the countless communication channels that run in both directions. In this view, the brain isn't so much the boss as an equal partner, working in close collaboration with the body to keep us alive and well.

Can you feel it?

As you read this, you might be wondering whether you actually have this sixth sense. If so, that's totally normal. Because unlike the more familiar, external-facing senses, such as sight and hearing, sensations from within the body mostly operate on a need-to-know basis.

We don't need to know anything about many of the organs and systems in the body. Our kidneys, pancreas and liver, for example, are quite happy doing their job, being kept on course by physiological checks and balances that we rarely know anything about. If we ever feel them, it's because something has gone seriously wrong. By and large, we can ignore them altogether and hope they never come knocking.

Then there are messages from organs that mostly stay quiet, but which we can consciously tune into if we choose. Mostly, though, we only become aware of them when they make themselves heard, usually in order to signal that urgent action is required. Our heartbeat is the most obvious of these, but the sensation of our lungs expanding and contracting, the feeling of fullness or emptiness in our gut, bladder and bowels all work to the same pattern. It's not exactly a 'don't call us, we'll call you' situation. More, 'you're welcome to call, but we'll be in touch if it's important.'

Between these two extremes are the low-key, almost imperceptible sensations that underlie gut feelings and intuition, providing a general sense of what the pioneering interoception researcher Bud Craig described as 'how I feel right now'. This might show up as a vague feeling of warmth and safety. It might manifest as a sense of feeling strong and capable one day, but anxious and vulnerable the next. Or it might present as a nagging feeling that something indefinable isn't right. These nebulous feelings are not easy to tie to one body part, or to describe, but they can be powerful drivers of our thoughts, actions and emotions, even when we aren't aware of what's nudging us one way or another.

For reasons that we don't yet fully understand, some people have a more sensitive inner sense than others. Some people can feel their heart beating in their chest when they're sitting perfectly still, while others can't. Some people notice sensations such as hunger, a slight tension in their muscles or the need to find a bathroom long before they become urgent. Others don't notice a thing until they are feeling faint, can't turn their head, or are desperate for the toilet.

We also all vary in how much conscious insight we have into our own body-reading ability, how much faith we put in our bodily signals as accurate sources of information, and whether we tend to pay more attention to our bodies, or to the world around us. These differences, which stem from a combination of genetics and life experience, influence everything from our emotional intelligence to our capacity for empathy. They also play into mental health, motivation and some of the challenges associated with neurodivergence. Sensory sensitivities in autism, for example, may lead to feeling anxious and overwhelmed, while problems with emotional regulation, which rely on an ability to sense and understand body signals, are seen both in autism and attention deficit hyperactivity disorder (ADHD).

The good news, though, is that it is becoming clear that our inner sense can be tweaked and trained. By getting better at sensing what's going on inside us and interpreting what it means, we all have the potential to take control of our health and wellbeing.

Uncomfortably numb

While it's difficult to prove without the aid of a time machine, it's possible that those of us living in the West are less aware of how our bodies affect the mind than our ancestors would have been. The closest approximation to how our ancestors lived can be found in modern hunter-gatherer populations, such as the Hadza people in Tanzania. According to a recent study, the Hadza tend to describe emotional moments in terms of physical sensations – they might say that they feel hot, for example, or that they can feel a pounding in their chest. An American comparison group tended to describe emotions in terms of mental experiences such as disbelief and shame, often without even mentioning the body.[1]

Whether this holds true in general is hard to say, but it is certainly true that Western science formally divorced the body from the mind at least 400 years ago, not only cutting up cadavers, but also separating the body and mind into two. The French philosopher René Descartes usually takes the blame for this, not least because of his hugely influential seventeenth-century works, *Principles of Philosophy* and *Meditations on First Philosophy*, in which he described the body as a machine with nothing to do with the ethereal, immeasurable mind. Given how little was known about how either the mind or the body worked at the time, it was an entirely reasonable assumption. A couple of hundred years later, in the mid-1880s, the body was briefly put back into the mind, when William James (an American philosopher widely considered to be the father of psychology) proposed that bodily sensations are the basis of all our feelings. At around the same time, the Danish physician Carl Lange put forward a similar proposal. In their view, which has become known as the James–Lange theory of emotion, we don't feel scared and then our heart rate increases; we feel scared *because* our heart is beating faster.

The idea was shouted down at the time, not least by the physiologist Walter Cannon, who coined the term 'fight-or-flight response'. Even Charles Sherrington,[2] the Nobel Prize-winning physiologist who invented the term 'interoceptive' in 1906, wasn't convinced. For many years, the prevailing view was that the body's sensory pathways to the brain were too slow to be involved in anything as clever as human thought and emotion; the brain surely noticed changes first and then the body followed. As neuroscience developed, it did so based on the principle that all the important stuff happened in the brain. Several centuries later, however, these two competing theories are finally coming together in ways that can help tackle today's challenges – and those that lie ahead.

To state the obvious, the twenty-first century has so far been quite a ride. From climate change to war, a global pandemic and political and financial instability, the existential threats just keep on coming, bringing with them a faint, yet unrelenting, sense that all is not well. This quiet sense of unease jostles for attention with the sensory overload and fast pace of modern life. In the maelstrom of information we receive thanks to our external senses, we become numb to the more subtle information coming from within. What we're left with is a vague sense of impending doom that we can't put our finger on; we would be unable to take action to fix it even if we could find the time. Young adults who are facing the full force of an uncertain future are feeling this most, leading the Stanford researcher Britt Wray to warn of a coming mental health crisis in what she calls 'Generation Dread'.[3]

The temptation, given the scale of the challenges facing humankind, is to harness the many distractions of the modern world and use them as a shield to protect us from the internal inkling that something isn't right. Having a highly attention-grabbing screen in your pocket at all times makes this only too easy. But in the long term it only makes matters worse, and when taken to extremes it can prove catastrophic. In 2005, a twenty-eight-year-old computer games addict called Lee Seung Seop died at his screen after playing the online game *StarCraft* for fifty hours without taking a break.[4] The official cause of death was heart failure, caused by exhaustion and dehydration. In reality, he died of a failure to notice, or act upon, his body's interoceptive cries for food, water and sleep.

It's a cautionary tale used by many mothers of teenage gamers, and a rare example of taking bodily numbness to the limit. Yet Lee's death wasn't a one-off.[5] Anyone who lives with a gamer – or any kind of screen addict, from social media scrollers to box-set binge-watchers – will recognise the tendency to neglect even the most basic physical needs. Even at what we might consider to be a healthy level, screen use seems to distract us from what our bodies really need. When the former Microsoft executive turned amateur researcher Linda Stone measured the breathing rate of 200 people as they checked and replied to their emails, she found that 80 per cent of them become so absorbed by their screen that they would occasionally forget to breathe – a phenomenon she named 'screen apnoea', and which has since been linked to an increased likelihood of stress and anxiety.[6]

Being sedentary for long periods, with or without a screen, has other consequences, too. The lack of sensory information from the body leaves us disconnected from our heart, muscles and joints, and numb to the fact that they are becoming stiff and out of condition. This leaves us feeling sluggish and lacking in energy, which kicks off a vicious cycle of fatigue and inactivity, punctuated by the occasional attempt to 'get in shape' that has little to do with how our body feels from the inside.

Modern diets don't help, either. Ultra-processed foods (UPFs), which comprise 60 per cent of the average British and American diets,[7] are designed to be tasty, calorific and to have a melt-in-the-mouth texture that makes them moreish without necessarily being filling. This diet disrupts the interoceptive system that tells us when to eat, what to eat, and when we've had enough. Many UPFs are high in salt, sugar and fat, which overstimulate gut–brain pathways that link high-calorie foods to sensations of pleasure, reward and comfort, turning a life-saving need into a potentially life-threatening one that leads us to eat too much of what we like at the expense of what we need.

Worse still, a bad diet, inactivity and stress trigger inflammation, which involves the release of body signals that tell us to hunker down. We experience this as a low-level malaise: feeling tired, demotivated, and with an aversion to the company of others. What would be a sensible strategy for healing from an infection or injury puts us at greater risk of depression, heart disease and almost every life-threatening ailment known to science,[8] not to mention feeling run-down and out of sorts.

These modern factors are layered on top of the basic human reality that we all vary, both in our natural tendency to listen to our bodies, and in how loudly they speak to us. And, as we'll see, our life experiences can make important changes to the set points at which we become aware of our body's signals, potentially making us over- or under-sensitive to them. Whether by nature or nurture – or more likely, both – we are all singing from a different hymn sheet and to our own personal backing track. If we can hear what music is playing and understand how it affects us, we have a better chance of being able to change the tune when we need to.

It's not (only) about you

There's one final reason why interoception should become a priority, and it's an important one. Our interoceptive abilities don't just affect us as individuals; they also have a huge impact on our relationships with others, and the health of our society. Having an accurate sense of what our bodies are doing on the inside is the biological basis of empathy – the ability to tap into the feelings of others. We don't just do this by recognising the outward signs of joy or pain in their bodies; our bodies also change so that we feel their emotions as if they were our own. There's even some evidence that our immune systems become activated when we are in the company of someone who is ill, and we start feeling their symptoms – even if we are not physically in the same room.[9]

Our ability to empathise stems from our unique evolutionary history as a social species combined with our long childhoods, in which we rely on others to help us regulate our physiological and emotional needs. These experiences in our early years stay with us for the rest of our lives, setting the tone for how we understand our bodies and minds.[10]

No matter how independent we become as adults, this need for connection never goes away; we can't live without it. A recent analysis of data from over 2 million people found that social isolation was linked to a 32 per cent higher risk of early death. Loneliness, meaning a lack of meaningful social interactions, raised the risk of early death by 14 per cent.[11] Even when it isn't fatal, it can make life feel harder than it needs to be. As became obvious during the Covid-19 lockdowns, when we can't connect with each other we can easily become emotionally and socially lost.

This lack of connection may even fuel some of the more troubling features of modern society. Manos Tsakiris of Royal Holloway University, London, argues that the resurgence of anger-driven populist politics has been fuelled by an anxious population that isn't fully able to process the turmoil that our modern world stirs within our bodies. It's a potent mix that leaves us at risk of being controlled by our gut feelings, vulnerable to leaders who promise to make these uncomfortable feelings go away, and conspiracy theorists who prey on our worst fears and insecurities.

With the road ahead looking even bumpier, now is a good time to get serious about understanding what we are feeling within – and why. Only then can we stop being divided and begin to understand ourselves and each other. When we can feel the uncertainty and dig deep to find common ground, we can use it to work together as only humans can.

Onwards and inwards

It might sound like a pipe dream, but this new way of living is within our reach. In the pages that follow I'll explore what mastering interoception means, and what it can do for all of us. I'll meet the small band of scientists and philosophers who are charting this unknown internal territory and mapping out how the system works – and how it goes awry in response to the modern world, negatively affecting our physical and mental health.

I'll meet people who are feeling the benefits of new body-focused approaches, and learn how interoceptive training is helping people with anxiety to get their symptoms under control and helping police officers to deal with the stresses of their job. I'll find out how touch is proving to be a powerful pain reliever, activating interoceptive pathways in the skin that signal comfort and care, and how increasing physical strength can lead to feelings of confidence and self-esteem. I'll discover why feeling energised is the result of an interoceptive conversation about whether what we need to do is worth the energy – and how we might game the system when the answer is 'no'.

I'll also meet people with above-average interoceptive abilities and find out how this helps them. They include a hostage negotiator whose empathy helps him connect with people during a crisis while keeping his own emotions in check, and a financial trader who thrived on Wall Street by listening to his gut intuition. Through such examples, we'll see that, far from being a fuzzy concept that makes no real difference, having a handle on your bodily signals can bring real benefits. I'll end by bringing all this research together and suggesting how you can bring interoceptive wisdom into your everyday life.

First, though, we need to take a deep breath and dive into the murky world within us, to understand why what's happening inside holds so much sway over our experience. As we'll see, the whole point of interoception is to learn from the rough bits of life so we can enjoy the unique experience of being human.

1

An inside story

Homeostasis, feelings, and the art of staying alive

'Look, I'm just a planet doing its thing, alright? If you want to live on me, that's your business…'

This quote on the satirical website the Daily Mash, attributed to Planet Earth,[1] is more profound than it seems. We might think of our planet as a nurturing 'Mother Earth', but in reality she's not the sort of mother who frets over whether you're warm enough or have had enough to eat. Life on Earth exists not because it has been looked after, but because it found a way to look after itself.

If it hadn't, of course, we wouldn't be here. Once the basic chemical ingredients for life had arrived on Earth, carried (we assume) by various asteroids, life probably emerged multiple times, only to be snuffed out by unexpected changes in conditions. Then, one day around 4 billion years ago, an attempt at life stumbled upon a solution, and went on to become the common ancestor of all life on Earth.

We don't know exactly what this solution was, but one idea is that several chemical reactions, each capable of creating energy from carbon in the atmosphere, somehow got trapped inside an early cell. Because each reaction worked in a slightly different way, it gave the cell back-up. If one or two of the reactions didn't work, one of the others would kick in and life could continue.[2]

As survival strategies go, it was dangerously hit and miss, but it worked for long enough for evolution to come up with something better – a toolkit of specialised sensors that allowed a cell to sense change in the outside world, adapt its internal state accordingly, and stop adapting when the coast was clear. This process of cellular self-care is called homeostasis, and it's non-negotiable for the survival of any living thing. A couple of billion years after life began, evolution had perfected a variety of cellular tools to detect physical, chemical or temperature changes, and a range of options for tweaking chemistry to get things back on track.

Fast forward a couple more billion years, and the business of maintaining homeostasis in our bodies is both the same and very different. Our bodies' cells are fitted with variations on the same old-fashioned, yet reliable, sensors to detect internal change. Some, the chemoreceptors, respond to changes in things such as carbon dioxide, glucose or salinity. Others, humoral receptors, detect changes in hormone levels, while mechanoreceptors specialise in detecting pressure or stretching.

Along the long road between single-celled organisms and human beings, though, some life forms became so complicated that the insides of their bodies contained almost as many variables as did the outside world. Our interoceptive system is the evolutionary result of needing to keep track of both of these ever-changing worlds simultaneously. The arbitrator is the brain, which evolved to keep track of these two worlds and to co-ordinate responses to keep us alive.

To make sense of where we have ended up, it's worth taking a brief tour of the evolutionary leaps that brought us here. These accidental strokes of genius were few and far between, and the first one was a long time coming. For the first 2 billion years, Earth contained only single-celled life. Then one of these single cells found its way inside another, and traded food and shelter in return for most of its DNA and all the energy it could make. This was the origin of what we now know as mitochondria (often called the 'powerhouse' of the cell). With a supply of extra energy and a glut of fresh new DNA, this new hybrid life form could experiment with a host of fresh designs.[3] Some of them were multi-celled new life forms, such as green algae,[4] slime moulds, fungi and sponges.

Then it all went quiet for a billion years or so – a period that has been nicknamed the 'boring billion'. Life bumped along, sensing and adapting to the world via the chemical equivalent of notes being passed in a school classroom. Messages travelled slowly from one end of a creature to the other, cell to cell or in the air or water. Then there was an ice age, and things slowed down even more.

When the Earth finally warmed up, life got back to experimenting. After a few million years of trial and error, a new kind of cell was born – one that could send messages faster and more accurately, vastly speeding up the process of sensing and adapting. These were the first neurons, and any creature that had them found that it could outcompete its rivals by beating them to food sources or by escaping danger before others had noticed it.

In many ways, these fancy new cells were a better designed version of the same idea. Sensory neurons feature many of the same sensors that evolved in the early days of life, but in neurons these sensors are concentrated at the ends of the cell's branching tendrils (called dendrites) that extend through tissues and detect any change in the chemical and physical situation or a potentially problematic deviation in temperature. When change is detected, the information speeds along a communication fibre (the axon) to trigger whatever action is necessary. Jellyfish, for instance, have sensory neurons that detect the touch of a potential predator. These relay the message to a different set of neurons, the motor neurons, which tell the jellyfish's muscles to contract so the creature can swim away. In a world where speed can make the difference between life and death, neurons allowed animals to sense and react in less than a second, which gave them an edge over their competitors.[5]

In the game of survival, speed is good – but speed with a plan is even better. That was why, within a few million years of the first neurons, some animals started to develop brains. They didn't show up in all branches of the animal family tree (jellyfish and starfish still manage without them), but in our branch they proved to make movement not only faster, but also smarter. The earliest versions showed up in our distant worm-like ancestors, in little bundles of nerve cell bodies called ganglia, which contained the neuron cell bodies from which the axons extended through the body. The biggest clump was at the head end, near to where most of their sensory kit was found.

At some point further down the line, the bodily branches converged into a central spinal cord: a kind of cable tidy with neat pathways for sending sensory information in and movement-based instructions out. A notable exception to this system is its most recent addition, the vagus nerve. Sprouting from the brain around 400 million years ago, it snaked through the body to connect with the various organs, which had by then evolved to take care of different homeostatic jobs. Its job was – and still is – to constantly monitor and tweak our organs automatically, without necessarily stirring the whole creature into action.

And this, in effect, brings us to the interoceptive system we have today. It looks complicated when you map it out, but that's because it is. And while we are still working out how it fits together and how we make sense of it all, what we do know is that every part was added over billions of years in the service of keeping us alive. Unfortunately, though, greater complexity brings a greater risk of glitches. Like a high-performance car that is too complicated for your local mechanic to understand, we find ourselves in possession of a finely tuned machine that can be baffling to own and maintain.

Feeling the future

The solution to the challenge of increasing complexity was smart, but it has brought problems of its own. Brains allowed animals to go one step further than merely sensing and adapting. They made it possible to learn, and to use lessons learned in the past to make an educated guess about what was most likely to happen next. Even in the earliest, simplest brains,[6] having bundles of neurons collected in one place made it inevitable that, as well as sending messages through the body, they would connect to each other and share information. That meant that animals could adapt to threats and opportunities – not just quickly, but often before they even happened.

This flexible version of homeostasis is called allostasis,[7,8] meaning 'stability through change', and as far as our lives are concerned, it's a mixed blessing. On the one hand, it has made us experts at adapting quickly to complex environments, allowing us to predict and prepare for them so that we don't get knocked too far off course. On the other, it means we spend time and energy adapting to situations that may never come to pass, but which involve changes to our body and mind that aren't always necessary, or healthy. When challenges keep coming, whether they are real or imagined, predicting and adapting can cease to be an energy-saving strategy and can start to put a strain on the body's resources. This, in a nutshell, is why stress is so exhausting – and so bad for our long-term health.

The good news is that our brains never give up trying to balance adapting in advance with wasting energy on non-existent threats. This can be explained in terms of what's called predictive processing: a fairly new idea in neuroscience that uses complex mathematical models to explain how the brain works. In less complex terms, it means that because the neurons share information, the brain is able to make experience-based predictions about what information is most likely to come in from the senses. Predicting what's coming means that the body can be prepared and start the process of adapting in advance, adding more speed to an already speedy system. While the body adapts its physiology to deal with what the brain expects to happen, sensory information coming from inside the body – and outside, from the eyes, ears, and so on – chimes in with real-time evidence that either confirms the prediction or proves it wrong.

If the signals coming in match what the brain predicts, all is well and not much happens. Any discrepancy between what the brain expects and what the sensors deliver, however, creates an error signal, flagging up that some form of adaptation is needed, either to change the prediction, such as from feeling safe and calm to alert and vigilant, or to change the signal, perhaps by moving away from the heat of a flame.

If adaptation is needed, the body–brain system has three options. First, the brain can change its prediction to match what the body is reporting. A rumbling stomach, for example, might lead to the prediction that you are hungry, even if you have just eaten. Second, the body sensation can be altered to match the brain's prediction – you might run around a corner and see a hill you weren't expecting, for example, at which point your legs feel tired in anticipation of the climb. The third option is that the volume of the body's signals can be turned up or down during their journey through the body and brain. That could mean temporarily disregarding them in favour of something more urgent (for instance, not feeling the pain of a broken ankle until after you've finished running away from danger) or boosting them until they can't be ignored (the overwhelming feeling of suffocation during a panic attack).

Which option is put into action depends on which source of information is deemed likely to be the most reliable. Nobody knows exactly how this decision is made, but somehow the brain–body neuron circuitry seems to place a bet on the option that seems most likely right now. The output of this is what we experience as reality: a 'best guess' based on the brain's expectations, what the body is reporting, and the need to take action when they don't match. But even when we don't become conscious of these body–brain discussions, they can still influence the way we think and feel, in ways that play into issues that have commonly been dismissed as 'all in the mind'.

The complexity, and ever-changing nature, of our interoceptive system explains how two people can have such different experiences in the exact same situation. It is also why it can sometimes be so difficult to explain why we think and feel the way we do. It all comes down to the 'best guess' of a highly complex body–brain system.

Who's in charge?

Arguably, the cleverest trick of the predictive brain is giving us the impression that it is solely in charge of how we think and feel: an all-seeing CEO of the body that dictates what we think and do. An interoceptive view of the mind, however, reveals that brain and body are jointly in charge of our mental experience. The brain wasn't created in a vat and bolted onto the body, fully formed; it emerged *from* the body with the sole aim of keeping the body alive. That means that there is no body–brain split; both are part of the same ingenious survival system, which began with a tiny bag of chemical reactions.

The main difference between us and a tiny bag of chemical reactions is that, as far as we know, bundles of chemical reactions don't have feelings attached to their homeostatic needs. For some reason – and no one knows why – we do.

Feelings act as a slick user interface that constantly summarises how life is going along two sliding scales: 'good' to 'bad', and 'urgent' to 'less urgent'. The interface usually ticks along behind the scenes, setting the mood, a bit like the background music in a movie. Occasionally, though, either because we decide to tune in and listen, or because the background music gets louder and more difficult to ignore, we become aware of it as a conscious feeling. One thing that all feelings have in common, whether they whisper or shout, is that they all feel *like* something. Anxiety, for example, is more than a factual assessment of a coming challenge. It feels physically uncomfortable, deeply personal, and too urgent to ignore. This, says Antonio Damasio, a neuroscientist and philosopher at the University of Southern California, makes feelings fundamental to understanding consciousness itself.

Damasio is an important figure in the history of interoception: in the 1990s he became the first modern scientist to resurrect the idea, in his research and in the popular books *Descartes' Error* and *The Feeling of What Happens*, that the body is important in our ability to think and feel.

At first, much as William James and Carl Lange had discovered a century earlier, nobody wanted to listen. When we meet via video call from his home in California, Damasio recalls one eminent scientist telling him that feelings were 'for girls' and that he should stick to the 'big stuff' like intellect if he wanted to understand the mysteries of the mind.[9] He ignored them and, working with his wife and long-term collaborator Hanna Damasio, has spent more than thirty years compiling evidence that the body is very much required for emotion and feelings. The basic idea is now entirely in the mainstream.

Bud Craig, a neuroscientist at the Barrow Institute in Arizona, was another pioneer of the bodily basis of consciousness. He died in 2023, having spent more than two decades mapping the route of sensory nerves from the body to the brain. Craig, like Damasio, believed that consciousness was rooted in the body and its current needs. His work was also important because it expanded the idea of interoception from something that concerned the internal organs to a sense that involves the whole body, from the deepest organs to the muscles and skin, with pain and temperature affecting how we feel just as much as the blood flowing around our bodies and the food in our bellies do. 'Humans perceive "feelings" from the body that provide a sense of their physical condition and underlie mood and emotional state,' Craig wrote.[10]

Feelings, the sensation-based shorthand for how things are going, underlie emotions, but most neuroscientists agree that the two are not the same thing. Feelings are the 'mood music' that plays in the background of our lives: things like unease, vitality, comfort or fatigue. In predictive processing terms, they are a kind of 'live stream' of prediction errors, which we become conscious of only when something has to be done to fix them, or when we deliberately decide to listen in.

Emotions, on the other hand, are the brain's interpretation of what caused the feelings and what they mean, says Lisa Feldman Barrett, neuroscientist and author of *How Emotions Are Made*. For example, if we feel jittery or have butterflies in our stomach, we might interpret this as excitement or anxiety, depending on the context. This, Feldman Barrett tells me, is good news, because emotions are potentially more malleable than the basic feelings of good or bad, urgent or less so. We can choose to interpret butterflies as excitement rather than anxiety – at least, in theory.

Feelings may seem less sophisticated than emotions, but they play an important role in building the mind. For one thing, they are the foundation of our basic sense of self: the idea that there is a 'me' who is the same person from one day to the next and who experiences the world from the inside out.

'Feelings tell you, in no uncertain terms, what is happening to you,' Damasio tells me. 'If I'm feeling well, or if I'm feeling in pain, that's because I have a body and I have a perspective on that body… It is part of the construction of a self.'[11] Since we are not the only animals that can feel an adrenaline rush or a pounding heart, I suggest to Damasio that perhaps consciousness isn't unique to humans. 'Correct,' says Damasio. 'That's one of the things that people get so wrong. They want to make human consciousness particular; I think human consciousness is just like the consciousness of any other creature.'

If he's right, it raises uncomfortable questions about how humans treat almost every other species on the planet – not least captive chimpanzees, gorillas and orangutans, whose nervous systems and social behaviours are the most like our own. Arguments have so far revolved around basic tests of self-awareness, such as whether an animal can recognise itself in a mirror, and demonstrations of their near-human cognitive skills. By Damasio's reasoning, though, how they think isn't the point. We should be trying to work out how they *feel*.

Damasio believes that the reason that consciousness has proven so tough to explain – both in human beings and in other species – is that most of our recent efforts have focused solely on the brain. 'People talk about consciousness as the great mystery that will be revealed by understanding the brain – and that's wrong. It's not about the brain – it's about what the brain achieves with the interoceptive system in relation to the body,' he says.

Not everyone is on board with the idea of extending human-like consciousness to other creatures. Critics argue that it doesn't account for the possibility that animals with less well-developed brains feel the same physical sensations as we do without interpreting them as emotions. A lion might feel the sensation of an empty stomach without feeling 'hungry', for example. And a gazelle might not experience anything like fear when it spots a lion, even though its heart will start pounding as it prepares for escape. Non-human animals also don't seem to possess the mental hardware to zip back and forth along an imaginary timeline, remembering how they felt in the past and getting excited about the future. In humans, this ability is considered to be a key component of the self. Whether other animals share this – and whether they can be considered to be conscious if they don't – is another debate entirely.

Nevertheless, the important thing is that as evidence for the body's role in constructing the mind has stacked up, neuroscientists are starting to agree that our sense of self, as the same person existing from one day to the next, is rooted in body–brain interactions that evolved to aid survival. And everyone now agrees that the brain alone is not enough to generate the rich inner experience that we call consciousness.

Could robots care?

This new embodied vision of consciousness has implications for our hopes – and fears – regarding the potential rise of conscious artificial intelligence (AI). AI is already an integral part of everyday life, so it seems reasonable to wonder whether we will soon be in the presence of conscious artificial beings. Incidentally, here's what ChatGPT said when I asked it:

> Some researchers argue that consciousness is a function of the information processing that occurs in the brain, and therefore it could theoretically be replicated in a sufficiently complex computational system, such as an AI... Others argue that consciousness is inherently tied to biological systems and cannot be replicated in artificial systems, no matter how advanced they become.

This, to be fair, is a pretty neat summary, but it doesn't take into account the fact that 'biological systems' means more than just the brain. Most attempts at AI involve neural networks that are based on our current understanding of how the brain works. If a robotic body is added, it's usually added last, as a fully formed robotic body part.

But as we have seen, human consciousness was built from the body up, not from the brain down. If we build AIs to replicate only our brains, they may never be conscious, no matter how intelligent they might seem.

Some robotics researchers are starting to wonder if continuing to build intelligent, yet unfeeling, and therefore unconscious, minds might be a very bad idea. In 2023 a team of researchers, including Damasio, flagged up the need to factor in an equivalent of homeostatic feelings in artificial minds.[12] They pointed out that all attempts so far to give something resembling empathy to artificial agents involves giving them an intellectual understanding of human thoughts, feelings and emotions, and an ability to read them and respond. But this doesn't give them the ability to feel our pain and care about the things we treasure, which essentially makes them sociopathic – able to read and imitate human empathy, but without feeling, or caring about, anything. Which raises a very important question: are highly intelligent but unfeeling minds really something we want to unleash on the world?

One way to get around this, Damasio and his fellow researchers argue, is to build in the capacity for artificial minds to feel the consequences of personal harm – pain, loneliness, and an awareness of their own mortality. In principle, this would not only give them some insight into how we feel, but it might also prevent them from harming us – or each other. 'Vulnerability and homeostasis in machines may provide ... common ground between themselves and living beings,' they wrote.

Of course, this raises a whole new set of ethical issues. If we engineer AI-powered robots that could feel, this brings up dilemmas much like those surrounding animal rights. With one crucial difference: unlike animals, robots will be able to tell us exactly what they think of us, and why.

Another option that roboticists are beginning to explore involves taking inspiration from evolution to build AI from the ground up, with its intelligence developing alongside its body. Josh Bongard, a roboticist at Vermont University, is training AI algorithms to learn about the world they are a part of, and to design and redesign their own bodies based on the results.

It's early days for this approach – Bongard told *New Scientist* in 2023 that so far they have built 'relatively simple robots, the sort that kind of shuffle around a little bit'. But as the technology improves, we could see the first body-conscious robots; whether they are more likely to be conscious than the existing 'brain in a vat' systems remains to be seen. For the time being, it might be helpful to remember that however smart AI seems, so far it has no idea what it is doing, or why. For now, Damasio describes chatbots as 'a wonderful example of what consciousness is not'.

Heart: felt

Back in the human body, each of our 30 trillion cells is responsible for a huge number of simultaneous signals. But amid the cacophony, a few of them are constantly saying something important about what's going on inside.

These constant, but ever-changing, rhythms are the most important link between what the body's doing and what's going on in the brain.

The most obvious of these is the heart. As far as the brain is concerned, the heart has always been there. In a human foetus, it starts beating within a few weeks of conception, at a time when the brain is still organising itself into three basic sections: the hindbrain, midbrain and forebrain. From the day it starts beating, the heart generates its own rhythm. As the brain grows, it does so to the rhythm of the heart.

Catherine Tallon-Baudry, a neuroscientist at the École Normale Supérieure in Paris, suggests that this makes the beating heart a good candidate as an 'anchor' for our sense of self. Sylvia Plath makes the same point in her novel *The Bell Jar*. The main character, Esther, in the depths of suicidal depression, describes being taunted by her heartbeat, an inescapable reminder that she's still alive: 'I ... listened to the old brag of my heart. I am, I am, I am.'[13]

Sure enough, there seems to be something about our heartbeat that marks the body as 'mine' and tells us that we are very much alive. In experiments designed to test whether our sense of self can be transferred to inanimate objects, people are more likely to feel that a rubber hand belongs to them if a projected version of it flashes in time with their own heartbeat.[14] The more keenly a person feels their own heart, the stronger the effect. Adapted versions of these studies in five-month-old babies suggest that heartbeat awareness may be hardwired at birth, or at least very early in life.[15]

Tallon-Baudry's idea is supported by the finding that heart and gut rhythms seem to have a special status in the brain. Brain imaging studies show a signal known as the 'heartbeat evoked potential' (HEP),[16] which echoes the timing and strength of the heartbeat in various regions of the brain. HEPs are most intense when the body's signals become stronger, or when we consciously tune into our own heartbeat. In the past few years, a separate signal that tracks stomach sensations has been found in other regions of the brain. This is known as the 'gastric evoked potential' (GEP).[17] There is also evidence that the rhythm of our breath, moving in and out of the lungs, acts as a metronome that sets the processing rhythm across the brain, the 'respiratory evoked potential' (REP).[18]

The constant and predictable rhythms of these signals also help to make sense of time. Bud Craig noted in 2009 that the main brain regions that put internal bodily signals in context and build a sense of 'me' are fundamental to our ability to perceive time. Experiments since then have confirmed his hunch; our understanding that there is a me, who is feeling this particular feeling in this particular moment, is built from the regular rhythm of our bodies as they keep us alive. This goes some way to explaining why time flies when our bodies are active, and drags when we are still and bored.

We are most aware of our body rhythms when we find ourselves in what feels like a life-or-death situation. At that point, what is usually background noise bursts into consciousness and demands action. Time stands still and our bodies are alert and ready to move. Yet while everybody has this reaction during an emergency, the level at which the background noise is escalated into consciousness varies considerably from one person to the next. And as it turns out, the differences between us have a lot to do with how we feel our bodies from within.

Chris White is no stranger to life-or-death situations. As a hostage and crisis negotiator for the Metropolitan Police in London, his job was to resolve hostage situations, armed sieges and terrorist stand-offs. It's the kind of job that demands a clear head and – you might think – an ability to tune out the bodily signals that let fear seep into a situation. According to the brain-centric school of thought, a sudden increase in heart rate or butterflies in the stomach would distract from the kind of calm, rational decision-making required in a crisis.

Yet when scientists talked to White about his work, they found that he was far from a cold, rational thinker. In fact, he told them that he actively listened to what his feelings were telling him, using his bodily sensations as an early warning system to know when the mood between him and the person with whom he was negotiating had changed – before the relationship had soured beyond repair.

Sarah Garfinkel, a neuroscientist at University College London, was intrigued. She tested White's ability to detect his own heartbeat while sitting quietly by asking him to count the number of beats in a short space of time – a standard test of a person's ability to tune into their interoceptive signals and which correlates with heartbeat-evoked potentials. It's not easy, and most people get an accuracy score of about 60–70 per cent; White, however, scored close to 100 per cent.[19]

Garfinkel was shocked. But as Chris White told me later, he is almost always aware of what his heart is doing, and had no idea that that was unusual. 'I can feel my heart, even sitting here now,' he told me. 'I don't go around all day thinking about it, but even at rest I can feel it. It surprises me that other people don't.'

White says that noticing these feelings is not just a party trick; it helps him pick his moments when intervening in negotiations. 'There's a radar that you pick up. Not everybody does, but I've always believed mine's been fairly acute,' he says. 'There's this sense of "I'm uncomfortable" … your blood pressure will increase, your heartbeat will increase, and in extreme circumstances you might get butterflies. You genuinely think that something is about to happen that you really don't want to happen.'

Having a particularly sensitive window into what his heart and gut are doing helps him to guide negotiations based on intuition. 'I can generally tell the moment when someone becomes receptive to suggestion,' he says. 'You need to pick that moment – because if you do it too early, they will shut down.'

While White jokes that his acute inner sense hasn't yet made him a millionaire, it seems that others who are similarly endowed have accrued considerable wealth. In the mid-2010s, Garfinkel studied a group of financial traders who, like White, often based decisions on what they claimed to be a sixth sense – in their case, about whether a trade felt 'good' or 'bad'.

Like White, they also turned out to have an unusually acute sixth sense, on average scoring close to 80 per cent on the heartbeat detection task while non-traders scored around 66 per cent. What's more, those with the most accurate heartbeat detection scores were more profitable over the course of the financial year. And those with the strongest sense stayed in the job for longer, while others burned out or moved on to lower-stakes jobs. Those who were still on the trading floor fifteen years after their first day had an average accuracy of 85 per cent.[20]

John Coates, a financial trader turned neuroscientist who collaborated with Garfinkel on these studies, dubbed these people 'hunch athletes'.[21] By some combination of genetic good luck and training, they have become highly attuned to their gut feelings – and with a score above 80 per cent on the heartbeat detection task, he is one of them. When he moved from Wall Street to the lab, he took his intuitive sense with him. 'I was relying on hunches that were every bit as gut feely as things I'd had on Wall Street,' he says. 'I could sense there was a message in the data, even though I hadn't found it yet.'

We may not all be hunch athletes, but we all have this 'spidey sense', and it contributes to the decisions we make, even when we aren't aware that it is happening.

In every moment, our body signals act as a kind of gatekeeper, determining whether something in the outside world is important enough to require further processing. Experiments have shown, for example, that we are faster to notice things – and to react to them – if they hit our senses at the same time as our heart contracts, sending blood around our body. This makes sense when viewed in the context of survival: in times of threat, when the heart is beating faster, we are both hypervigilant to signs of danger and able to react faster to escape if necessary. Memories are also laid down more strongly when the heart is pounding – which makes sense if you want to learn from your brush with death so you can react more quickly next time. Something similar happens as we breathe. When we see something scary during an in-breath, we are faster to notice and to react. Again, this makes sense: when faced with danger, you want to notice, act quickly and learn for next time.

This system does have downsides, however. A small, preliminary study led by Yoko Nagai at the Brighton and Sussex Medical School used biofeedback to nudge volunteers into a state of either high arousal (heart racing, palms sweating) or relaxation. They were then subjected to the Weapons Identification Task, a psychological test used to investigate how unconscious racial bias affects perception and behaviour.

In the test, a face briefly flashes up on a screen, followed by a glimpse of either a gun or an innocuous tool, such as a spanner. Previous experiments had shown that after seeing a black man's face, white participants were quicker to spot a gun than a tool, and were more likely to mistake an innocuous tool for a gun than they were after seeing a white face. Nagai and others have also shown that this effect is particularly strong if a volunteer sees the face at the exact moment their heart contracts. Which led her to wonder, what if a person's heart was already beating fast? Would they be more likely to jump to a racist conclusion?

The answer was a resounding yes – which was especially worrying because all these reactions are subconscious. It's important to note that these associations between ethnicity and violence aren't hardwired; they are learned associations that most likely become entrenched through racist stereotypes in society and their reinforcement in popular media. This means that people who have watched enough crime dramas, or who consume certain media channels, might be primed to react in ways that might not reflect what they really believe, especially when they are stressed, angry or scared. This feels like something that everyone – and particularly those in positions of power – should be aware of.

Wired for change

The good news is that none of this is set in stone; from the very beginning of human life, our interoceptive system comes wired to adapt and change. When babies are born, their systems are far from finished. The sensors and basic wiring allow them to detect when homeostasis isn't going well, but all they can do is cry and hope that someone interprets what they need and fixes the problem.

Anyone who has been in charge of a baby will know that it's not easy to translate their cry into a specific need for food, a change of nappy or to be helped to sleep. But according to the researchers Manos Tsakiris and Aikaterini Fotopoulou, the process by which adult and child work out the problem allows us to make the link between homeostatic needs and ways of fixing them. It's a process of trial and error that rarely goes without a hitch – but as long as a parent responds and eventually solves the problem, all is well.

If, on the other hand, a baby cries and no one comes to help – or if they are punished for expressing their needs – the system doesn't develop as it should, and this can lead to poor mental health in later life. The same process may account for the 'sensitive periods' for mental health during our lifetimes: puberty and adolescence, pregnancy, menopause and old age are all periods when the body and brain are undergoing upheaval. Our bodies are changing and our brains are rewiring themselves, and anything we relearn about the world and our chances of surviving or thriving may be more likely to stick.

Even outside these key periods, our inner sense is telling a constantly changing story that is written and rewritten every day. Intriguingly, the brain–body connections that run the show may be edited and updated while we sleep. It has long been known that during REM (rapid eye movement) sleep, when we do most of our dreaming, our bodies are mostly paralysed, apart from the occasional twitch. Until recently, these twitches were thought to be a remnant of the dream, somehow sneaking out of the brain and being expressed in the body, but according to a new theory it's quite the opposite. Neuroscientist Mark Blumberg found that these twitches happen in the body first, and the brain responds milliseconds later.[22] He suggests that one explanation for this is that when we twitch in our sleep we are running maintenance on our body–brain connections, keeping them updated with the latest interoceptive lessons so they are ready to go the next morning.

With new insights like these emerging all the time, we find ourselves at an exciting juncture for the understanding of the mind. Learning how interoception works by mapping its pathways through the body and brain can provide us with tools to understand why we think, feel and act the way we do. Once we know that, we can make better-informed decisions about how to read and respond to our own bodies and what they really need. Then we can do much more than just survive through the many challenges of living on modern Planet Earth – we can thrive.

2

The interoceptive superhighway

Navigating the vagus nerve, and other roads less travelled

The human brain is amazing, but if you could remove it from the body and somehow translate its activity into thoughts, you would almost certainly be disappointed. A disembodied brain wouldn't be wise, it wouldn't be rational, it wouldn't even be angry about its predicament. If you got anything from it at all, it would probably be something along the lines of 'Huh?'

For all its bells and whistles, without the rest of the body, the brain has nothing to think – or care – about. Even memories would cease to make sense if there was no body for us to feel them through. So, for all the impressive discoveries in neuroscience over the past few decades, if we are to truly understand our minds, we need to look at the brain in the context of the body it works with. Anything less would be like trying to understand how a tree produces leaves and flowers while ignoring its trunk and roots, or how a great city came to be, without factoring in the flow of people, ideas and materials in and out of its borders over centuries or millennia.

In short, if we are ever going to move beyond vague conversations about mind–body connections, we are going to need a better map: one that not only puts the brain in the context of the body but is also interactive, plotting the major highways and byways, and providing updates on any blockages in real time.

It's a big ask, but for the body's major interoceptive highways, efforts are well under way. What has been discovered already makes it clear that the body–brain pathways are far from passive carriers of information. They are way smarter, and far more interesting, than that. And they offer new opportunities to understand – and influence – the mind.

Lines of enquiry

According to the neuroscientist Soyoung Park, there's a word that perfectly sums up the body–brain connection. It is, she told the audience at a recent conference on emotion research: the neck.

It got a good laugh, because as everyone in the room knew, it's a bit more complicated than that. In fact, another scientist I met while researching this chapter suggested I skip the details entirely. Another suggested I bury the specifics somewhere in the notes section. Nevertheless, having spent many hours wading through anatomical treacle, I still think that the basic map is well worth a brief guided tour – if only to hammer home the point that the body–mind connection is not a woolly concept but is actually very real.

The obvious place to start is with the three main body-to-brain pathways (Figure 1). First, there's the vagus nerve,

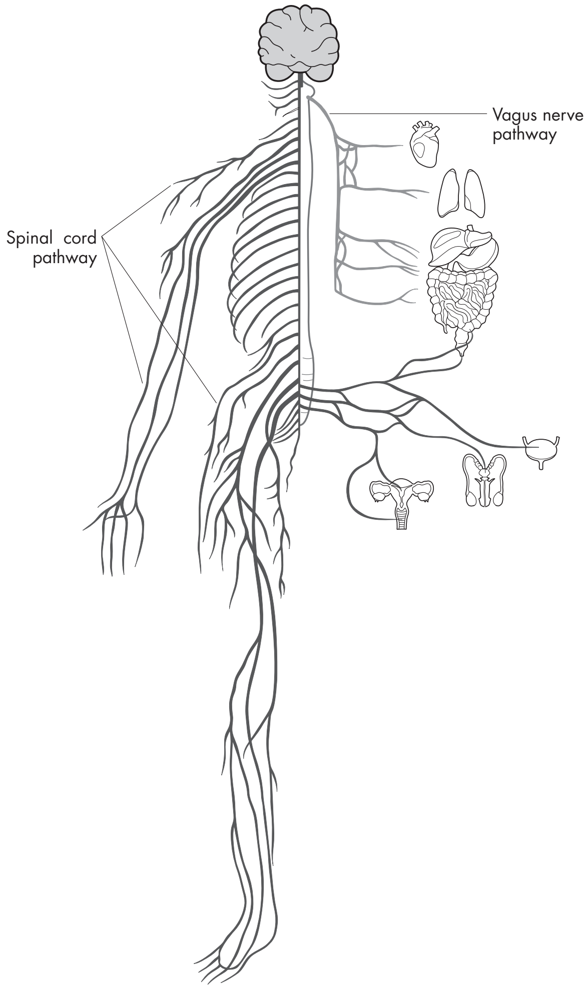

Fig. 1: **Body–Brain Interoceptive Pathways**

The body–brain conversation takes place along two main nervous system pathways. The vagus nerve carries signals from the major organs directly to the base of the brain. The spinal sensory nerves report from the pelvic organs, including the bladder and genitals, and also from further afield, from the muscles, fat and other body tissues, and travel to the brain via the spinal cord. A third pathway (not shown) carries chemical and hormonal messages between body and brain in the bloodstream.

which connects the brain to and from the major organs and blood vessels of the body. It takes a winding route through the body, branching out often, seemingly with little regard for straight lines or tidiness. That is how it got its name: 'vagus' is the Latin word for 'wandering'.

Then there are the sensory nerves of the spinal cord, which take a more direct route through the centre of the body. A few of these nerves (2 per cent of the total) report in from the organs, but the rest send news from further afield, from the muscles and connective tissues such as skin, fascia and fat. These nerves feed into nerve bundles called the dorsal root ganglia, which contain the cell bodies of the nerves and sit just outside the spinal cord. Then the nerve fibre sneaks in the gaps between the vertebrae and heads up the back of the spinal cord to the brain.

Finally, there's a blood-vessel-based slow road for chemical and hormonal messages. These take the scenic route around the body, at some point passing through the brain. Most of what's carried in the blood sails right by; the majority of the brain is protected by the blood–brain barrier, which only lets in a few pre-approved molecules. Notable exceptions include a handful of brain regions called the circumventricular organs. These are more open to the outside world, and specialise in sampling sensory signals from the blood. Any urgent blood-borne signals are detected at staging posts along the way and can be diverted onto the nervous system-based fast track.

All routes lead to the same place – the brainstem. As its name suggests, it resembles a stalk poking out of the base of the brain. This is the first interoceptive processing hub and relay station, and a key place where the bottom-up updates interact with top-down predictions from the brain.

Before we delve further into the brain though, an important question about the below-neck pathways needs to be addressed – not least because of its increasingly high profile in the wellness industry.

What *really* happens in vagus?

The vagus nerve is *everywhere* right now. I don't mean everywhere in the body (it actually stops wandering somewhere around the intestines), but in popular culture. Every wellness guru in the world seems to know how to 'hack' into it for better health and less stress, and you can even buy a vagus nerve stimulator to do the job for you.

The short version of the story goes like this: the vagus nerve is the main arm of the parasympathetic nervous system, which transmits 'rest and digest' signals from the brain to the body's organs and dampens the inflammation response. So, the story continues, if we stimulate this part of the nervous system, we can calm the body from the top down. This, in turn, changes the body's bottom-up signals from fight-or-flight to the biological equivalent of a chill-out playlist. Everyone is happy – not least your overworked organs and immune system.

Stephen Porges' polyvagal theory, first published in 1995,[1] is a common addition to this basic tale. Porges believes that mammals evolved an extra branch of the vagal parasympathetic pathway that was added to the more 'primitive' fight-or-flight response. According to this theory, this new pathway evolved to adapt to living in social groups – when mammals started working together, we could trust our family and friends to keep us safe. So, Porges' theory says, a new vagal pathway evolved that is primed to detect social signs of safety – such as a calm voice or friendly face – and helps us keep a lid on our more primitive responses.

The theory has been particularly influential in trauma therapy, where it forms the rationale for interventions aimed at making a trauma survivor feel safe in their own body. On the other hand, some neuroscientists have pointed out a number of problems with the theory. For one thing, what Porges describes as an evolutionary new pathway for mammals is actually a lot older than he thinks, and also exists in fish and reptiles. Neuroanatomists, who trace where nerve pathways actually go, have also argued that there's no evidence that a social 'special branch' exists. That doesn't mean that social support isn't important – there's huge amounts of evidence that it's vital to our health and wellbeing – but that we don't know for sure that it has anything to do with a special branch of the vagus nerve.

That aside, a bigger concern for the popular view of the vagus nerve is the common belief that it is a 'one-stop shop' to parasympathetic activity and calm. In fact, parasympathetic nerves actually only make up around 20 per cent of the total in the vagus nerve; the other 80 per cent is made up of so-called sensory afferent fibres that carry bottom-up sensory information from the organs and other viscera to the brain. These are the ones that are implicated in everything from the sense of self to feelings, motivations and emotions, what we eat and when to stop, and how we feel about what's around us. So, for all the hype and excitement, if we really want to know how to 'hack' the vagus nerve, we need to know more about which fibres go where and what they do. Thankfully, several research groups around the world are working on exactly that.

As J.R.R. Tolkien famously noted, 'Not all those who wander are lost'.[2] That's certainly true of the vagus nerve. When I visit the Feinstein Institutes for Medical Research in New York, where researchers are attempting to map all 100,000 fibres in one branch of the nerve, it isn't long before I find myself in a debate over whether 'the wandering nerve' needs a better name. 'Is it wandering, really?' ponders the neuroscientist Naveen Jayaprakash. 'It knows where it's going...'

Jayaprakash leads me through the office – an open-plan set-up that would be entirely unremarkable were it not for the brightly lit, glass-walled lab that has seemingly been dropped among the rows of cubicles. Inside what looks like a scientific aquarium, Jayaprakash introduces me to the project lead, Stavros Zanos, and their colleague Ibrahim Mughrabi. Wearing a white coat and blue latex gloves, he is preparing sections of human vagus nerve for the microscope.

The three of them talk me through what they are working on: a three-year, $7 million project to map the vagus nerves of people who had pledged their bodies to medical research. The ultimate aim of the study is to use the dissected nerves to build a 3D interactive map that will show where the individual nerve fibres that make up the vagus nerve go in the body, and in which direction they carry information (body to brain or brain to body). This is part of a larger effort funded by the US National Institutes of Health (NIH) that will be shared with scientists all around the world, with the aim of harnessing these pathways in health and disease.

Removing the nerve from the body is, says Jayaprakash, 'a long process' that is carried out by a neurosurgeon over several days. The surgeon picks up the nerve at the base of the skull, near where it exits the brain, before carefully following it down one side of the neck (there are two branches, one on each side) and through the chest and abdomen, where it branches out to meet the organs.

Jayaprakash shows me a photo of a recently dissected nerve. It looks like a yellowish, slightly frayed piece of rubbery string, just under a foot (30 cm) long and with stumps where its main branches would have been. Each stump has been tagged with a colour-coded stitch – red for the heart, blue for the lungs, and so on – and a dye has been added to the underside, so the scientists can keep the nerve the right way up.

Jayaprakash explains why they cut the nerve off just after the major junctions. Once a branch leaves the main highway it splits into two every half a millimetre (two-hundredths of an inch), on average. On the branch to the heart, things get particularly complicated. 'If I showed you the nerve with all the branches, you would think it was a web,' says Jayaprakash. By the time it gets to the gut, he adds, 'it looks like a ball of spaghetti.'

Once the nerve has been extracted and labelled, it is put into a tiny CT scanner which provides a kind of 3D X-ray that reveals the outline of the fascicles, a series of tiny tubes that separate different fibres from each other within the nerve trunk. With a bit of processing, this provides a colour-coded 3D video that simulates flying through the nerve from the neck. Jayaprakash shows me a video clip from a nerve that has already been scanned. It looks like a bundle of flexible drinking straws that occasionally change their position within the larger nerve and often split into two and head off in another direction.

What the CT scan doesn't show is which type of fibres are within each fascicle – whether they are body-to-brain sensory pathways or brain-to-body parasympathetic ones. That's important to know if you want to target a particular organ or pathway without involving the others. To find out, the next step is to encase the nerve in wax, slice it thinly and stain it with fluorescent dyes that only stick to certain types of nerve. This will allow the scientists to distinguish thick, fast-conducting fibres from skinny, slow-conducting ones, and to tell apart those that send messages from the body to the brain from the ones that run from brain to body. When that is done for all thirty of the donated nerves, the final stage will be to create an interactive 3D map showing what kinds of nerve fibres go where, and in which direction they send signals.[3] There are dozens of nerves still to be dissected and analysed, but there are reasons to think that it's worth all the effort.

Initial studies using the same method in pigs have shown that fascicles for different organs tend to bunch together on one side of the nerve just before exiting at the major branches.[4] If the same is true in humans, it should be possible to target stimulation for certain organs or pathways, and to avoid others. A pilot study, also in pigs and using an adapted stimulator, showed that the lungs could be stimulated without affecting the heart. On the other hand, because the organ branches only seem to bunch together as they near their exit junction, it might be tricky to selectively target the stomach and intestines using a stimulator in the neck – you'd probably have to stimulate much closer to the stomach. This is a more invasive procedure, but one that's being tested to manage interoceptive hunger signals as a lower-risk version of gastric bypass surgery (see Chapter 4 for more on this).

On the other hand, there is a clear separation at neck level between bottom-up messages from the organs, which carry bodily signals to the brain, and the top-down, parasympathetic nerves that are in charge of the 'rest and digest' response. This is good news, because in the few conditions in which vagus nerve stimulation is currently used, including epilepsy and severe depression, the stimulators are implanted in the neck. But the technology has been limited by the fact that when an implant is attached to the nerve in the neck via an electrode, all the fibres in the nerve are stimulated at once – all 100,000 fibres in the left branch of the nerve, with no way of controlling where the current goes.

Because of this, side effects range from sore throats and coughs to shortness of breath, nausea and a potentially dangerous drop in heart rate. These can be managed by turning down the stimulator, but Stephen Liberles, a neuroscientist at Harvard University, told me, in many cases this also gets rid of the benefits. The team in New York hope that when their map is complete, it will lead to the design of stimulators that can target specific organs while leaving others untouched. This would make it easier to devise treatments that work, and to avoid side effects.

Stimulating discoveries

Vagus nerve stimulation may have attracted a lot of attention in recent years, but it isn't actually all that new. Implanted vagus nerve stimulators have been used for decades to help reduce seizures in people with epilepsy who haven't responded to other treatments, and more recently in treating severe depression.

And for epilepsy and depression, it does work – at least for some people, and some of the time. What makes it a treatment of last resort is the fact that it requires expensive surgery and that we have little idea *how* it works – let alone who will be most likely to benefit.

The technology only exists at all thanks to a series of happy scientific accidents. The first occurred in the late nineteenth century when a neurologist called James Corning invented a device to stimulate the carotid artery in the neck as an experimental treatment for epilepsy. The idea was that the device would boost blood flow to the brain, which he believed would reduce seizures.[5] It worked, but not because it changed blood flow to the brain. It worked because it also stimulated the vagus nerve, which runs alongside the carotid artery in the neck. After much experimentation and several clinical trials, implanted vagus nerve stimulators were approved as a treatment for epilepsy in 1997.

Then came a second accidental discovery, when people with the implanted stimulators who had depression as well as epilepsy began to tell their doctors that the stimulation made them feel happier. Further studies confirmed the link between vagus nerve stimulation and mood, and the technology was also approved by the US Food and Drug Administration (FDA) as a therapy for treatment-resistant depression in 2005.

Several decades later, we still know little about how these treatments work, other than that they probably stimulate bottom-up sensory pathways to the brain and, in the case of epilepsy, smooth out the errant nerve-firing patterns that cause seizures. Beyond that, it's all a bit of a mystery, so it's hard to predict who it will work for. It helps 40 per cent of people with epilepsy, and is worth trying in severe cases, where seizures can be life-threatening and all drug treatment has failed. The same can be said for depression, in cases where drugs have failed and people may be at risk of suicide. In those circumstances it's worth a try, but there's plenty of room for improvement.

According to the neurosurgeon Kevin Tracey, these problems don't apply to all forms of vagus nerve stimulation, including the kind he works on, which targets inflammation, increasingly thought to be one of the most important ways in which interoceptive messages can affect our state of mind. And as Tracey discovered in the early 2000s, it's all managed by a dynamic flow of information in both directions along the vagus nerve.

Tracey discovered the link between the vagus nerve and inflammation thanks to yet another happy scientific accident. In the early 2000s, he was studying whether an anti-inflammatory drug, injected directly into the brain, could reduce inflammation after a stroke to prevent further damage. The answer to that question was yes, but the drug also reduced inflammation throughout the whole body. This was surprising; large molecules like this particular drug can't pass between body and brain through the blood, so how was the message getting through? After a few years of experiments, it turned out that the body was getting the memo to reduce inflammation via the vagus nerve.

At the time, it was a totally unexpected finding. As Tracey described the moment to *New Scientist*, 'Scientists don't say "Eureka" any more, they say "Holy shit", and that's what happened.'[6]

What he went on to call 'the inflammatory reflex' is triggered when, in response to a perceived threat, white blood cells release messaging molecules called inflammatory cytokines into the blood. Sensory neurons in the vagus nerve detect these signals and speed them to the brainstem, which responds by sending a message back down the parasympathetic branch of the vagus nerve to the spleen, which sends out anti-inflammatory signals to calm things down.

This might sound like an enormous waste of time, but inflammation is more interactive than the idea of an on-off switch makes it sound. Tracey uses the analogy of a hermetically sealed house, fitted with central heating and an air conditioning unit. When the house gets too hot there are two options: you can turn off the heating and wait for the house to cool down, or you can leave the heating on and add cool air from the air conditioner until it's more comfortable. Ignoring the implications for energy bills and concerns about climate change, the second approach makes more sense; it avoids wild swings between too hot and too cold, which you'd get if you turned one system off when the other was on. 'If both are on, you can get fine-tuned control,' says Tracey. 'I think that's how the nervous system works.'

When the system gets out of balance, though, it can prove disastrous. Too little inflammation and we are at risk of infections that won't clear up and injuries that won't heal; too much and we are at risk of sepsis or a cytokine storm, an out-of-control immune response that can be more deadly than the initial infection (this was seen in many of the people most severely affected during the early days of Covid-19). An overactive immune response can also cause many autoimmune disorders, including rheumatoid arthritis and Crohn's disease – conditions that are increasingly linked to mood disorders including depression, and for which the available drugs are imperfect at best.

Having identified the inflammatory reflex, Tracey explored whether vagus nerve stimulation could be used to help calm down overactive immune responses. He has done much of his research into this at the Feinstein Institutes, where Jayaprakash and Zanos are mapping the vagus nerve and where Tracey now serves as director.

One thing that becomes immediately clear when we speak is that Tracey is fed up of people thinking of all forms of vagus nerve stimulation as a shot in the dark. 'It's wrong to talk about vagus nerve stimulation as some sort of generic activity,' he says. 'For epilepsy, nobody knows how it works. But that's not the same as inflammation, where we know what we're doing. We understand the mechanism – arguably, better than we understand the mechanism of some drugs.'

The main difference, he tells me, between the stimulation used for epilepsy and what he uses for inflammation is that you don't need anything like the same amount of current. The anti-inflammatory pathway involves the easy-fire, fatter nerve fibres that are much easier to trigger, he says, which means that the relevant pathways can be activated with a lower level of current, and far fewer neurons are caught in the crossfire. And while it isn't possible to select only the nerve fibres running to the spleen, Tracey doesn't think that's a major barrier to using it as a treatment, for the simple reason that 'it works'. He refers me to the first clinical trial for vagus nerve stimulation in rheumatoid arthritis patients, published in 2016, which showed that the technology not only decreased inflammatory markers in the blood, but also reduced symptoms and improved quality of life. Similar studies have shown success in Crohn's disease, he says.

'We have patients now – eight years later – who are in complete remission and drug-free,' he tells me. He pauses to adjust his computer screen so I can see the corner of his office, where a walking stick is propped against the wall. 'One patient gave me her cane,' he says. 'She doesn't need it. The first patient was implanted [with a stimulator] in 2011 and he's still in remission, taking no medication.'

A phase three clinical trial in 250 people with rheumatoid arthritis has just finished[7] and, while the findings are under wraps when we talk, Tracey hopes that it will lead to the approval of vagus nerve stimulation as a treatment for rheumatoid arthritis and for other autoimmune disorders. A large clinical trial is also under way for depression, which aims to implant more than 6,000 stimulators into people with depression and track their symptoms over five years, with results expected by 2030. Meanwhile, a team of researchers in the US and Australia is embarking on a study that hopes to capture what implanted vagus nerve stimulation does, by measuring what happens in the organs and the brain at the same time. The study aims to narrow down which pathways in the vagus are stimulated, and to shed some light on how it works – and on why it sometimes doesn't work.

No surgery required?

Most people aren't on the market for this kind of surgery for everyday levels of stress, low mood or inflammation, but several companies have stepped into the gap in the market to offer non-invasive versions that aim to stimulate the vagus nerve through the skin. One such stimulator, the GammaCore, a handheld device that aims its current through the skin of the neck, has been approved as a treatment for migraines and cluster headaches. As with the implanted versions, these devices do seem to reduce the number and severity of headaches in some people, some of the time, but only when used consistently.[8,9]

Most of the other stimulators that are available to buy target a sensory branch of the nerve that runs close to the surface of the skin in the ear and clip onto the tragus – the hard flap of cartilage where the ear meets the cheek. According to a recent review of the evidence, this is one of the best places in the ear to find vagus nerve endings.[10] There is some encouraging early evidence that non-invasive stimulation may help to relieve symptoms in some heart arrhythmias[11] and reduce inflammation after heart failure,[12] but for the most part the jury is still out on whether, and how, these stimulators work.

The main issue is that it isn't clear how much of the current that leaves the device actually reaches the nerve, and how much is scattered or absorbed by the skin, cartilage and muscle on the way. There's evidence to suggest that at least some current does get through – some studies have reported increases in activity in the same areas of the brain as can be found using implanted stimulators. Other studies have measured changes in various physiological parameters that the vagus nerve is known to be involved in, including inflammatory markers and heart rate. But whether this is a direct result of the stimulation is difficult to say. 'There's no evidence when you stimulate through your ear – or your neck – that you are directly stimulating your vagus nerve,' says Tracey.

Even if they do stimulate the vagus, going through the skin means that it is even more difficult to target specific branches of the nerve than if you implant an electrode that surrounds the whole nerve shaft. 'I think this whole idea that you just touch the vagus nerve and it doesn't matter which nerve you're touching, you're going to activate all of it, seems a little archaic, to be honest,' says Liberles. 'I think there's a ton of therapeutic potential but there's also a lot of noise.'

Meanwhile, we know little about what many of the popular lifestyle hacks that are bandied around as sure-fire ways to trigger the vagus nerve do to the nervous system. A cold-water plunge may well activate the parasympathetic arm of the vagus nerve, which reduces heart rate, but it also engages the sympathetic nervous system, which can briefly send it through the roof. The same can be said for exercise. Saying that vagus nerve activation is responsible for these effects is simplistic at best. 'It seems that people who do many of those things have less inflammation, but is that because you've activated fibres in the vagus nerve that control inflammation? No one knows!' says Tracey. 'It's not fair to advertise that we understand all this without explaining that there's a lot more we have to learn.'

For now, then, the answer to 'What's happening in vagus?' is 'a lot'. And while we're well on the way to understanding how we are wired, those wellbeing hacks, whether they're expensive or free, aren't quite as cut and dried as they seem.

Secrets of the superhighway

To return to our highways analogy, the fact remains that while drawing roadmaps is useful, whether for the tangled vagus nerve or the slightly more straightforward spinal cord pathway, knowing what kind of traffic is moving along those roads is just as important. A huge amount of information is constantly being shared between body and brain, and to truly understand how our bodies speak to our minds, we need to listen in to hear what they are talking about. And to know that, we need to find out what all these sensory nerves are sensing – and how.

The equivalent information regarding our external senses – sight, smell, and so on – was worked out long ago. Receptors at the back of our eyes detect particular wavelengths of light, for example, and different taste receptors on the tongue decode various molecules in food as sweet, salty, bitter, and so on. It has proven trickier to do the same for the inner senses, partly because they don't come concentrated in obvious sense organs; there is no equivalent of the eye that picks up the sense of feeling slightly worried, for instance. But over the past decade and a half, new technologies have allowed scientists to start tracking down our interoceptive sensory receptors. And some of them are really quite bizarre.

First, the more obvious ones: our bodies are packed with sensory nerves that detect pain, pH, toxins and pressure, all of which show up in fairly unsurprising places, such as the muscles, blood vessels, gut and heart. These have been known about for decades, although in some cases the details only came to light much more recently. For instance, while we knew that our bodies were able to detect pressure and stretch, we didn't know how until 2010, when Ardem Patapoutian at Scripps University discovered two large receptors, shaped like propellors that have been squashed from above into a cup shape. These receptors (called piezo1 and piezo2) detect pressure and stretch by flattening out under pressure. This opens an ion channel in the membrane and causes the neuron to fire. Piezo receptors have since been found in tissues all over the body, from the lungs to the bladder and the skin, and have proven to be so important for our understanding of the senses that Patapoutian was awarded a Nobel Prize in 2021 for his discovery.

In addition, as recently as 2015, it was discovered that specialised cells in the gut lining don't only speak to the brain via the blood vessel slow road; they are also wired into the vagus and spinal nerves. These high-speed lines of communication, it turns out, update the brain on what you've eaten within milliseconds, in ways that can affect appetite, mood and motivation.

Both of these breakthroughs were possible thanks to developments in genetics that allow us to work out what particular cells are detecting. While all the cells in the body carry the same DNA, each cell type uses only a small section of DNA to do its job. To replace the roadmap analogy with a food-based one for a moment, it's as if every cell shares the same recipe book, but each cell type – kidney, heart, and so on – only ever cooks its own signature dish. By finding out which ingredients are in a cell and where that cell is found in the body, scientists can work out what it's cooking and why.

Liberles says that for the vast majority of the newly discovered types of sensory receptor, we have no idea what they are sensing. He calls this the 'dark matter of the vagus nerve', a term he also applies to the nerves in spinal pathways, which contain ten times more sensory neurons than the vagus.

We know that the universe is made up of a mixture of dark matter and dark energy, but we have absolutely no idea what these are formed of. Something similar can be said for the interoceptive system, says Liberles. 'There are additional body–brain physiological pathways that are controlling physiology and behaviour that are dormant to our knowledge,' he told me. 'What are those neurons doing?'

As scientists begin to figure it out, it seems that these neurons are doing all kinds of surprising and unexpected things. For example, those found in fat can detect pressure and stretch and can also detect light at wavelengths that are invisible to the naked eye.

Feeling fat

Fat has long been known to be involved in signalling fullness to the brain via the hormone leptin. But more recently, it has become clear that fat is not just padding and hormone storage – it's also a sensory organ.

Of all the things that fat could sense, light wasn't regarded as a likely candidate. But then Richard Lang at the Cincinnati Children's Hospital found light-sensitive proteins sitting within the cell membranes of fat cells in mice, where they detect violet and blue light.[13] These frequencies of light are invisible to the light receptors in our eyes, but experiments in mice reveal that light at those wavelengths can penetrate the fur and reach at least as far as the fat under the skin.

While we are not mice, this matters to us for two reasons. First, Lang says it's highly likely that all mammals, including humans, have the same light-sensitive receptors in their body fat as mice do. And second, these receptors seem to be important for staying metabolically healthy. If mice that lack light receptors in their body fat get cold, they are less able to use their fat reserves to keep warm. And if they miss a meal, they struggle to break down fat to burn as fuel. Worse still, mice that have all the right receptors but lack access to the full spectrum of natural daylight end up with similar problems.

This is worrying, Lang believes, because most of us spend most of our time indoors, living a lot like light-deprived laboratory mice. Modern windows filter out short-wavelength light, and artificial lighting doesn't produce enough to stimulate the proteins; whether this plays into the obesity crisis remains to be seen, but Lang thinks it's a possibility. 'I do expect that these new light-sensing pathways will be part of the explanation for the accelerating incidence of metabolic disease,' he says.

A chronic lack of light might have a negative impact on mental health, too. Lang points out that when we don't get enough light – or get the wrong kind of light at the wrong time of day by staying indoors all day then staring at screens in bed, for example – it messes up everything from metabolism to mood. Light-sensitive fat cells, Lang suspects, are the tip of the iceberg. 'I suspect we will learn that mammals are systemically light-sensing – and that this is of fundamental importance for normal physiology,' he says. And perhaps, for feeling our best, too.

There's also evidence that fat has feelings in a more direct sense. It has been known for some time that it is shot through with sensory nerves that report to the brain via the pathway in the spinal cord. What they sense hasn't been clear, and most research into fat–brain signalling involved hormones secreted in the blood. It later turned out that hormones also take the fast route to the brain along the sensory nerves, which made sense; what makes less sense is the recent discovery that the neurons running through fat also contain piezo receptors – the ones that detect touch, stretch or pressure. And there aren't just a few here and there – piezo receptors are as common in the fat sensory nerves as they are in the skin.

Unlike the sensory nerves in the skin, which respond to touch, we can't consciously feel the output of the piezo receptors in our fat cells – but that doesn't mean it doesn't affect us. For whatever reason, the brain unconsciously keeps track of how our fat is getting squashed or stretched. One explanation is that this information allows it to estimate the amount of fat coming in and going out of storage. The neurons connect to the fat cells and to the blood vessels that bring new fat to be stored and take away the fat to be used as a source of energy; perhaps knowing how stuffed and stiff the existing fat cells are and how full of fat droplets the blood vessels are, it can keep an eye on its energy stocks as they fill up or get depleted. So far, though, Patapoutian admits, we don't know exactly what the neurons are sensing.

These few examples show that our bodies are sensing more about what's going on inside us than anyone previously suspected. In fact, when Patapoutian and his team were looking for piezo receptors in fat, the original plan was to rule them out. 'We started with fat, thinking that was the last place we would think mechanical force would be important,' says Patapoutian. 'It's the one place where it's all chemical signalling, not mechanical – and we were very wrong.'

As well as the sensations we don't expect to find, there are many we do know about – because they are consciously available to us, but we don't know how they are being detected. How our muscles detect tension is one example – we know when we are stiff or tense, but how is that information picked up, and where does it go? Similarly, we have very little idea what is being sensed in our fascia, the wrapping containing our organs and muscles, that was recently found to contain a similar quantity of sensory neurons as our skin. Research suggests that stretching the fascia stimulates cells within the tissue to release anti-inflammatory molecules, but how this is sensed by the nerves and what the brain gets to hear about it isn't yet known. 'There are whole new waves of biology to uncover,' says Liberles.

Directing traffic

Just as the brain is nothing without the body, all this information would go to waste without the brain to sift through the noise and work out which is most important. That, after all, is what the brain evolved to do.

At this point, it feels important to reiterate my general point about the body–brain split – or rather, the lack of one. The brain is neither the starting point for our mental experiences nor the end point for our body's live updates. The brain isn't the control centre of the mind; it is more a collaborative hub where body and brain work together to decide what is the most sensible plan of action, given the current state of affairs.

Support for this view comes from recent evidence that the so-called 'inputs' to the brain are not the passive carriers of information that they have long been presumed to be. Studies of real-time activity in the spinal cord have found that, rather than staying quiet unless there's something to report (such as an injury or change in temperature), the spinal cord – like the brain – generates its own background chatter, through which it communicates in local networks[14] and with the brain.[15] This was only discovered recently, when a handful of scientists worked out how to take real-time images of activity in the spinal cord. This is challenging because the movements of the body's organs as the heart beats and the lungs expand make it difficult to get a clear image. They eventually managed it by imaging at neck level, where there is less movement to contend with.

Intriguingly, there's evidence that activity in these spinal cord networks adapts with training. A study from 2014 found that when expert meditators were asked to focus their attention on a specific body part, there was significantly more activity in the section of the spinal cord that corresponded to the body part on which they were directing their attention, with less body-part-specific activity when novice meditators were asked to do the same thing. This raises the intriguing possibility that when a guided meditation invites you to focus on the strength in your legs or the tension in your neck, what you can feel isn't in your imagination – it's an actual sensation that, with practice, can become more vivid and easier to switch on and off.[16]

It's early days for spine–brain imaging, but it raises the possibility that we might one day be able to look at activity across the whole body, and to spot – and begin to fix – any errant activity or blockages that may be causing problems, such as chronic pain. According to Nawal Kinany from the University of Geneva, spinal resting state activity is a crucial part of the body–brain puzzle that neuroscience has so far all but ignored, and that is ripe for further research.[17]

Similar background chatter is almost certainly going on in the vagus nerve, too. But if the spinal cord signals are difficult to disentangle from the background noise created by the organs, those in the vagus nerve are nigh on impossible – at least in humans. Studies in mice, though, have provided some clues. So far, it looks like the vagus, which has far fewer neurons than the spinal cord, keeps things fairly simple. Incoming nerves are tagged with three basic pieces of information: what organ the nerve is coming from, which part within the organ, and what kind of information is being sent (whether stretch, a particular chemical, temperature change, and so on). It is, according to the work of Rui Chang at Yale University, a clever piece of coding that squeezes a lot of information into a small number of nerves, so the nervous system can start making sense of the signals before they reach the brainstem.

And so to the place where all three bottom-up pathways meet. Once presumed to be a relay station on the way to processing centres further on, we now know that the brainstem is a key point at which signals can be boosted or turned down. A recent paper in *Nature* found that a particular region of the brainstem where the vagus nerve feeds in, the nucleus tractus solitarius, acts like a dimmer switch for inflammation, dialling it down if the coast seems clear and turning it up if the challenges keep coming, particularly if supporting evidence starts coming in via the blood.[18] Other studies suggest that parts of the brainstem process and regulate interoceptive signals involved in pain, heartbeat and breathing rate. Brainstem processing doesn't involve thinking, but we certainly feel the knock-on effects if body signals get boosted there, and what happens is important for our state of mind, even when we are not consciously aware of it.

Signals that aren't dealt with in the brainstem carry on up to the thalamus – a key organisational hub in the middle of the brain. From this point, it's difficult to draw lines from one brain region to the next because connections go in so many directions, but the key regions include those involved in memory (the hippocampus), emotional processing (the amygdala), attention and control (the prefrontal cortex), and weighing priorities (including the cingulate cortex) (see Figure 2).

Then there's the insula, which is possibly the most important region of the brain you've never heard of. It's difficult to pinpoint on 2D diagrams, but to get a rough idea of where it is, imagine you could push the fingers of both hands into your brain just above each ear and pull apart the topmost layer of the brain in the gap where the two most obvious lobes meet. If you peered into the canyon between the folds, you would find the insula tucked away at the bottom. There's one on each side of the brain.

Its name may derive from the Latin word for 'island', but the insula is anything but isolated from the rest of the brain. At one end, towards the back of the brain, it receives updates from the body about what's actually happening down there. At the other, it takes in predictions about what's probably happening in the body based on previous experience, with the help of those regions in the brain that are involved in memory, emotion and alertness.

It's here, in the insula, that the magic happens. Top-down prediction meets bottom-up signalling, and the brain somehow makes a call on which is likely to be the

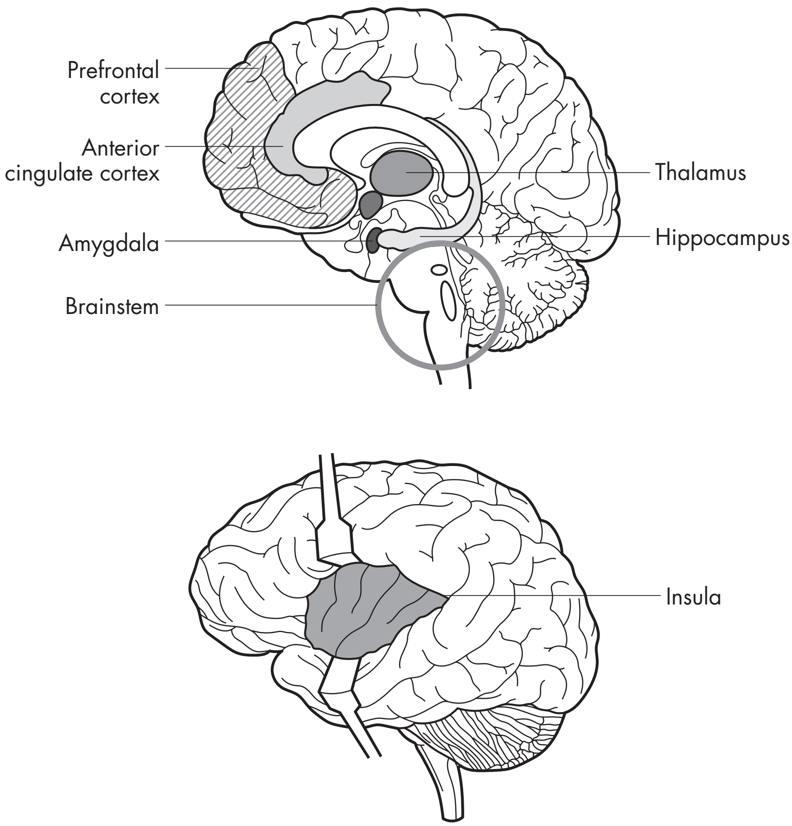

Fig. 2: **Interoception in the Brain**

Interoceptive signals pass through the brainstem before being sent to the thalamus: a switchboard for signals that need further processing. The thalamus sends signals to the insula, and loops in regions involved in memory (hippocampus), emotional processing (amygdala), attention and control (prefrontal cortex) and weighing priorities (anterior cingulate cortex). The insula puts it all together to make sense of what it means. It's this that dictates how we feel and what we are motivated to do next.

most reliable. Some scientists argue that the default position is to trust the brain, while others argue that internal signals are more likely to be the go-to trusted source if there is any uncertainty, because the state of the body is what the brain cares about most. Either way, it probably varies from one moment to the next, and between different people. What we know for sure is that somehow, amid all the noise, a signal emerges that adds up to a sense of me, here, now – our own private virtual world.

Armed with an increasingly detailed map of the highways and byways that are involved in building this virtual world, scientists are beginning to understand how problems with the map, or a change in traffic conditions, can leave us worn out and running on empty. Lacking in energy is a key symptom in many mental and physical health disorders, but while it's part of a system that drives us to solve an underlying physiological problem, it's also one of the most difficult symptoms to address. Part of the issue is that the question of what it means to 'have energy' has been essentially ignored since the beginning of medical science. Now, though, researchers are beginning to understand what it means. The feeling of being full of pep is an interoceptive assessment of how much energy we have to spare at any particular moment. Thankfully, as we'll see in the next chapter, this key part of our inner sense is finally being brought into the spotlight – and there are important implications for how we understand what it means to be healthy.

3

Power up

Life, energy and the emerging science of chi

'Being an adult is all about being tired, telling people how tired you are, and listening to other adults tell you how tired they are.' Nobody knows who is responsible for voicing this eternal truth, but whoever it was forgot to tell Bob Arnot. After a decades-long career as a doctor in New England followed by a stint as a TV news correspondent, he was well into his sixties when he decided to take up paddleboarding, looking for a low-impact, full-body workout. Within a few years he was entering – and winning – international competitions. Now seventy-six, he's still going strong. When he's not out on his board, he's ski-mountaineering, mountain biking, or writing and recording classical orchestral symphonies. And when he's not doing any of those things, he works as co-CEO and chief innovations officer for a global non-profit.

Frankly, it all sounds exhausting. But when we meet online, the man once known to NBC News audiences as Dr Bob looks anything but tired. He pops up on my laptop screen, rosy-cheeked and wearing a Lycra bodysuit from an afternoon ski-mountaineering workout. 'Skimo' involves climbing a mountain wearing specially adapted skis covered with removable grippy 'skins'. At the summit, you remove the skins and ski back down. It's anything but a gentle stroll, but Arnot insists that this had been a low-intensity day. 'I went at a fairly slow pace, and I only did one lap,' he tells me.

There aren't many people Bob's age – or indeed any age – who would regard skiing up a mountain as a rest day. In fact, for a large proportion of us it's a struggle to summon the energy just to get through the day. According to a recent estimate based on over 1,000 people from 32 countries, more than 1 in 5[1] otherwise healthy people complain of being tired all the time.[2] It has become so common as a reason to seek medical attention that doctors have come up with a shorthand for it: TATT. Much of the time, medical science can offer very little except advice to get more sleep, and perhaps a blood test to rule out any obvious nutritional deficiencies. And so, on we go, dragging our feet from one caffeine hit to the next.

From a scientific point of view, the question of why we all feel tired all the time is an important one. Why is a lack of energy such a problem in modern life? It can't be for the lack of fuel; for most of us, calories have never been easier to come by. According to the laws of physics, and specifically the first law of thermodynamics, which states that energy can neither be created nor destroyed, we should be positively bursting with the stuff. And given that the average adult spends 70 per cent of their time sitting or lying down, most of us probably aren't in danger of burning it all off.

The short answer is that the amount of energy we have isn't as simple as reading the gauge on a fuel tank. Our energy levels are an interoceptive feeling: a body–brain estimate of how much energy is available in the body, how much is accounted for, and an educated guess of how much an activity will require and whether we can spare the energy to do it. If the answer is no, as the rules of allostasis dictate, the body–brain system needs to adapt, which we become aware of as a lack of motivation or energy. Whether we feel full of pep or dead on our feet is the result of an ever-shifting body–brain estimate of whether we have energy to spare or whether we should conserve what we have.

As with all things interoceptive, expectations and interpretations matter just as much as the dry facts. If we feel great, it might be because we have loads of energy to spare or it could be because the outcome of the body–brain conversation is that what we're doing is a worthy investment in terms of our survival. On the other hand, when we don't feel great, it might be because we really are running on empty. Or – more likely – it's a prediction or interpretation issue: perhaps what we have in stock is earmarked for something more urgent. Or it could be that the future looks uncertain, so it makes sense to be frugal for the time being. The reason that our energy levels can seem so fickle is that the balance between spending and saving energy is always changing.

Seeing energy as an interoceptive feeling explains why 'boosting your energy' isn't as simple as taking a supplement, drinking more water, or trying whatever trick is currently going viral online – contrary to what the well-being industry would have you believe.

Instead, it's a matter of working out whether the problem is one of supply, demand or over-cautious budgeting – and doing something to correct it. Understanding what energy is and decoding the interoceptive pathways that give us an estimate of our energy level opens up new ways of intervening.

Force of nature

The sliding scale between feeling great and feeling exhausted is something that psychologists call 'subjective vitality'. Surprisingly, given how important it is for living a good, healthy and fulfilling life, Western medical science has spent little time trying to work out what it actually is. While Eastern traditions have been built around the idea of energy as the key to health ('chi' in Chinese medicine or 'prana' in Indian ayurveda, for example), Western medicine was put off by the fact that this invisible force can't be measured, and focused instead on things such as broken bones, infections and tumours which could be seen, measured and, when necessary, surgically removed.

While this approach has undoubtedly led to a huge improvement in life expectancy, it has its limitations. For one thing, it has led us to a place where we know a lot about what it means to be ill, but little about what it means to be healthy.[3] As a result, many people spend the extra years that modern medicine has added to our lives playing whack-a-mole with age-related diseases, rather than enjoying a healthy, energetic retirement like Bob Arnot. Statistically, the chances of bucking the trend aren't great; according to one recent global estimate, people outlive their healthiest years by an average of nine years.[4]

This approach to health didn't sit well with Doug Wallace. As a young researcher at Yale in the 1970s, he couldn't help noticing that while physics was making great leaps forward in understanding how energy and matter interact to make the world work, the biological sciences were carrying on as if energy had nothing whatsoever to do with health. 'I couldn't get my head around that all we talked about in medical science was structure and anatomy, and nobody seemed to be talking about what it means to be alive, what made us animated,' he recalled in 2018.

Wallace illustrates his point with a stark example. Imagine two human bodies lying next to each other, one living and one dead. Both are anatomically perfect, and neither shows any evidence of disease; the only difference between them is that one body has energy flowing through its cells and the other doesn't. Life isn't about having the right body parts stuck together in the right order, Wallace believes; it's about whether those parts are animated by the flow of energy. 'Life is the interplay between structure and energy,' he argued in a 2018 paper – and to really understand it, we need something more akin to a science of chi.[5]

Far from being a purveyor of woo, Wallace is a respected geneticist who channelled his fascination with energy into understanding the mitochondria – the cellular compartments widely known as the powerhouses of the cell, for their role in releasing the vast majority of the energy we need from the food we eat. At a time when biology was obsessed with what the newly discovered structure of DNA meant for health and disease, Wallace followed his own path and went on to pioneer the study of mitochondrial medicine, looking at how energy production problems in the mitochondria affect health.

This still involved DNA, but not the DNA in the nucleus of our cells (half of which we inherit from our mother, and half from our father). He was interested in the separate set of DNA that is found in our mitochondria. As we saw in Chapter 1, until a couple of billion years ago mitochondria were free-living bacteria. When they moved into their host permanently, they handed over most of their DNA but retained thirty-seven genes out of their original thousand or so, many of which are directly involved in releasing energy from food in the presence of oxygen.

Wallace wanted to know if mutations in this tiny pool of DNA were linked to health and disease. He reasoned that if energy is as important in keeping humans alive as he assumed, it would make sense if problems with its release played a role in disease, and the fatigue that often accompanies it. Sure enough, having discovered that we inherit our mitochondria only from our mother, Wallace identified several mutations in mitochondrial DNA that cause rare inherited diseases that only pass down the maternal line. Many of these diseases show up as problems with the brain and the rest of the nervous system, which have the highest energy requirements and so struggle most without healthy mitochondria.

In the early 2010s, a young researcher in Wallace's lab called Martin Picard became fascinated by the connection between mitochondria and the mind. Studying people with mitochondrial diseases, he says, 'gave us a unique opportunity to ask what happens in the human mind and body when the mitochondria cannot provide enough energy. The answer is that people don't feel good.'

This is relevant to interoception for three important reasons. First, if we feel exhausted when mitochondria are struggling, it suggests that there is a specific interoceptive signal flagging a literal lack of energy in our cells. Second, research suggests that there are many routes to malfunctioning mitochondria, many of which are linked to lifestyle, ageing and our changing state of mind. This brings us to the third, and most important, reason: if we can find out how to read the body's distress signal and work out how to fix the problem, we might be able to dig deeper into our energy reserves and live our best lives.

Like Wallace before him, Picard couldn't understand why no one was making the link between energy, health and the mind. So he, too, founded a new scientific discipline: mitochondrial psychobiology,[6] setting up a lab at Columbia University to explore how genetics, stress, diet, exercise, rest and ageing affect mitochondria and the mind. By studying isolated cells in the lab and people in airtight metabolic chambers, his aim is to make the link between cells and feelings, and to understand how tweaking one might improve the health of the other. 'If we could connect this immaterial substance of life with the molecular biology of mitochondria and energy transformation, I suspect there's something quite important there,' says Picard.

What mitochondria want

In a very real sense, all our energy comes from the mitochondria. There are trillions of them in the human body – hundreds to thousands in each cell, depending on how much energy they need to supply (heart and liver cells have the most). Only red blood cells, which deliver the oxygen to feed the mitochondria in all our other cells, have none of their own.

When you get into the details of what mitochondria actually do for us, it's easy to see why anyone who studies them becomes fascinated. The metabolic scientist Herman Pontzer describes them as 'alien life forms' that perform 'the ordinary miracle of turning dead food into human people every day'.[7] Nick Lane, a biochemist who studies mitochondrial evolution at King's College London, is so enchanted by them that he has written three books on their inner workings. 'If we were to iron out all the mitochondrial membranes in the body, so they were flat, they would cover an area equivalent to about four football pitches – all charged with the power of a bolt of lightning,' he writes. So if we really want to feel as much of that enormous power as possible, it makes sense to find out what mitochondria need to do their job.

Mitochondria are not especially picky about their working conditions. As long as we are breathing, providing a steady flow of oxygen through the blood to the cells, they are equally happy whether they are burning carbohydrates, fats or proteins. With a few adjustments they can switch from one fuel to another – a bit like a wood-burning stove that can also handle oil, coal and gas.

The use of 'burn' is more than just a metaphor here.

Thanks to some ingenious experiments involving a guinea pig, some charcoal and some ice,[8] the eighteenth-century chemist Antoine Lavoisier demonstrated that, chemically speaking, our bodies' use of food is the same process as combustion. He did this by designing a device called an ice calorimeter, which looked like a fat steel bottle balanced upside down on a tripod. Inside were three compartments, small, medium and large, stacked inside each other. In the innermost compartment he placed the guinea pig. The next compartment was packed with ice and was fitted with a tap at the bottom to collect the water that was released as the ice melted. The outermost chamber was packed with snow to insulate the ice, so that it only melted from the guinea pig's body heat and not from the heat of the room.

By comparing the rate at which the guinea pig melted a certain amount of ice compared to a burning lump of charcoal, and measuring the amount of carbon dioxide released by each, Lavoisier was able to show that burning and metabolism were exactly the same. Our bodies are essentially furnaces. As Lavoisier put it, 'animals which breathe are really combustible substances burning and consuming themselves'.[9] We now know that what our cells are burning isn't ourselves, but the food we eat.

The key difference between our cells and a burning flame is that mitochondria don't release all the energy in one go. The 'burning' takes place as a series of tiny chemical steps in which much of the energy released is harnessed in a chemical form that the cell can use, with only a little given off as heat.

These chemical steps – the Krebs cycle and the electron transport chain* – have to happen in order, and they can't be rushed. You can't just shovel in more fuel and expect more energy to come out the other end; in fact, experiments suggest that if too much fuel arrives at once, the production line gets jammed and energy release grinds to a halt.[10] When that happens, the cell starts storing the excess fuel for later. All this activity consumes energy at a time when the mitochondria are taking a break, with the consequence that a glut of fuel leads to less available energy, rather than more.

From the point of view of a person who has just overwhelmed their mitochondria by taking on too much fuel at once, it's not too much of a problem if it's the occasional slap-up meal followed by an afternoon nap. But if too much food keeps coming, day in, day out, it can prove disastrous for our energy levels as well as our waistlines. Studies suggest that high-sugar and high-fat diets lead to inefficient mitochondria[11,12] and sleepy people.[13] And despite the popular wisdom that eating a sugary snack can help perk you up, controlled studies have shown that such treats are more often followed by a wave of fatigue and low mood.[14]

Too much food, then, drains our energy at the source, and stress does the same. As well as producing energy, mitochondria produce steroid hormones, including cortisol – widely known as the 'stress hormone'. This is actually

* The ins and outs of these fascinating, but complicated, reactions have been traumatising biology students for generations. Anyone who wants to know the details should read *Transformer* by Nick Lane (Profile Books, 2022).

a misnomer; cortisol is more of an 'action' hormone that mobilises energy whenever we need a small boost (to help us get up in the morning, for example) or a large one, to power a quick getaway from danger. Made by mitochondria in the adrenal gland, it is carried in the bloodstream to the mitochondria in all the other cells in the body, which respond by upping their energy production. It's no wonder that stress feels so draining; it literally saps our energy at the same time as it sends out a call for more. According to one of Picard's recent studies, it makes cells burn through fuel 60 per cent more quickly.[15]

If the high demand continues, at some point it becomes unsustainable and something has to give. Long before we get to the point where we are actually running out of fuel, allostasis kicks in to make sure that we can survive this new normal, with its unusually high energy demands.

The instruction to save energy can come from the brain, but it can also come from the cells themselves. When cells sense an uptick in energy usage, they save energy by cutting back on maintenance and repair – damaged DNA goes unfixed and metabolic waste goes uncleared. The build-up of mess stresses the cells further and they respond by sending out distress signals including inflammatory cytokines, the first line of the immune response to signal that action is needed to put things back on track. The brain responds by updating its predictions to reflect the lack of energy, broadcasting this as a feeling of fatigue, demotivation and irritability – collectively known as 'sickness behaviour'.

There are many more pathways that exert control, whether top-down or bottom-up, and the details of these are still being worked out. But what we do know is that when we feel dreadful, there is almost certainly a biological explanation. So rather than beating ourselves up for being lazy or weak-willed, we should see fatigue for what it is – a distress signal that all is not well. Being tired or demotivated isn't a character flaw; it's a signal that something needs to change in the body–mind conversation that underlies our feelings. And this suggests that it might be possible to change the conversation and feel better.

Break the cycle

The brain's predictions and interpretations of what's happening in the body can carry a lot of weight in the equation that adds up to how we feel. So it stands to reason that if we could somehow change what the brain *thinks* is happening in the body, it might help to change how energised we feel.

An important aside: I'm not suggesting that anyone with chronic fatigue is able to think themselves better. Research suggests that this condition is usually the result of a physical glitch in the system, not an imagined one, and the same is true of many incidences of everyday fatigue. But since some of the burden of TATT in our society comes from the energetic challenge of mental, emotional or social stress, anything that can change the brain's viewpoint from 'unsafe' to 'safe' is worth a try. An all-inclusive month in the Maldives would probably do the trick. Or, more realistically, we could make time for what the psychologist Elissa Epel, who researches stress and ageing at the University of California in San Francisco, calls 'deep rest'.

Epel is a psychologist who studies why practices such as prayer, meditation, chanting and paced breathing are so strongly linked to lower stress and better wellbeing. In a recent paper on the subject – written with other researchers, including Picard – she raised the possibility that they work by effectively putting a spanner in the works of the stress response. This ends the vicious cycle of stress, which leads the stressed person to feel drained – followed by more stress, because stuff still needs to be done.

One explanation for how it works is that, whether by coincidence or design, relaxing mind–body practices all involve slow breathing – often at a rate of six breaths per minute.[16] 'Resonance breathing' is a physiological sweet spot that maximises the exchange of oxygen and carbon dioxide in the lungs. This rate of six breaths per minute also stimulates the parasympathetic (calming) arm of the vagus nerve,[17] which moves the needle of arousal from 'fight or flight' towards 'rest and digest'.

If anything could be said to make mitochondria happy, it would be more oxygen and a break from overwork. It would thus make sense that deep, slow breathing acts as a reset, which puts us on track to having energy to spare, all the way from our cells[18] to our mind.[19]

For anyone who is averse to deep breathing and prayer, other activities can have the same effects while also being much more fun, including – but not limited to – seeing friends, laughter, and watching online videos of cute baby animals.

This particular strategy comes down to one of the most mysterious aspects of our day-to-day experience of energy: that it can change in a flash. One minute you are dragging your feet after a stressful day, the next you're laughing with friends and feeling invincible. The opposite can also happen – one minute you're feeling motivated and positive, the next you receive a message that drains the life out of you.

This quick turnaround suggests that what's changing isn't a physical boost – or drain – of energy. So what's going on? The neuroscientist Lisa Feldman Barrett coined the term 'body budgeting' to explain the connection between interoception, allostasis and how we feel. She says that the answer comes down to the fact that we don't manage our energy reserves by ourselves. We are a social species, and other people contribute to how we feel. And that means that our interactions with the people around us can either boost or drain us. If they go well, it feeds into our calculation of whether we have the reserves to deal with the stresses of life. If not, we feel tired in anticipation of what will happen next. As Feldman Barrett puts it in her book *Seven and a Half Lessons About the Brain*: 'The best thing for your nervous system is another human. The worst thing for your nervous system is also another human.'

Studies suggest that the presence of others can make a huge difference to how energised we feel. One study found that people can manage more intense exercise, and can work their muscles harder, when they are in the presence of a trusted friend. They also report finding the workout easier.[20] Another study found that rowers can keep going for longer before giving up if there is someone there to support them, and they can expend more calories before feeling exhausted. One explanation for this effect is that having support helps us to dig deeper into our energy reserves, safe in the knowledge that there is someone to take up the slack for other things. 'Social support may signal the availability of the resources we need to recover from exercise, so we can be less conservative or cautious with our bodily resources,' says Arran Davis from Oxford University, who led the research.

Conversely, if you feel that a person or situation drains your energy, they almost certainly are, perhaps because you take the cost of their needs into your own energy calculation. Why helping people can be either energising or draining isn't clear, but it likely comes down to other factors being fed into the equation, such as whether the other person will appreciate your efforts, will help you in the future, or whether you think your help will make a meaningful difference to their predicament.

This suggests that we should choose the people we spend time with wisely. Or, if circumstances make that impossible, make time for deep rest, and schedule time with someone who makes you laugh until your belly aches: laughter stimulates the vagus nerve just as effectively as deep breathing. There is no one rule that will suit everyone – it's all about what feels good for you. Cuddle your dog. Have a bath. 'I have a friend who looks at pictures of kittens online before she goes to sleep,' says Feldman Barrett. 'Whatever works!'

A change of perspective not only helps in the moment; it also takes the pressure off in ways that can even be detected in the cells. In one of Picard's recent studies, people who reported a positive mood the evening before a blood test had better-functioning mitochondria the following day than those who were in less good spirits. All the people in the study were caregivers, and all were under chronic stress. But on the days they felt more able to cope, their cells also seemed to have more energy to play with.[21]

Admittedly, telling people who are already stressed to cheer up can be unhelpful – but Feldman Barrett thinks it's worth bearing in mind that our energy levels are more malleable than we might think. She points out that the brain's predictions don't stay in the brain; they are put into action so the body can start adapting in advance. 'If you expect your world to be a particular way, you will act on the world in such a way that your expectations are confirmed,' she says. If you are convinced that a work meeting, family get-together or exam is going to be draining, it might not matter whether your cells are well fed and rested; their activity may change to match your expectation.

This also explains why enthusiasm and motivation are easier to come by if you're doing something you believe is worthwhile. Bob Arnot puts his boundless enthusiasm down to the fact that he's always genuinely excited to master a new skill. The more things you have on the go, he thinks, the more likely it is that one of them will be going well, which will keep you energised. He compares it to spreading stock market investments; if one fails, the others make up the shortfall. 'One of them might tank, and that might be your main job, but if you have other successes – a good workout, a new piece on the piano or a new sentence you put together in Arabic – that can keep you happy and energised,' he says.

As for where you find the motivation and energy to start the workout, piano lessons or Arabic lessons, not even Bob can answer that. It may be that some people simply have more motivation than others. Psychological studies have identified a trait called 'reward sensitivity'. In a nutshell, some of us feel small gains as big wins, and others feel big wins as nothing to get excited about. Why we differ isn't clear, but it does suggest that those of us who don't have Bob's level of enthusiasm probably shouldn't beat ourselves up about it. Stress, after all, is far too draining.

Measuring mitochondria

'See you soon!' Kathryn Whyte beams at me and shuts the door, locking me into an airtight chamber the size of a small single bedroom. I'd been expecting it to feel claustrophobic, but it's surprisingly cosy – there's a bed, toilet, a TV in the corner, and a blind on the window for privacy. Having spent the morning navigating the New York bus system, it was the perfect place to rest and recharge – and then to see how my mitochondria responded to a short bout of exercise.

I've come here to investigate how we might help the mitochondria to work smarter, not harder, to boost energy supply at its source. Whyte is a researcher at the New York Nutrition Obesity Research Center at Columbia University, home to one of only about fifty full-room metabolic chambers in the world. She is working with Martin Picard and others to measure exactly what happens to people's mitochondria as they eat, sleep, exercise and meditate – and how this relates to how energetic they feel.

The reason for doing all this in a sealed room is that you can measure metabolism pretty accurately with just two pieces of information: how much oxygen a person breathes in and how much carbon dioxide they breathe out. The reason we breathe is to provide oxygen to our mitochondria – it's the final link in the electron transport chain. This means the carbon atoms left over from breaking down food can be converted to carbon dioxide, carried away to the lungs and breathed out, and that hydrogen atoms get bound up with oxygen to make water. What's more, because scientists already know the rate at which different types of fuel are burned in mitochondria, they can work out which kinds of fuel are predominantly being burned, and under what circumstances the body switches from one to another.

One way to do this is to get people to breathe through an airtight mask and measure the volume of oxygen they consume and the carbon dioxide they breathe out over a period of time. The metabolic chamber is essentially a scaled-up version of the same thing, which means people can spend a day or so there while researchers track their metabolism as they sleep, eat and exercise.

Whyte's studies have so far looked at the effects on metabolism of high-intensity interval training, shadow boxing and Irish tap dancing. One highlight was persuading a busker in Times Square to perform in the room while she measured his energy expenditure. A while later she showed the data to the tour manager of the thrash metal band Megadeth, only for him to offer her a job as the band's tour dietician, tasked with helping the rockers manage their energy levels.

Herman Pontzer, an evolutionary anthropologist who also studies metabolism, has spent over a decade working with the Hadza people: modern hunter-gatherers who live on the savanna of northern Tanzania. He wanted to know what the metabolic activity of people who live as our ancestors did could tell us about metabolic health and disease. With little access to a hermetically sealed room on the savanna, Pontzer used an alternative method to measure their metabolic rate. The doubly labelled water method involves asking people to drink water in which the hydrogen atoms have been tagged with a harmless radioactive label, then tracking the atoms as they move through the mitochondria and out through the urine. Since hydrogen is one of the main outputs of the mitochondrial production line, you can use this information to work out a person's metabolic rate.

Taken together, studies using these methods have given us a pretty good understanding of what happens to our mitochondria during exercise. My short stint in the chamber demonstrated the basics. After a fifteen-minute rest on the bed, I got up and danced for ten minutes. When Whyte crunched the data, there was a clear uptick in energy expenditure when I started moving: my oxygen consumption rose threefold compared to when I was resting on the bed. Around five minutes into my dance break, my mitochondria switched from burning mostly fat to a mixture almost entirely made up of glucose.

This, Whyte and Picard assure me, is totally normal. Fats are a good fuel at rest because they are slower burners; glucose, a faster-acting fuel, is saved for emergencies and to feed the brain, which is always hungry for energy and prefers to burn quick-release glucose.

If I'd increased the intensity of my exercise, the mitochondria in my muscles would eventually reach their limit. In the short term, they would top up with anaerobic respiration, which doesn't involve oxygen – or even the mitochondria. Instead, glucose molecules are split into two in the cell cytoplasm, releasing a small amount of adenosine triphosphate (ATP), the energy currency of the cell. This process, called glycolysis, is how many cells powered themselves before mitochondria showed up and changed the game, but it's slower and less efficient, and it can't be sustained for long.

If this level of exercise became a habit, the mitochondria in my muscles would adapt to boost capacity, clearing out old and damaged mitochondria and making new, more efficient ones to replace them. This adaptation costs a bit of energy, but it's an investment in capacity that pays off during both exercise and rest.

There's no easy prescription for how much exercise is required to make this happen, not least because we are all physically very different. Nevertheless, since we evolved as hunter-gatherers, that's probably a good guide to the amount of exercise our bodies were designed for. It's worth noting that the Hadza seem to be doing plenty. According to Pontzer, who has thousands of hours of data on their activity patterns, they rarely run. So it seems that the idea we have of what exercise means may not match what our bodies evolved to want or need.

The Hadza may not run, but they do spend a lot of time on their feet. Adult Hadza men and women – even those in their seventies – spend two to three hours per day on the move. The vast majority of that time is taken up with moderate intensity exercise such as walking, and a few minutes each day involved vigorous exercise, such as digging in dry soil for tubers, or climbing a tree to collect wild honey.[22] And adults remain strong, mobile and metabolically healthy to a ripe old age.[23]

If high-intensity exercise isn't strictly necessary, we almost certainly need to move more – and perhaps to rest smarter, too. Pontzer's studies showed that the Hadza spend as much time sitting down as the rest of us. But instead of flopping on chairs and sofas, they squat or sit on the floor, engaging the muscles of their legs and core.

No worries, more energy

What all this has to do with their perceived energy levels isn't something Pontzer has studied, but they are known to have an unusually upbeat outlook on life. Their standard response to challenges, Pontzer recalls from his time with them, is '*Hamna shida*' (no worries). 'Hungry? Tired? Still ten miles of hard walking from home? Of course you are! *Hamna shida*,' he writes.

Interestingly, other studies suggest the Hadza are more interoceptively aware than their Western counterparts. A study by Feldman Barrett and her colleagues found that they were far more likely to describe their emotions in terms of how their body felt, rather than as a mental event. One man, for example, described his fear at seeing an elephant ready to charge. He said: 'My body, it was too hot because of that situation. There was pressure coming out through me. I feel pain in my chest for the situation ... My chest feels like it has a fever, like something inside the chest is pounding.' The same study noted that the Hadza tend to leave these intense bodily emotions in the moment, rather than wasting energy thinking about what could have been different. When challenges are dealt with in the moment, they don't hang around as low-level, chronic stress.

Culture is almost certainly a factor in this, but so is the environment that provides the context for the Hadza's energy-budgeting equations. Unlike us, with our clean, warm homes and well-stocked food cupboards, the Hadza can't afford to let the energy-expensive stress response hang around for any longer than necessary. Stress costs energy that would be better spent on finding the next meal.

Evidence for this comes from a surprising result from one of Pontzer's studies. Having monitored the metabolic rate of a group of Hadza for several weeks, he found that despite doing more physical activity in one day than most people manage in a week, they burned almost exactly the same number of calories as the average sedentary Westerner: around 2,000 calories each day. The same was true of a group of farmer-foragers Pontzer worked with in Bolivia, who were similarly active.

It didn't make any sense – unless, Pontzer suggested, the human body and brain work with a fixed energy budget, set by our species' evolution. Pontzer calls this idea 'constrained total energy expenditure'[24] – and, while it is still theoretical, it fits with the idea of predictive processing and body budgeting, and could also explain why comfortable Western lifestyles leave us feeling that we have less energy, not more.

The logic goes like this. Human beings have evolved to keep to an energy budget of around 2,000 calories per day: 1,600 or so are spent on the basics of keeping us alive, and the rest is shared between digestion, physical activity and extras like the stress response. If the energy budget is capped at 2,000 calories, a rise in one of these outlays means that one of the others will need to be scaled back.

The Hadza, the theory goes, spend their 'optional' calories on hunting and gathering, so have less to spare for things such as stress responses and chronic inflammation. We, on the other hand, spend so little on moving around that our bodies have ample resources to keep inflammation going just in case, and to manufacture hormones including cortisol, oestrogen and testosterone in higher quantities than we actually need. Perhaps we are worn out not because we don't have spare energy, but because we have too much left over. And the reason we feel this as a *lack* of energy is because in the conditions our bodies evolved to survive, stress and inflammation were an expense that could only be afforded by hunkering down and making savings elsewhere.

So, what can we do about this? One option is to increase your activity levels as much as possible. This doesn't have to mean running around all day, every day – low-intensity movement, little and often, works well for the Hadza. Take movement breaks during long spells of sitting; try sitting on the floor to engage more muscles than slouching on a chair. All these things add up.

The diet of the Hadza is a harder sell. Meals based around charred meat, honey, berries and tubers will appeal to few except devotees of 'paleo' – a diet that claims to recreate that of our ancestors. The paleo diet isn't based on science, but there is emerging evidence that ketogenic diets (diets in which nearly all the calories come from protein and fat) stimulate mitochondria in a similar way to exercise. Some studies have found that ketogenic diets, which are low in carbohydrates and so force the mitochondria to burn fats for energy, are linked to improvements in depressive disorders, in which a lack of energy and motivation is a symptom. The jury is still out regarding whether this will work for everyone; given how restrictive the diet is, and how difficult it is to stick to, it may prove to have limited impact on the mental health burden. Even so, the link between challenging mitochondria to work harder and people feeling better makes it worth keeping an eye on.

The final lesson from our ancestors is that the need to stay active becomes increasingly important from middle age. According to Daniel Lieberman, evolutionary anthropologist and exercise enthusiast, the rule of 'use it or lose it' is baked into our evolutionary history in ways that may explain why physical activity not only makes us feel better but also slows the ageing process. In hunter-gatherer societies, middle-aged and older people are vital to the group's survival: they bring in the calories and help look after the grandchildren. But staying active from middle age comes with inevitable wear and tear on the muscles and joints. So, Lieberman speculates, activity in older years came to be linked in our evolutionary story with the need to ramp up cellular repair and maintenance. This costs a lot of energy, so it only gets switched on when we exercise. But when it does, it has the side effect of keeping all our cells – and mitochondria – in good repair and as healthy as possible.

Wallace, who in the 1970s suspected that mitochondria were key to our health, was on to something. Staying alive and healthy is a matter of keeping energy flowing through the cells. To truly understand health, we need to find a way to measure this energy flow. Then we can use that knowledge to rethink what we know.

Towards a science of chi

As intriguing as these insights are, 'energy flow' is not yet something we can measure to provide an indication of overall health. For that, we would need a reliable way to somehow capture an image of the energy flowing through the body in real time. Or, perhaps more realistically, some way to listen to the body–brain energy calculation that is involved in energy budgeting from the brain down, the cells up, and the multiple levels of regulation in between.

It isn't easy, not least because it isn't simply a matter of finding *the* signal that links all levels of energy budgeting and the brain. Energy is such a crucial signal for survival that evolution has built in multiple lines of communication by which the alarm can be sent out that it's being spent faster than it can be produced. This means there are many possible signals that could be used as biomarkers – tell-tale signals of changes in the body that could be used to keep track of our energy levels and health.

Nevertheless, Wallace is no longer alone in advocating for an energy-based view of health. In 2021, the World Health Organization (WHO) assembled a working group of researchers to thrash out a definition of healthy vitality and to draw up a shortlist of biomarkers that could be measured in the clinic with a blood test or other physiological measure. Their aim is to find a way to easily take a snapshot of how well the body is functioning physiologically, so that any changes can be picked up before they start to cause symptoms. The project was initially designed to detect early signs of frailty in the elderly, but in an article summarising their findings in the journal *Lancet Longevity*, the group argued that this information would be useful much more widely, and could allow health problems to be detected and treated long before symptoms arise.

To be useful in general medicine, a biomarker needs to only show up in the body when the problem you are trying to identify occurs. It also needs to be easy and cheap to test, without requiring too much expensive specialist equipment. There also needs to have been sufficient research carried out all over the world to indicate what counts as a healthy score and what signals a potential problem. The WHO working group has identified several potential options, ranging from simply asking people how energetic they feel, to measuring physical strength and biomarkers of metabolism in the bloodstream.

One idea is to go right to the source and track how efficiently the mitochondria are releasing energy. This can be done by taking a blood sample and isolating the mitochondria from the white blood cells, which – unlike red blood cells – do contain mitochondria. White blood cells are also a central part of the immune response, so they're a good place to look for the effects of stress and ill health on mitochondrial function.

Using this method, Picard's group came up with a 'mitochondrial health index' (MHI) that measures the levels of key enzymes involved in the Krebs cycle and electron transport chain in relation to the number of mitochondria. The higher the MHI, the more efficient the mitochondria.

Various studies have shown that emotional stress, mental health issues and mitochondrial diseases lead to a lower score on the MHI. What isn't yet known, though, is how these scores might vary in the same person over a period of time, and in large numbers of people. Mitochondrial health is dynamic, says Picard, so more research is needed before we can use it as a biomarker. 'We need to measure the mitochondrial health index over time, then you can ask whether there is a signature about you that is stable from today to tomorrow, to next week, to next month. We don't know yet, but we are planning to do those studies,' he says.

The various signalling molecules that circulate in the blood and keep the wider body – and brain – informed of energy-related news are also potential biomarkers. The most obvious are inflammatory cytokines, which are released as the first line of the immune response and, as well as setting our defences in motion, stimulate the release of energy to deal with infection, injury, or a real or imagined threat. It's now well established that these cytokines also stimulate the low-energy state known as sickness behaviour and communicate – through feelings – that we need to save energy in order to fight back.

While inflammatory markers are an interoceptive signal that flags a drain on resources, it's not always easy to tell what's causing their release. Inflammation might signal a short-term, healthy adaptation to something like exercise or a mild cold, or could be a sign of a more serious, long-term problem. A signalling molecule called GDF-15 (growth differentiation factor 15) is an alternative candidate for an energy biomarker. Released from cells when they are struggling to balance their energy budget, it is a 'mitokine' – a metabolic signalling molecule – and it doesn't seem to matter whether the energy shortage is caused by overworked muscles, an infection, faulty mitochondria or stress. It finds its way into the bloodstream and heads to the brainstem which, as we saw in Chapter 2, is a major hub for interoceptive processing. The brainstem is so far the only place in the body where receptors for GDF-15 have been found.

Because of this, researchers including Picard suspect that GDF-15 is a specific interoceptive distress signal that energy is running low. It is produced at low levels in the body all the time, which means that there is a stable baseline that can be used as a comparison. Interestingly, in recent studies of people who have mitochondrial disease, GDF-15 levels tracked perfectly to their reported levels of fatigue. 'The more GDF-15 people have, the more tired they are,' says Picard. 'The signal travels to the brain and says "We're burning way too much energy in the periphery. Chill out."'

A test that can indicate energetic distress would be hugely important for a symptom that is so easy to dismiss as 'all in the mind'. A blood test would show quite clearly that what's going on in the mind is intimately connected with what's happening in the body.

Even better would be a way to measure fatigue-based changes in body and mind at the same time, cheaply and easily, and without the need for blood tests or specialist equipment. Ivan Bautmans at Vrije Universiteit in Brussels heads up the WHO working group and has spent the past twenty years working on such a measure. He has come up with what he calls the 'capacity to perceived vitality ratio', which divides a measure of muscle endurance by the score on a questionnaire that marks motivation levels, mental fatigue and general levels of tiredness. The ratio gives a number that can serve as a marker of what might be an unhealthy drain on a person's energy resources, long before it starts to cause real problems. And it can be measured in a handheld device that connects to a smartphone.

The device that Bautmans shows me looks like an old-fashioned car horn – the kind that is commonly brandished by clowns on unicycles. A rubbery bulb at one end is a sensor that measures grip strength, while the electronics in the other end capture maximum strength and measure how long a person can squeeze before they lose 50 per cent of their maximum power.

This device, Bautmans explains, grew out of his PhD research twenty years ago. At that time it had been known for a while that hand grip strength is a good proxy for overall strength, but it is less useful as a measure of endurance – which is, in turn, a better measure of fatigue. He developed a way to measure the rate at which fatigue sets in, using a clunky device involving wires, a computer and a stopwatch. Twenty years on, the sleek, brightly coloured Eforto connects to a smartphone app and is so simple that anyone can use it. Bautmans is keen to make it clear to me that he has no financial stake in the device and is motivated by getting something simple to use into the community and clinics.

Studies so far show that it provides a quick measure of overall health and vitality that takes into account both mental and physical aspects; Bautmans says the score tells you something important about how well the body is adapting to life's challenges. 'It is a proxy measure that is easy to capture and tells you something about whether the underlying physiology is in homeostasis or is becoming problematic,' he says.

So far, the technology has been used in hospitals, where it seems to effectively predict which patients will recover well from surgery and who will need more care. And a study of almost 1,000 healthy middle-aged people found that those with the lowest muscle endurance and the highest fatigue were significantly more likely to have low-grade inflammation than those with better scores.[25] That's important, says Bautmans, because chronic inflammation is known to be a driver of ageing. If we can detect it in healthy middle-aged people, perhaps it offers a window for intervention before it starts causing health problems or irreversible damage.

Optional ageing?

Studies from Picard's lab suggest that reversing the signs of ageing is more plausible than we may think. He reasons that if a lack of energy makes cells age more quickly, freeing up some energy could make cells young again. While he was talking this over with his partner, she happened to mention that some of her grey hairs had regained their colour. Intrigued about what could be going on in the cells to make this happen, he set up a study to investigate.

The result was a small study of fourteen people with an average age of thirty-five, all of whom had hair that had gone grey and then had regained colour from the root. Picard took samples of these striped hairs and estimated when the change happened, as well as asking the volunteers to recall the rough dates of any unusually stressful recent events. Sure enough, the results showed that the volunteers' reports of stressful periods lined up perfectly with the grey bands. Once the stress had passed, the colour returned; what was left was the equivalent of rings in a tree trunk, showing a record of the prevalent conditions at the time that hair was growing.

Picard explains greying hair as an energy-saving strategy that kicks in when the body needs to use its resources elsewhere. 'If you don't make colour for your hair, you are saving a bit of energy ... and making colour and pigment is probably not so high in terms of needs for survival,' he says. Once the energy crunch has passed, the hair can afford to make colour again.

It's likely that there is only a brief window in the ageing process when greying is reversible – at some point, the whole-body challenges of ageing make grey hair an inevitability. But it also suggests that there is a window of opportunity in middle age to spot early signs of a lack of vitality – and turn things around.

This raises the question: what can we learn from the likes of Bob Arnot about how to stay young and energetic? If we could learn from the secrets of high-energy outliers like him, it could provide the boost humanity needs to face life's challenges.

Bautmans wants to know the same thing, and he is working on a study with a group of sprightly eighty-year-olds to try to find out what they are doing that other people their age might not be. Right now, though, the best we have is the usual advice: to eat healthily, move as much as possible, and rest well. Bob swears by this exact prescription, as well as maintaining a wide range of intellectually stimulating interests. He manages stress by keeping a close eye on his heart-rate variability (HRV) – a proxy for how well the vagus nerve is managing to calm the body. This metric, available on many smart watches, can be a useful way to work out if you are physically tired and should rest, or whether you are just lethargic and would probably feel better after a workout. If Bob's HRV score suggests that he's run-down, he has a rest; if his HRV is looking good, he seizes the day – and it seems to be working for him.

Meanwhile, in a corner of human biology where serious science meets woo, another intriguing line of enquiry is emerging. It's based on the almost unbelievable fact that whether we are bursting with energy or feel as if we are dragging our feet, our bodies are constantly emitting tiny quantities of light. These 'ultraweak photon emissions' or 'biophotons' are emitted by all living cells, from bacteria to plants and animals, and can be detected by highly sensitive cameras. With a bit of processing, the data can be transformed into heat-map images showing regions of the body with high, medium and low emissions of biophotons.

The earliest studies were done in the 1920s, but there has been surprisingly little research into what, if anything, biophotons have to do with health and vitality. We know that tumours emit huge quantities of them, and that their release has something to do with the mitochondria. But what this has to do with metabolism, or the energy we can feel in ourselves, is another question. Biophotons might be an accidental by-product that don't do, or signal, anything. And if they are a signal of some kind, we have no idea whether they are sending the message that the body has loads of spare energy, or whether they're a distress signal from a cell that is burning out.

It's intriguing, but there's a lot of science to do before we can work out what biophotons mean. There's no shortage of entirely unproven claims from less scientific quarters of the internet that biophotons are a way to measure a person's 'aura', evidence of 'chi' or an invisible force that we tap into when someone gives us good or bad vibes. Yet while there's no evidence that we literally feel the energy of others, that doesn't mean that gut feelings aren't real. In fact, they seem to be based on interoceptive mechanisms that we may be able to tap into. Which is why the murky world of the gut, with its bespoke nervous system and hordes of bacteria with a hotline to our brains and a say in our feelings and actions, is where we are going next.

4

Gut reading for beginners

Making sense of hunger, and other gut feelings

I'm not sure what I expected when I agreed to swallow a vibrating pill, but I don't think I realised it would be quite this big. In the palm of my hand is a shiny white capsule, roughly the size of a very skinny grape. I'm at the Laureate Institute for Brain Research (LIBR) in Tulsa, Oklahoma, to try some of the tools they are developing to probe our body–brain connections. Sahib Khalsa, a neuroscientist and psychiatrist who, when I visited, was in charge of the clinical research programme, had generously invited me to visit the lab and set me up with all manner of things to try. One of his research assistants has just activated the battery inside the pill; now all I have to do is swallow it before it starts to buzz.

After an embarrassing false start when I accidentally inhale the water they've given me to help swallow the pill, it goes down with no problems. Once I've stopped coughing, I can relax and concentrate on tuning into my gut feelings, which for the next half an hour are dominated by the sense that I've swallowed a tiny phone set to vibrate.

You don't need to swallow a battery-powered pill to know that the gut, particularly the stomach and intestines, has a lot to say for itself. From a rumbling empty stomach to feeling nicely full or uncomfortably bloated, our guts never stay silent for long. And usually, what they have to say comes loaded with feelings that spur us into action, even if it's just to reach for the biscuit tin. From an evolutionary point of view, this is all part of the design. Finding enough food to fuel the body is non-negotiable in terms of our survival, but hunting and gathering are not risk-free. Both cost precious energy that there is no guarantee you can replenish, and it comes with the constant risk of becoming someone else's lunch while you're out looking for your own.

That's why gut feelings are so important. If hunger didn't make us feel bad and eating didn't feel good, our prehistoric ancestors might have wasted away in a cave rather than risk going out hunting and gathering. If being sick didn't feel so miserable, we might not learn to avoid bad food, and the next rotten piece of meat could kill us. And if we didn't know to stop eating when we felt full, we might keep seeking out food at the expense of other important things, such as staying safe and warm and fostering life-enriching relationships.

These relationships are as important for our survival as finding enough calories. Humans are relatively puny compared to our natural predators, and we have long childhoods, during which we are dependent on others for food. It makes sense that at some point in our evolution, the basic motivational feelings for finding food were recycled as motivators that prompted us to seek out social interaction. As a result, we get hungry for food, but also for human connection and comfort. We feel sick not just when we've eaten something rancid, but also when a creepy stranger stands too close to us. And we feel warm and fuzzy inside when eating our favourite meal and when we're with someone we love. For most of our evolutionary history, this system has guided us well. But in a world where comfort food is easier to come by than meaningful human connection and where much of what we eat is tastier than it is filling, it can be a struggle to know what our bodies – and minds – are asking for.

To make things even more complicated, food and comfort aren't the only things our guts communicate with the brain about. The gut is hardwired into the fight-or-flight system, meaning that it also sends out signals that are a side effect of a body-wide call to action. We all know what it feels like when our stomach flips when we are nervous; when we're faced with a life-or-death situation (or a more trivial social encounter that feels like one), digesting our last meal can wait. The blood that would usually be required for digestion is diverted to the muscles and brain, so its share of glucose and oxygen can be used to deal with the emergency. The sensation of a knot deep in your stomach, the fluttering of butterflies or a cold wave as the blood drains from your belly is a direct result of digestion grinding to a halt while the blood is sent elsewhere.

This system also works well – at least, when we need a burst of energy to deal with a challenge – but it can easily get out of whack in the stressful modern world. The link between emotional issues and digestive problems that has long proven difficult to explain is becoming increasingly clear – and even harder to treat in a medical system that thinks of conditions as being either physical or 'all in the mind'.

All things considered, the overlap between our gut feelings and emotional state means that trusting your gut is not always as straightforward as it might be. Thankfully, scientists are beginning to dig deeper into the gut–brain connections, to find a way to make them work again.

How much is enough?

When he was a child, my father-in-law was taught that the polite way to end a meal was to say, 'My sufficiency has been suffensified. Please may I leave the table?' Lots of families have a variation on this theme – and most of them probably make much more sense than this one. But it does beg the question: how do we know when we are full? And how does what we learn as children affect how we eat as adults?

One way that we know we've eaten enough is when stretch-sensitive receptors send a message to the brain along the vagus nerve that our stomach is filling up, prompting us to slow down our food intake. The point at which this response kicks in varies, but studies in which volunteers drank water until they felt satisfied, then continued until they felt uncomfortably full, suggest that people start to feel sated when they are at 50–60 per cent of their personal maximum, which is roughly around a litre (just over 2 US pints) for most people.[1,2]

A study of an extreme case of overeating suggests that we can change this limit ourselves – sometimes to the point where it's no longer possible to feel full. In a

2007 study at the University of Pennsylvania, researchers imaged the stomach of a world-class competitive speed eater while he swallowed as many hot dogs as possible in twelve minutes (the usual time allotted in speed-eating competitions). He managed to eat thirty-six hot dogs in ten minutes, at which point the researchers stopped the experiment, worried that his stomach had expanded so much that it might burst. Remarkably, even though his stomach became, as the researchers wrote, 'a giant, flaccid sac occupying most of his upper abdomen', the man didn't feel full or bloated, and didn't report any discomfort. By comparison, a control participant managed seven hot dogs before he couldn't force another down without feeling like he'd be sick.[3]

Anecdotally, competitive eaters train before an event by eating beyond fullness to stretch their stomach for the big event. One competitive-eating star, Takeru Kobayashi, announced his retirement from the 'sport' in 2024, because after twenty years of forcing excessive quantities of food into his stomach, he was no longer able to feel hungry or full. With no gut feelings to guide him, he would sometimes go three days without eating. He was worried that he'd done himself permanent damage.[4]

Whether less extreme forms of overeating also stretch the stomach and muffle interoceptive fullness signals isn't yet properly understood. Some studies have found that people with obesity have significantly larger stomach capacity than leaner volunteers,[5] while others have found that larger stomachs are able to hold more food before the fullness signal kicks in.[6] It's unclear which comes first: whether people who develop obesity are those with naturally larger or less sensitive stomachs, or whether they *become* less sensitive to their fullness signals, causing the stomach to stretch and require more food before it feels full.

It's certainly true, though, that some people are more sensitive to their stomach sensations than others, and that this affects how much we eat. How people differ, and what that has to do with both the signals and the brain's interpretation of them, is something that Sahib Khalsa wants to use his vibrating capsule to find out.

In the team's first study, published in 2023, healthy volunteers wore one set of electrodes on their stomach, to measure their normal gut rhythms, and another on their scalp to measure brain activity. The researcher Catherine Tallon-Baudry's group at the École Normale Supérieure in Paris had already identified a 'gastric network' in the brain that monitors gut activity, and Khalsa was intrigued to see whether the vibrating capsule would fire it up.

It did. Activity in the brain's gastric network showed up within half a second of the capsule starting to buzz,[7] and the stronger the capsule vibrated, the louder the signal in the brain. Conscious awareness of the vibrations (judged by how quickly the volunteer pressed a button) came about half a second later for the lowest vibration setting – which, to me, felt like a barely perceptible faint flutter. The stronger vibration, which felt more like the buzz of a trapped fly, popped into consciousness a little more quickly, around 0.2 seconds after the brain had registered it. Importantly, electrodes on the volunteers' bellies showed that the capsule did not change the gut's natural rhythm – a wave of electrical activity that passes along the length of the gut every twenty seconds, starting in the oesophagus leading from the throat to the stomach, and continuing through the small and large intestines and out the other end. The changes in the brain were thus coming from stimulating the gut–brain pathways and not because the capsule was causing the gut to churn abnormally.

Khalsa and his team now plan to use the capsule to explore how gut sensitivity varies in people with eating disorders, obesity and gut-related disorders such as irritable bowel syndrome. The idea is that once we have a better idea whether under- or oversensitivity to gut signals is the issue in these disorders, and whether the problem is at the gut or the brain end, it might be possible to train people to read their stomach sensations.

It might be a while before this is available as a therapy, but a lower-tech version we can all try now is something called intuitive eating. It was first put forward by the dieticians Evelyn Tribole and Elyse Resch in the mid-1990s as an alternative to diet culture, which, they argue, doesn't encourage a healthy relationship with food or allow people to maintain the weight loss a diet can help achieve.

The idea of intuitive eating is to pay attention to your gut signals whenever you start eating, and to keep paying attention so that you notice when you feel full. Among the guidelines laid down by Tribole and Resch are 'honour your hunger' and 'respect your fullness'. They also recommend paying attention to your psychological needs as well as your physical ones. If you feel the need for food-based comfort, that's fine, as long as you notice what you're doing and why. In other words, intuitive eating is about detecting and interpreting your interoceptive signals – and understanding how they relate to how you feel.

Intuitive eating wasn't designed as an interoceptive intervention, but researchers have become interested in how it relates to appetite and emotion. Some studies suggest that people who are better at accurately detecting their heartbeat are more likely to eat for physical rather than emotional reasons, and to trust their body's signals when they are hungry and full.[8] Interestingly, Chris White, the hostage negotiator we met in Chapter 1 who achieved an almost perfect score on the heartbeat detection task, has an approach to food that sounds a lot like intuitive eating. 'I know when I need to eat – and it isn't always breakfast, lunch and dinner,' he told me. Even if it's the middle of the day and someone announces that it's time for lunch, he can't be swayed. 'If I'm not hungry, I'm not interested,' he says.

I can relate to this. As a child, I would stop eating when I was full – and no punishment on Earth could make me clear my plate if I'd had enough. Despite my stubbornness, my mum and stepdad managed to drill it into me that eating whatever was put in front of you was 'good table manners'. The message must have eventually filtered through, because as an adult I can override my fullness when politeness dictates. I've even heard myself telling my teenage son that eating food you don't want is a vital life skill – just shove it in, chew, swallow and say thank you.

Yet while intuitive eating does seem a more sensible approach than ignoring or overriding your gut sensations, it bumps up against a major problem in modern Western society. Because for better or worse, fullness isn't the reliable signal that it used to be.

According to recent estimates, 60 per cent of the average diet in the UK and in the US consists of ultra-processed foods (UPFs). The term was coined by a group of Brazilian researchers in 2010[9] and was adopted by the United Nations in 2019.[10] The degree of food processing has since been introduced as part of official dietary advice in countries including Brazil and Canada, both of which advise replacing UPFs with whole foods when possible. In recent years this has caused a stir in nutrition research circles and among the wider public, after a wave of media interest in how UPFs and modern diets are linked to obesity and ill health. Various criteria make a food qualify as ultra-processed but, as a rule of thumb, if it has been mass produced and is cheap and moreish, it probably counts. Carlos Monteiro, the nutritionist who leads the Brazilian team, has described UPFs as 'formulations mostly of cheap industrial sources of dietary energy and nutrients plus additives, using a series of processes'. In other words, not really food at all.

There has been a lot of debate about the usefulness of the 'UPF' label, and the deeply entrenched social inequalities that make these foods difficult to replace.* In terms of gut feelings and how to read them, the most important thing to know about UPFs is that they seem to mess with the interoceptive pathways that tell us when to eat and when to stop, and with the connections between food and how we feel.

* Read Chris van Tulleken's book *Ultra-Processed People* (Cornerstone Press, 2023) or *Unsavoury Truth* by Marion Nestle (Basic Books, 2018) if you want to delve deeper into these issues.

Melt in the mouth

Part of the problem lies in how easy these kinds of foods are to eat. As a general rule, UPFs are chemically designed to be delicious, with a melt-in-the-mouth quality – think chocolate, corn snacks like Cheetos or processed cheese – that reduces the need for chewing. As Chris van Tulleken puts it in his book *Ultra-Processed People*, these foods are 'predigested' during the manufacturing process. As a result, they are generally lower in fibre than whole foods, which means they don't take up as much space in the stomach. Think about how full you feel after a bag of crisps compared to a medium-sized baked potato. Both contain more or less the same quantity of potato,[11] but one is far easier to munch through – and far less likely to spoil your appetite for your next meal.

This all makes intuitive sense, but until 2019 there wasn't much hard data to back it up. Then came a study led by Kevin Hall, who researches how diet affects the body and behaviour at the US National Institutes of Health. He asked twenty people of a healthy stable weight with no food-based psychological issues to move into the NIH clinical research centre for four weeks and to eat only what was given to them by the researchers and the on-site chefs.[12]

For two of the four weeks, the volunteers were offered only ultra-processed foods, such as Cheerios® cereal, pre-packed beef chilli and burgers. For the other two weeks, they were offered only whole foods, such as oatmeal, fish, potatoes and chicken salad. The volunteers were randomised; some received the ultra-processed diet first while others had whole foods first. The two diets each had the same number of calories and nutrients, and the volunteers were told that they could eat as much or as little as they liked at each meal. Between meals they had access to snacks that were either processed or whole foods, depending on that week's diet.

The results were clear. When they were on the ultra-processed diet, the volunteers ate an average of 500 more calories per day than when they could choose from only whole foods. They also ate significantly faster, cramming in around twenty extra calories per minute at mealtimes – possibly because the ultra-processed food didn't need as much chewing. The two diets were matched for fibre, but fibre comes in two types: soluble fibre, which dissolves in water, and insoluble fibre, which stays bulky as it moves through the gut, clearing the pipes as it goes. The two diets were matched for soluble fibre by adding it to the volunteers' drinks – there was no other way to do it. Indeed, one possible reason why the volunteers were able to eat UPFs more quickly is that they contain far less insoluble fibre.

To make matters worse, measurements of the volunteers' metabolism during the study showed that their bodies were more likely to store fat when on the ultra-processed diet. Unsurprisingly, the volunteers gained nearly a kilogram (just over 2 lb) in weight in just two weeks – compared to no weight gain or weight loss on the whole food diet. The study concluded that 'a diet with a large proportion of ultra-processed food increases energy intake and leads to weight gain'.

Tricking us into eating more before we get full probably isn't the only thing going on, though. In Hall's study, the volunteers rated both diet options as equally tasty, but other studies have suggested that not all of our food choices are conscious. No matter how tuned in we are to our fullness sensations, other channels of communication between the gut and the brain operate outside our consciousness and can subvert our best efforts to eat intuitively.

Brains, plural?

It's often said that the gut has a 'second brain' that operates semi-independently from the brain in our heads. The enteric nervous system is embedded in the gut walls along most of the gut, and contains more neurons than the spinal cord. Its reputation as a second brain comes from the fact that it can manage the complex process of digestion without any input from the actual brain, regulating the contractions that push food through the gut and the hormones involved in digestion.

While the enteric nervous system can do a lot without the say-so of the brain, they are not totally disconnected. Over the past decade, it has become clear that the insides of the gut not only talk among themselves via the enteric nervous system, but are also in constant contact with the brain, via the vagus and spinal sensory nerves. These lightning-fast connections mean that the brain hears what's happening in the gut in milliseconds. It also means that whatever is happening in the brain affects the gut just as quickly. This is the much-talked-about gut–brain axis, which is proving to be a new frontier in understanding what makes us tick – and what makes us sick.

The gut–brain axis involves a complex dance between nutrients, hormones, gut microbes and the three main body–brain interoceptive pathways: the vagus nerve, the spinal cord sensory pathway and the transportation of hormones and other molecules in the blood. Until around ten years ago, only the latter was thought to be involved in regulating appetite. The main players in this pathway include ghrelin, a hormone that is secreted in an empty stomach and makes its way to the brain, where it acts on hunger neurons in the hypothalamus and stimulates the drive to find food. Working in opposition to ghrelin is another hormone called leptin, which is secreted by fat and sends the counter-message to the brain that there are calories in stock, so there's no immediate need to prioritise finding food. When the fat stores are becoming depleted, the fall in leptin levels in the blood means that ghrelin – and hunger – has the upper hand.

Unfortunately, as with so much of our biology, this system was calibrated for a world where food came in waves of feast and famine. If a hunter-gatherer loses fat quickly, they are likely having trouble finding enough calories. The release of ghrelin to motivate them to prioritise finding food is a sensible strategy for survival. But in the modern world, where food shortages are rare, boom and bust, in terms of the calories going in, is most likely to happen when we get caught in a cycle of yo-yo dieting. When the fat goes, the fall in leptin sends out a clear signal that energy stores are running low and we need to prioritise food. Hunger soars and the weight piles back on.

Worse still, a high amount of body fat doesn't necessarily translate into a strong leptin signal that more food isn't a priority. In people with obesity, the fat sends out the right leptin signals, but the brain becomes insensitive to them. At this point, this particular arm of the brain–body pathway ceases to be a reliable source of information about the body's need for calories.

Thankfully, other gut–brain pathways are involved in our decisions about what to eat, when to eat and when to stop. The main one revolves around specialised cells that line the gut from the stomach through to the colon. These are the enteroendocrine cells (or EECs, entero meaning 'inside', and endocrine meaning 'hormone-related'), and their job is to secrete a particular cocktail of hormones depending on what is passing through the gut. Another group of cells called enterochromaffin cells (ECCs) detect stretching as food is squeezed through under the control of the enteric nervous system, letting the brain know how much food is in which part of the gut at any moment.[13]

Until 2015, hormonal signals from EECs were thought to only reach the brain via the blood-vessel-based slow road, and that they only interacted with the local nerves of the enteric nervous system to speed or slow the rate at which the gut squeezed through food. Then Diego Bohórquez, a neurobiologist at Duke University in North Carolina, discovered that two-thirds of the EECs also pass messages directly to sensory nerves, forming a fast track that reaches the brain within milliseconds.[14] Bohórquez named these specialised EECs 'neuropod cells', and they were subsequently found to connect directly to the brain via the vagus nerve.[15] Neuropods are strange-looking cells, with openings at the top through which they sample the gut contents and arm-like projections at the bottom that connect to vagal neurons. They aren't nerve cells, but they speak the language of the nervous system well enough to translate the chemical contents of the gut into neurotransmitters, the chemical messengers that tell neurons to fire. This is information that the brain can work with.

Neuropods are masters of chemical sensing. They sample whatever passes by, detecting different forms of the main nutrients, fats, sugars and protein along the length of the stomach and intestines. They detect any toxins that require immediate ejection, and keep an eye on temperature, pH and salinity. Depending on what they detect, the cells put together a bespoke mix of signalling molecules, including the appetite-regulating hormones CCK, PYY and GLP-1,* in tiny packages that reach the brain via both the bloodstream and the vagus nerve.

As well as the nutritional content of food, neuropods detect the secretions of the trillions of microbes that live in our gut. Most of these are bacteria, but there are also yeast and fungi. The gut microbiome is now well known as being important for our general health, but what's less well known is that it is also involved in when we eat, when we stop and the kinds of foods we crave. It's almost as if the microbes demand to be fed and we, their obedient hosts, head out to find what they want. If the enteric nervous system is our second brain, our microbes could well be our third.

It would be nice if there was a neat set of rules about which microbes ensure a healthy gut–brain conversation, but research on this is only just getting started. And there's

* Their full names are cholecystokinin, peptide YY and glucagon-like peptide 1.

just too much variability – not just between people, but in the same person over time – for anyone to be able to advise a microbiome that will help everyone enjoy healthy food and resist the less healthy stuff.

What we *can* say is that the more types of microbes there are in the gut, the better. Different kinds of gut microbes can only survive when they live together, with some bugs needing to use their neighbours' waste products as a source of food. Studies show that gut microbe diversity is lower in people who eat a lot of processed foods and higher in people who eat a lot of whole foods and vegetables. As boring as it might sound, a healthy diet builds a microbial community that works together to provide us with nutrients and signalling molecules that help us to regulate our food intake and make us more likely to crave what our bodies really need to feel good. There's some evidence that eating fermented foods, such as kimchi or live yoghurt, can help to boost healthy microbes, but a healthy diet is still important to help them survive. Keeping them alive and well is important. If we don't have a healthy set of gut microbes, neuropod cells can get mixed up and start driving us towards sugary, fatty foods that, in the long run, can make us feel considerably worse. As we saw in Chapter 3, for example, high-sugar diets interfere with energy production in our cells, leaving us tired and moody.

We have a lot to learn about how neuropods summarise all this chemical complexity into an electrical signal that makes sense to the brain. For a long time it was assumed that each neuropod specialised in a particular hormonal signal, but recent experiments have shown that individual neuropod cells can sense all kinds of different things and have the capacity to send a different mix of signals.[16] They seem to work like tiny composers: each nutrient or chemical is like a musical note, which neuropods turn into a tune that tells the brain what's going on. Somehow, they transform the mix of nutrients and other chemicals in the gut into a signal that is more than the sum of its parts. Until we understand it properly, it will be difficult to understand how our modern lifestyle sends the symphony off-key. But some clues are starting to be found – and it seems that there are many gut–brain interoceptive pathways that can lead us to make bad food choices, despite our best intentions.

One calorie or two?

Anyone who has ever tried to count calories will know that, even if you spend all day measuring everything that passes your lips, it's difficult to gauge how many you have actually eaten. So spare a thought for the calorie-counting neurons of the hypothalamus, a tiny brain region that helps to control our appetite. The hypothalamus receives information via the vagus nerve and in the bloodstream; a group of cells called AgRP (agouti-related protein) neurons keeps count of how many calories we have eaten from each of the main nutrient groups, reducing our appetite for them when we've had enough. Trouble comes when we eat a large amount of one nutrient at the same time; the neuropods start repeating themselves and the calorie-counters start to lose count. This was demonstrated in a series of studies in mice by Lisa Beutler and her team at Northwestern University in Illinois. In one experiment, they gave mice a high-fat diet,[17] and then, in a second study, they gave different mice a diet that was high in sugar.[18] Predictably, both sets of mice gained weight, but for different reasons. The AgRP neurons of the mice on the high-sugar diet started to undercount the calories coming in from sugar, while the neurons of those on the high-fat diet did the same thing with calories from fats. As a result, the mice carried on craving foods they didn't need.

More worryingly, when the mice were put back on a normal diet, they lost the excess weight but their calorie-counters continued to undercount the nutrient they'd previously overeaten. If the same thing happens in humans – and Beutler suspects it does – it suggests that the average Western diet, high in both fat and sugar, may cause our brains to keep working against our best interests, even after we've started to eat more healthily.

Incidentally, switching to artificial sweeteners might make you feel like you're cheating the system, but the sensing cells in your gut aren't as easily fooled as the ones on your tongue. Experiments in Bohórquez's lab showed that neuropod cells in the intestines can detect the difference between sugar and sweeteners. While sugar is counted in the brain and contributes to how much we crave, sweeteners are not counted – which leaves us craving carbs, whether we realise it or not.[19]

The confusion doesn't stop at the hypothalamus. The gut–brain vagal pathway goes further into the brain and connects to regions that regulate dopamine – a neurotransmitter that is involved in cravings. These, too, get confused by a diet that is high in fat and sugar. One study involved thirty people who had obesity at the start of the experiment and who then lost 10 per cent of their body weight. Brain imaging before the weight loss showed that the people who had gained their weight on a high-fat diet got a lower hit of dopamine from fatty food than a comparison group; consequently, they needed to eat more fatty food to get the same satisfaction. A second brain scan after they had lost weight showed that, although they were no longer on a high-fat diet, their brains still required more fat to switch off the craving. Despite the change in diet, their brains were still set at their previous point. This may help to explain why diets can be so difficult to stick to.

Another study found that it doesn't take much to alter our brain's circuitry so that we are more likely to crave delicious treats. People who added a high-fat, high-sugar snack to their normal diet had more activity in dopamine-related brain regions after eight weeks than a comparison group who had a low-fat, low-sugar version of the same food.[20] Whether this system can return to a baseline after a period of abstinence, and how long this would take, is an unanswered – but important – question.[21]

Wanting and needing

The link to dopamine is important because, as anyone who has struggled with their weight knows, hunger is not necessarily the main cause. Food is also connected to feelings of comfort and satisfaction, anxiety and stress, wanting and pleasure. Again, this makes sense in evolutionary terms: as hunter-gatherers, and even as early farmers, it was beneficial to choose high-fat, high-sugar options when they were available, because they give the biggest nutritional payback. The Western diet, which tends to be high in fat and sugar, has the power to subvert this pathway and make us crave foods that are bad for us.

At this point, I should admit that I have little first-hand experience of this pathway. Eating is something I only remember to do when I'm hungry or when I feel like dipping something sweet in my cup of tea – the rest of the time I don't give food a second thought, which I think must be quite unusual. I have my fair share of unhealthy coping strategies; it's just that (chocolate biscuits aside) none of them are related to food. Reading scientific papers about comfort eating and food addiction didn't help me to understand how it feels to lose control of what you eat, so I was grateful when Sam, whom I have known for many years, offered to explain.

A physiotherapist who works with dogs and horses, Sam makes a living reading the signals of the animals she treats. Watching her at work with my dog Jango, it's impressive to see her respond to the tiniest change in his body language that signals that he is uneasy or in pain. Her own body signals, though, are a different matter. She learned to tune those out decades ago.

Growing up in a family where portions of food were large and everyone struggled with their weight, Sam was bullied from an early age – an experience that was made considerably worse by a sadistic primary school teacher who had a habit of loudly referring to her as 'the fat girl' in front of the entire school. At the age of eight, she started to secretly eat crisps, chocolate and biscuits to cope with the bullying; by adulthood, binge eating had become her default strategy to deal with stress.

During a couple of particularly challenging periods in her twenties, Sam tells me, her entire day revolved around food. If she had to go out, she'd plan stops to buy snacks on the way and eat them in the car. On days off work, she would shop for food, go home and 'just sit around and eat' for the rest of the day. If she had plans to go out for dinner, she'd calculate when she'd have to stop eating so that she'd still have room for an evening meal.

It can be difficult for anyone who hasn't experienced binge eating to understand how it's physically possible to consume such huge amounts of food. Sam says that she did feel full but, perhaps like a competitive eater, she learned that if she tuned out the sensation she could push past it. Fullness was an irrelevant signal because it wasn't hunger that was driving her eating. 'I was trying to satisfy something else, so I had to override the connection with my stomach,' she says.

In many ways, Sam's experience echoes what research tells us about how the gut–brain interaction can encourage overeating. Stress, particularly in early childhood, is a known risk factor for obesity; it seems to change the brain's sensitivity to satiety signals. Exposure to delicious, high-calorie, often ultra-processed foods in childhood exacerbates the problem, disrupting fullness signals and solidifying the link between calorie-dense foods, comfort and pleasure. Over time, as with any addiction, the dopamine neuron pathways become less responsive, which encourages further eating and, inevitably, weight gain.

Once the weight has been gained, social stigma, fat shaming and bullying keep the cycle going by increasing the person's stress; some studies suggest that this leads to further interoceptive numbness.[22] In Sam's case, this numbness contributed to an extremely stressful life event: she found out that she was pregnant just four weeks before her daughter was born. There was more than one factor that meant she missed the signs of pregnancy, including a long history of irregular periods, but Sam thinks her habit of ignoring her internal senses also played a role. 'I was so out of tune with everything in my body that I'd basically trained myself to ignore any symptoms,' she says. 'This and this,' she says, pointing to her belly and then to her head. 'They don't talk.'

The good news is that research into how genes, the environment and stress interact to affect appetite and food-related pleasure circuits is showing that problems regulating food intake is not a moral failing, nor due to a lack of willpower – it's a sign that your gut–brain pathways have gone wrong. This new understanding is chipping away at the stigma attached to excess weight and leading to new interventions that tackle the problem – not by telling people to control their unconscious urges, but by targeting those urges directly.

Not hungry

The past few years have been pivotal in the hunt for interoceptive solutions to gut–brain problems. GLP-1 agonists are a group of drugs that mimic one of the pathways that tell the brain that the gut is full. These drugs, better known by their brand names Ozempic® and Wegovy®, were designed to treat diabetes, but they have also been proven to help people lose weight. Having been licensed to treat obesity since 2014, their use really took off in 2021, when a new version became available that could be injected weekly rather than daily.[23] Several variations are now available, and they have proven to be so effective that *Science* magazine named them the 2023 'Breakthrough of the Year'.[24]

The drugs work by hijacking the gut–brain pathways, changing their dominant signal to 'food is not a priority'. GLP-1 is one of the peptides released by neuropods when they detect nutrients in the gut and report this news to the brainstem. It also acts locally in the gut, slowing down the rate at which the stomach empties, so we feel full for longer. In drug form, the dose of GLP-1 is more than a thousand times what you'd get from the most satisfying meal, so it's no surprise that it is effective at transmitting the message that there's no need to seek more food.

Because many of the signals that govern appetite are unconscious, it can be difficult to explain what this experience feels like, says Colin, who, when we speak, has been taking the GLP-1 agonist tirzepatide for two months. He felt the effects more or less instantly, he says, but struggles to describe what they were. 'Within an hour, it was obvious that something had just switched off, but it's really hard to describe what that thing was,' he says. 'I still enjoy food, I still want to eat, but I have full control of how much, how often and when.'

Colin's experience shows the power of interoceptive sensations at changing how we think, feel and behave, even when we're unaware of them. It also demonstrates how much we rely on these nebulous feelings to feel at home in our own bodies. At first, the experience of being disconnected from his gut feelings was discombobulating – Colin struggled to sleep the night after his first dose, unable to shake the feeling that 'something had changed'. Since then, though, not being controlled by his cravings has been liberating. He has lost weight many times before, but this time the experience has been very different.

'Weight loss is a fight, because you're trying to go against the constant feeling of "I want to eat, I want to eat, I should be eating",' he says. With GLP-1 agonists, though, that fight doesn't happen. 'Now, it's just a decision. I won't eat this. Or I'll eat half of this,' he says.

After three months of dieting followed by two months on tirzepatide, Colin has lost 17 per cent of his body weight – the rate of weight loss sped up noticeably once he was on the medication. His body mass index (BMI) has moved from 'obese' to the upper end of a healthy weight range. He plans to keep going a little longer, and is working with a therapist on the triggers that lead him to overeat. 'I'm seeing it as a learning experience so I can identify why it's happening. I don't want to use the drug, lose the weight and then – bang – go straight back to where I was. I think it's a good opportunity to learn.'

There's no doubt that these kinds of drugs have transformed the treatment of obesity, but some scientists warn about assuming that the problem has gone away. 'Obesity is not solved, regardless of what the media says,' Lisa Beutler told the audience at a recent US National Institutes of Health research conference on gut–brain interactions. She pointed out that these drugs are expensive and not easily accessible. In the UK, it's only available on the National Health Service (NHS) for people who have obesity and who also have weight-related health issues, and medical insurance coverage in the US varies. Plus, these drugs don't work for everyone. Around 15 per cent of people lose little to no weight; even among those who do, weight loss tends to plateau after six to nine months.[25] Then there's the fact that stopping the drug removes the appetite suppressant effect, leaving people with the choice of staying on medication over the long term or risking weight gain.

Another issue is that in some people the drugs work *too* well. In a 2024 paper published in *Obesity Reviews*, Khalsa, working with obesity specialist Jesse Richards from Oklahoma State University, described several case studies of obese patients whose loss of appetite became dangerous. One restricted her diet to just 400 calories a day and started to rapidly lose muscle as well as fat. Another had so little appetite that she put herself on a liquid diet of water and Diet Coke, restricting solids to one day per week. Another lost their appetite not only for food but also for water, becoming dangerously dehydrated. Colin hasn't experienced anything so severe, but it is easy from talking to him to see how it could happen. 'There's no body response telling me to eat,' he says. 'If you said to me "I dare you to not eat for three days", that wouldn't be a problem for me now.'

Now that these drugs are becoming so widely available – at least, for those with the means to access them – there is a real potential for harm, Khalsa warns. Without proper oversight and regular medical check-ups, these drugs could fool the gut–brain pathways so effectively that even the most basic survival signals would fail to get through.[26]

All this means that we must continue the search for other ways to reset the gut–brain axis. As with so many other body–mind issues, it's a question of working out where the glitch in the system is and intervening where possible. For Sam, things came to a head in 2023 when her weight spiralled to a point where she struggled to walk her dogs. A severe bout of depression followed, leading to therapy and a diagnosis of ADHD. The therapy allowed her to unpack the emotional triggers of her overeating, while ADHD medication allowed her to deal with impulsive eating and had the welcome side effect of suppressing her appetite.* The net result was that she could use the mental energy that had previously been taken up by issues around food to relearn to listen to her body. 'The last couple of years, I've completely changed how in tune I am with my body,' she says. 'I think I've retrained my stomach to realise what a normal portion is and what an overeating portion is. If I tried to binge-eat today, I don't think I could.'

This treatment plan wouldn't be right for everyone, but there are other interoceptive-based options for dealing with overeating, ranging from minor lifestyle changes in those least severely affected to GLP-1 agonists and major surgery for those whose eating behaviours have become life-threatening. Starting at the most extreme end of the spectrum, bariatric surgery works well when all else has

* Lisdexamphetamine, the medication Sam has been prescribed, is also used to treat binge eating disorder.

failed, or if the body–brain pathways are broken beyond repair. There are several versions of the surgery, all of which reduce the size of the stomach, so that fullness sensations are triggered after a smaller amount of food. The way the surgery completely cuts off a large part of the gut–brain conversation is drastic, but research suggests that, as well as restoring a sense of fullness, it increases the diversity of gut microbes. It also sometimes even changes food cravings to healthier options, possibly because a smaller stomach empties into the intestines more quickly. Too much sugar and fat in the intestines at once overwhelms the intestines and causes 'dumping syndrome', which features nausea, bloating and cramps. Over time, the unhealthy options are associated with discomfort and become less attractive options.[27] The hope is that, as we gain a better understanding of exactly how the gut–brain conversation can spiral out of control, we'll be able to intervene long before drastic measures become necessary.

One slightly less invasive option is gut-focused vagus nerve stimulation. In 2015, the US FDA approved the vBLOC system, which is surgically implanted on each branch of the vagus nerve that connects gut and brain. A clinical trial in over 100 volunteers showed that the implant was safe: compared to a placebo group, those who received stimulation reported fewer cravings, more satiety and better control of their eating habits. They lost, on average, 10 per cent of their starting body weight over two years.[28] As with most vagus nerve interventions, how it works isn't clear. It also isn't clear whether it blocks bottom-up hunger signals or enhances bottom-up signals about fullness.[29] But it does, at least, seem to lead to meaningful amounts of weight loss and a better quality of life, while also being less invasive than bariatric surgery.

Feed the bugs

At the other end of the spectrum, the easiest lifestyle change is to simply eat more fibre. Many microbes that live in our intestines release short-chain fatty acids as they break down fibre in the intestine. Some bacteria also turn fibre into amino acids, the building blocks of proteins. Neuropods can detect both of these types of microbial molecule, then they translate them into appetite-suppressing signals that are sent to the brain. If they can't get hold of fibre, some of the microbes start tucking into the mucus lining of the gut, which stops the immune system treating them as a foe and setting off a wave of mood- and energy-sapping inflammation. Eating as much fibre as possible, then, is a good idea for many reasons, one of which is that fibre helps with appetite control.[30]

Studies in mice have also shown that gut microbes may be able to reset the dopamine-based pathways that are behind our craving for sweet and fatty foods. In one study by researchers at Sarkis Mazmanian Lab at Caltech (the California Institute of Technology) in Pasadena, California, mice that were given antibiotics to reduce the diversity of microbes in their gut showed increased activity in dopamine-related regions related to appetite. When they were offered a range of foods, they were more drawn to high-fat and high-sugar options; they also ate for longer and consumed more calories in each sitting. Intriguingly, adding back two particular microbes, *Lactobacillus johnsonii* and

S24-7, got rid of the abnormal brain activity, the cravings and the overeating. It isn't yet clear how this works, but it seems likely that gut–brain communication via the vagus nerve is involved.

Another strategy is to prioritise protein, which of all the macronutrients has been found to be the most satiating per calorie. There is also evidence that eating protein can make you more tolerant of other people, even when they are being a pain in the backside. A 2017 study reported that, when playing a competitive game, people were more likely to tolerate other players acting unfairly if they'd had a high-protein breakfast rather than a high-carb breakfast.[31] Why this might be the case isn't clear, but it seems to have something to do with the way gut microbes turn food into neurotransmitters that affect our behaviour, via the relative balance between serotonin and dopamine.[32]

We're still a long way from understanding the complexities of gut–brain signalling well enough to prescribe a neat list of weird diet-related tricks to hack the system. One thing is for sure, though: a diet that revolves around food that is high in fat and sugar, and low in fibre, is not a great idea. Beyond that, there's not much to add to the journalist Michael Pollan's suggestion in his classic 2007 essay on nutrition in the *New York Times Magazine*: 'Eat food, not too much, mostly plants.'[33] Then, with a bit of luck, the gut, brain and microbiome will do the rest.

Gaining weight is by far the most common outcome of gut–brain interactions going awry, but it is not the only one, such is the complexity of connections between the gut and the brain. The growing understanding that many disorders which were previously thought to be either a problem with the gut or 'all in the mind' are actually caused by a problem with the interaction between the two is quietly revolutionising medicine. Now it's clear that treating one element of the gut–brain axis without factoring in the others is a flawed strategy.

In some ways, it's mystifying that medicine has treated emotions and the gut as separate for so long. Many languages around the world have a saying that is the equivalent of 'gut feelings': in Turkish, it's a 'voice from inside'. In Russian, it roughly translates as 'I feel it in my insides' or 'I feel it with my very being'. In Spanish and Portuguese, they are a 'presentiment', a feeling that comes before conscious awareness.[34]

There hasn't been a huge amount of research carried out into whether gut feelings help our ability to make good decisions, but several studies suggest that having insight into what's happening inside can be a useful skill for both adults and children.[35,36] John Coates, the financial trader turned neuroscientist we met in Chapter 1, has an unusually acute sense of his heart, but says that the sixth sense that showed up on the trading floors of New York and London was not in his heart but in his gut. 'My stomach is incredibly sensitive to risk – when things were wrong, they would show up in my stomach. When they were right, it was more a feeling of certainty; I'd feel galvanised.'

Studies in which people are asked to mark on a diagram of a body where they experience different emotions show that the gut features in shame, disgust, anxiety, jealousy, love and fear.[37,38] A few studies are exploring the physiological basis of these sensations. Research by Giuseppina

Porciello's group at Sapienza University in Rome has used smart capsules, similar to the one I swallowed earlier, but designed to record changes in temperature, acidity and pressure, to explore what happens in the gut when we experience various emotions. The group found that stress and disgust made the gut more acidic, while happiness made it less acidic.[39] Another part of the study was designed to discover whether moral disgust was like physical disgust (e.g. associated with feeling as if you need to vomit up something toxic). They asked the volunteers who had swallowed the capsules to listen to various disgust-related sounds, some physical (the sound of vomiting) and some moral (stories involving incest). It was a small study, with just twenty-four participants, but the results suggest that both kinds of disgust stem from similar physical changes in the gut.

Both kinds of disgust made the gut churn, but physical disgust evoked a much stronger reaction and almost triggered vomiting. And while each kind of disgust made the gut colder – perhaps because it diverted blood away from the area – moral disgust, which made the gut more acidic, evoked a less extreme change. Other studies have probed the same connection in reverse: when people are given anti-nausea drugs, they seem to feel less disgusted by revolting images.[40]

These results suggest that we're not imagining the link that our gut has with emotions. Something physiological is actually changing inside us – so it's hardly a surprise that so many gut-related disorders are linked with emotional distress. Irritable bowel syndrome (IBS) is the most obvious example.

IBS affects up to 10 per cent of people worldwide and is strongly linked to stress, anxiety and depression. By some estimates, around half of people with an anxiety disorder also have IBS, and those with IBS are three times more likely to have an anxiety disorder.[41]

At the gut end, symptoms can be partly explained by problems with how food moves through the gut. The enteric nervous system sets the speed of the contractions that propel food through the gut (this process is known as peristalsis) and dictates the opening and closing of various valves along the way that let food through to the next section. The enteric nervous system is independent in a similar way to a teenager. It can do a lot by itself, but it is heavily influenced by those around it – in this case, microbes, the immune system, and the pathways that link the gut to the brain.

In a crisis, the sympathetic arm of the autonomic nervous system, which kicks in to activate the body when we need to respond to a potential threat, can step in to tell the enteric nervous system to put digestion on hold for a while – a sensible strategy every now and again, but problematic for anyone who is exposed to chronic stress or who has anxiety. There is some evidence that problems with gut motility can cause signals to be sent to the brain indicating that all is not well, changing the brain's predictions. This may explain why, in many cases, gut problems come first and a mood disorder follows.[42]

The microbiome plays a key role in this, in particular by producing and regulating serotonin, a neurotransmitter well known for its role in mood. More than 90 per cent of the body's serotonin is produced in one type of neuropod

– enterochromaffin cells, which work closely with the gut bacteria to manage the translation of the amino acid tryptophan into serotonin and other signalling molecules. The connections go both ways – the brain can tell ECCs to release serotonin into the gut, where it is taken up by microbes. Other microbial production, including of the short-chain fatty acids that help regulate appetite, also act on the enteric nervous system to change the rate of gut contractions. They also help prevent inflammation, by maintaining the gut mucus barrier that keeps the gut microbes at a safe distance from the bloodstream, where they would be treated as invaders and stimulate an immune system response.

The connection between inflammation, gut disorders and depression is well known, as is the fact that people with depression have less diverse microbiomes. In now-famous experiments from 2016, rats that had been bred specifically to have no microbiome showed signs of depression – spending more time in dark corners and less time exploring a maze and eating tasty treats – after receiving a transplant of gut bacteria from humans with depression, as well as a reduced ability to turn tryptophan into serotonin.[43] Studies that have tried to use this knowledge to treat depression by tweaking the gut microbiome have had mixed success, perhaps because microbes are just part of a much larger, interconnected system.

The question, then, is how to fix problems in such a complex system when there are so many factors to consider. One option is to focus not on the signals themselves, but to work on changing how we interpret them. Nancy Zucker, a clinical psychologist at Duke University, has pioneered an intervention for children who severely restrict their food intake following gut-related pain. Her programme uses a variety of cartoon characters for different sensations, including 'Sabrina Stuffed' and 'Gassy Gus'. It aims to help children differentiate between gut sensations; rather than experiencing all gut sensation, whether fullness, bloating or hunger, as negative and to be avoided, they can learn to decipher what each sensation means.[44]

One place where an adapted version of this could be useful is in the treatment of eating disorders. Hindy Friedman, a woman with anorexia (we will meet her properly in Chapter 5), says that the bloating and discomfort she feels after eating is a huge barrier to her recovery. 'A lot of people with eating disorders struggle with gut issues,' she told me. 'I don't feel good when I eat. Having any sensation in my stomach, it's uncomfortable. I'll do anything to run away from that.'

Sahib Khalsa's studies have shown that while some of this is a result of errant predictions from the brain and the assumption that all gut sensations are bad, it can also be linked to actual problems in the gut. Studies of the electrical activity generated by the enteric nervous system have shown that people with anorexia often have a slower gut rhythm, which means that food moves along more slowly than in healthy people; this correlates with their experience of feeling over-full and bloated after even a little food.[45] But it's not clear whether this is a risk factor for developing an eating disorder or the result of long-term restricted eating.

In Khalsa's words, it's complicated, and just how all these moving parts fit together is still being worked out. But all this research is already demonstrating how much impact our gut feelings have on our mental and emotional lives, whether we realise it or not.

Conscious or not, the signals from within clearly have a huge impact on our mental state, and vice versa. As interoceptive research has begun to accumulate, it is becoming ever clearer that it no longer makes sense to think about physical ailments and mental disorders as separate entities. Some of the most common and disabling disorders, such as anxiety, fatigue and chronic pain, can only be truly understood – and treated – by broadening the focus of medicine so that body and brain are treated not as separate entities but as an interconnected whole.

I call this new view of medicine 'bodymental health'. It has a lot in common with the work of psychiatrist Bessel van der Kolk, who published the bestselling book *The Body Keeps the Score* (Penguin, 2015). Van der Kolk's work, which has been hugely influential in trauma therapy circles, hinges on the body–brain conversation, which is the foundation of our conscious experience. Yet, as scientists look for answers to common health problems in all parts of the body, not just the brain, they are finding that the body doesn't so much 'keep the score' as 'hide the ball and move the goalposts' – and it sometimes blindfolds the referee. 'Bodymental' isn't yet an accepted term but, based on what we're learning about how body and mind are inextricably connected, it absolutely should be.

5

Bodymental health

Keeping the score when body and brain have lost count

As a rule, I try not to dribble during meetings with scientists. So when neuroscientist Ryan Smith handed me a bib and a bunch of tissues, I started to regret agreeing to take part in his latest experiment. Back at the Laureate Institute for Brain Research in Tulsa, Oklahoma, I was hoping to find out how a better understanding of interoception is revolutionising what I'm calling bodymental health, and to experience some of the new treatments that are becoming available. I had no idea what I was in for that day – but since it had to do with interoceptive threat processing, I was prepared to be scared.

Smith explained that the experiment was designed to investigate how threat-related body signals become conscious, and how the process differs between individuals. In this case, the danger would take the form of a sudden shortage of air, a sensation known as 'air hunger'. It might not be particularly pleasant, the researchers told me, but it was perfectly safe. Even if I *felt* like I was suffocating, I'd be getting plenty of air throughout.

I sat down in the corner of a small room while Smith's team wired me up to various sensors. Then, with my chin on a rest and a clip on my nose, they asked me to breathe through a snorkel-like tube in my mouth, which was connected to an air tank. All I had to do was breathe and press a button when I thought that inhaling had become more difficult.

Pretty soon, my embarrassment at soaking the bib with dribble was the least of my worries. Once it became difficult to breathe, it was as if nothing else mattered – all I could do was tell myself that everything was fine and hope that the next breath would be easier. It was the perfect demonstration of why certain interoceptive signals loom so large in our consciousness. From a survival point of view, being able to breathe is non-negotiable. Without oxygen, every cell in the body would soon die.

Just as a lack of air is always urgent, the same can be said for heart sensations. A steady supply of blood is another non-negotiable, so a surge in heart rate – at least when the brain hasn't predicted it – is big news. Khalsa has illustrated this by giving volunteers an adrenaline-like drug called isoproterenol that ramps up the heart and breathing rate. Because the drug doesn't cross from the bloodstream into the brain, the first the brain hears about the change is via sensors in the blood vessels and chest – through 'bottom-up' interoceptive pathways.

What's interesting is that neither breathing nor heart-rate sensations are experienced as just 'information' if the brain isn't expecting them; both are part of an ancient response to threat, which marks them as important and urgent, and the connections between sensing and responding go both ways – a racing heart[1] or shortness of breath[2] can trigger anxiety even if there's nothing, objectively, to fear.

For this reason, anxiety disorders are considered the classic example of how body signals play an important role in mental health, and research into anxiety forms a large portion of the research that has been carried out so far. But as research has developed, a more nuanced picture of the body's role in mental health has emerged: one in which glitches in body–brain connections are involved in everything, from our sense of self, our emotions and relationships, to our awareness of our own health. In this new view of health, the best treatments aren't trying to tackle physical and mental issues separately, but as one fully integrated system that only makes sense when viewed as a whole.

The body in mind

In the early days of this research, most studies focused on a single measure of internal sensitivity: how accurately a person could detect their heart rate while sitting quietly and not touching any part of their body where they could feel their pulse. This, along with standardised questionnaires that ask people to rate statements such as 'I notice when I am uncomfortable in my body' on a scale from 1 (never) to 5 (always), was used as a measure of a person's 'interoceptive awareness', and early studies suggested that it was key to everything from a person's susceptibility to mental health disorders to how they respond to pain, fatigue and stress. Other studies found that interoceptive accuracy was important for a person's awareness of their own emotions and how strongly they respond to the emotions of others – the biological basis of empathy.

As studies on interoceptive awareness started to mount up, though, they raised more questions than answers. What explains the variation between people? Are differences in interoceptive accuracy genetic or learned? Do some people have stronger signals coming from their bodies, or are they just better at detecting and interpreting them? Perhaps some people are simply better at shifting their attention between the world around them, their bodily signals and the internal chatter of their mind? Without this information, it would be impossible to measure what it meant to have a healthy interoceptive system, let alone work out how to correct the interoceptive version of short-sightedness.

Sarah Garfinkel, who is now a professor of Cognitive Neuroscience at University College London, decided to try to fix the problem. Working with Hugo Critchley at Brighton and Sussex Medical School, she set about dividing the process of interoception into multiple levels, to make it easier to find differences between people and how they might relate to various symptoms. There has been some disagreement about how to best measure each dimension, but by and large interoception researchers have taken the framework on board as a way to narrow down what can go wrong along the various body–brain lines of communication, and how we might intervene.

With the disclaimer that the following are paraphrased from Garfinkel's original descriptions,[3] the main questions that are relevant to bodymental health are as follows:

How strong are the bodily signals?
How loudly does the body tend to shout? How strongly does the brain react, and at what volume do the various signals break through into a person's consciousness?

How accurately can a person detect them?
Compared to the actual number of heartbeats in a minute, for example, how accurately can they count the contractions of their heart?

How confident are they in their interoceptive ability?
Does a person believe they are sensitive to their body signals, or do they think they are guessing? Do they notice, and use, their body sensations in everyday life?

Are they more or less accurate than they think?
How well does a person's confidence in their interoceptive ability relate to their actual accuracy?

What does the body sensation mean?
Does it feel good or bad? How does a person interpret the cause of an unexpected change in the signal?

Are they flexible?
How fixed is a person's belief about what their body signals mean? And how readily do they adapt if their initial interpretation is proven wrong?

Research in this area is revealing that our inner senses are far more complicated than our external ones. There is no test for anxiety that's the equivalent of having your sight checked, for the simple reason that there is more than one sensory signal involved. There's no equivalent of a hearing test to show that you feel depressed, because while sound only comes in waves, any number of factors can lead to low mood and a lack of motivation.

Understanding our own inner senses, then, is about more than simply identifying the receptors and pathways that are involved in building a feeling. It's about understanding the many factors that feed into the construction of that feeling – whether conscious or unconscious – and deciding when is the best point to intervene. When seen through this lens, it becomes clear that many different bodymental health issues have glitches in the same few parts of the system. Some of these happen in interoceptive stages that are outside our conscious awareness, which, as we'll see next, explains why so many bodymental health disorders, from anxiety and depression to chronic pain and fatigue, make no sense – often, not least to the people experiencing them.

Signalling problems

Debbie is not an obvious candidate to have an anxiety disorder. A veteran of the Royal Air Force, she is fit and capable, and a vocal campaigner for military mental health services. However, her adult life has been punctuated by panic attacks that, to her, have often seemed 'totally random'. A few years ago, she told me, she was enjoying a summer's day at the beach with her family. She had just finished bodyboarding and was walking back up the beach when she noticed that the beach felt uneven under her feet. Combined with the waves crashing around her legs, she started to find it tricky to walk. 'The next thing, I'm having a horrible panic attack,' she recalls. 'The world is crashing in on me. Everything is disappearing, I can't see properly and I can't breathe.'

Such an extreme reaction would have been understandable if Debbie couldn't swim or was afraid of the sea, but she's a strong, confident swimmer who swims in the sea all year round, even in the depths of winter. In fact, she considers fresh air, exercise and immersion in nature to be vital for her mental health.

At the time, Debbie had no explanation for what was going on. But according to research by Jessica Eccles and other researchers at Brighton and Sussex Medical School, Debbie's symptoms were far from random; they can be explained by the fact that she, like 20 per cent of people, has hypermobile joints.

Joint hypermobility, more commonly known as being double-jointed, is when one or more joints extends further than a normal range of motion. In some walks of life, notably dance, yoga and gymnastics, being unusually bendy is a genetic blessing, but in terms of bodymental health it can prove a liability. The first person to notice that the two things were linked was the rheumatologist Jaume Rotés Querol, who in 1957 observed that people who are unusually bendy are more likely to experience what was then called 'nervous tension'. With no explanation of why this might be, his observation was largely ignored, but recent research has confirmed the link. People with hypermobile joints are up to sixteen times more likely to have anxiety or panic disorders.[4] Even when they don't qualify for a clinical diagnosis, they score significantly higher on measures of 'trait anxiety' – better known as having an anxious disposition.[5]

Eccles believes that the link between hypermobility and anxiety doesn't come directly from the bendy joints, but from the way that bendiness throughout the body disrupts bottom-up interoceptive signals. Hypermobility stems from an underlying genetic mutation that causes collagen, a protein that makes up the ligaments and tendons in the joints, to be unusually stretchy. But, because the mutation in the gene is present throughout the body, stretchy collagen is also found elsewhere, including in the walls of blood vessels. And it's the effects that stretchy blood vessels have on circulation that lead to anxiety.

When the heart pumps blood to the extremities of the body, it relies on pressure from the collagen in the blood vessels and muscles to squeeze it back to the heart. In hypermobile people, though, the blood vessels don't squeeze as well as they should, meaning there is less pressure to help send the blood back to the heart. If a hypermobile person stands up too quickly, blood will rush to their feet – and their body won't be able to react quickly enough to counteract gravity. A similar problem can arise in hot weather when blood is pumped to the skin to help cool the body down, and pools there rather than being squeezed back to the heart; similarly, after a big meal, blood heads to the stomach and stays there. When blood hangs around where it shouldn't, the heart has a problem – it needs to keep blood circulating to vital organs, including the brain, and the only thing it can do to get the blood moving is to beat faster.

The resulting rise in heart rate throws up a mismatch between what the body is saying and what the brain has predicted, based on observations of the world. The brain has no evidence of a threat, but the body is responding as if there is one. To make sense of the mismatch, the body either needs to reduce its heart rate to match the original prediction – impossible, given the need to maintain blood flow – or to update the brain's prediction from 'all is well' to 'be vigilant'.[6] This is experienced in the body as a feeling of sudden, unexplained unease. 'Maybe you haven't twigged that this happens to you every time you stand up, every time you eat a large meal, or every time you are in a hot environment,' says Eccles, who has hypermobile joints herself. 'You just perceive it as an aversive phenomenon that makes you feel weird and anxious.'

The fact that so few people are aware of the link between hypermobility and anxiety means that people like Debbie often have no idea why they feel this way – and medicine's long history of focusing exclusively on the brain in mental health means that neither do the doctors they turn to for help. But the way to help people make sense of what's happening is to give them the information they need to reinterpret what's happening. For Debbie, working with Eccles to understand what's going on inside her has made a huge difference. 'It's about noticing what's happening and working out what you need to do when you have that sensation,' she says. 'If I get on the floor and breathe, I can bring myself out of it. I wish I'd understood it when I was younger.'

Interestingly, it's possible that people who don't have hypermobility but who are physically inactive may have a similar reaction to sudden changes in heart rate because they have never learned through experience that a racing heart can be normal, healthy and safe. What's more, studies suggest that even without hypermobility or a lack of fitness, some people may just happen to be more sensitive to their bottom-up signals. In experiments, Khalsa gave people with generalised anxiety disorder and a non-anxious comparison group a low dose of the adrenaline-like drug isoproterenol, at a level where many people wouldn't feel its effects on their heart rate. It turned out that the heart rates of people with anxiety disorders sped up significantly more than heart rates in the non-anxious group. And while most of the non-anxious people felt little or no change, the anxious group noticed the change in their heartbeat and breathing, and reported feeling more anxious. This suggests that some people, for whatever reason, have a lower threshold than most for detecting their own stress hormones, which makes them feel anxious more often than others.[7]

What do you expect?

It would be easier to solve disorders such as anxiety if problems with the bottom-up signals were the whole story; if the body did indeed keep the score and the brain just sat there, ready to read it out. But as we've seen, interoception is not just about the sensations coming in from the body. The brain is constantly predicting what it expects to sense based on previous experience, setting in motion any necessary adjustments and checking its predictions against incoming sensations. If the prediction and signals match, then no action (or conscious sensation) is necessary. But if they don't, an error message – in the form of a feeling – flags up that there's a need for further adaptation and learning to update the prediction for next time. Most of the time this is also no problem. We learn the lesson and get on with our lives. But as we've seen, sometimes the bottom-up signal can be more dramatic than is necessary, as can the prediction. And when they clash, we have a problem: which one should we believe?

Our predictions vary, for the simple reason that we all have a different mix of genetic tendencies and life experience that affect what our body signals mean to us. Depending on what has gone before, what the brain expects to happen and prepares for may be wildly out of step with what is actually happening. Someone who was bullied as a child might find that their brain prepares their body for the worst when they walk into a school reunion, for example.

This, in itself, may not be a problem if the situation plays out as predicted. Hypervigilance might prove to be a good strategy if the mean girls are still mean. But in an ideal world, the body and brain would quickly readjust the prediction if evidence came along that disproved it. An extreme example of when this process goes wrong is in post-traumatic stress disorder. A sudden loud bang will cause everyone's heart rate to rise, but whether a person's expectations were formed in safe, tree-lined streets or in a war zone makes a huge difference to whether the initial shock will spiral into a panic attack.

Ideally, our brain would quickly work out whether the prediction or the live signal is most reliable, before responding to solve the problem. But it doesn't always work like that. How and why this process can go wrong is the subject of Ryan Smith's dribble-inducing experiments.

In previous experiments, Smith measured volunteers' ability to detect their own heartbeat when sitting quietly. In one trial they were told that guessing was fine, and in another they were told only to count the heartbeats they actually felt. The purpose of comparing these two measures is to determine how much of their conscious awareness comes from the actual body signal and how much is based on prior expectation. Then Smith asked them to hold their breath for as long as they could and repeat both heartbeat counting tasks – the theory being that holding your breath makes the heartbeat signal stronger, boosting the bottom-up signal without changing the prediction.

The question Smith wanted an answer to was: how strong does the signal have to be before the brain changes its prediction? And what, if anything, do differences in shifting from one to the other mean for a person's vulnerability to poor mental health?

It turned out that people with anxiety disorders, depression, eating disorders and addictions were significantly less flexible. They were more likely to stick to their brain's prediction about what their heart was doing, regardless of the change in evidence from the body. Healthy people, meanwhile, were much better at shifting their allegiance to the live information when it changed. In other words, healthy people are more likely to trust their body, while people with mental health disorders tend to stick to the hard-won lessons of the past.[8]

The breathing experiment is designed to look at whether this is also true of sensations other than heart rate. The study was only just getting started when I visited the lab in Tulsa; they were yet to enrol volunteers, but when I road-tested the set-up, I was surprised by how stubborn and inflexible my own brain turned out to be.

In the experiment, a tone was played through the speakers immediately before I took an in-breath. Sometimes it was a high-pitched tone, and sometimes it was low-pitched. Sometimes the breath that followed the tone would be harder to take, other times not. My job was to say (a) whether I expected a hard breath after hearing a tone and (b) whether I actually felt that taking a breath was harder. Given how horrible it feels to take a restricted breath, it should have been easy – and while I was doing it, I thought it was. After a few breaths I deduced that the high tone tended to precede a restricted breath. But when the results came in, it became clear that I'd been duped – not just by the researchers, but also by my own brain.

In the first few rounds of the experiment, it was true that the high tone signalled that the next breath would be restricted. But after a while, they switched it up without telling me, so that the tone and breath combination was random. As far as my brain was concerned, though, it wasn't random at all. I was so convinced, in fact, that even when a high tone was followed by an easy breath, I felt like I was struggling to breathe about a third of the time. And because I'd learned to associate a low tone with an easy breath, on half the occasions when a restricted breath followed a low tone, I didn't feel a thing.

Since the study is still ongoing, Smith wouldn't be drawn on whether this was an indication that I'm unusually inflexible and prone to anxious catastrophising. But in the longer term, the idea is that this kind of approach might reveal why some people are more vulnerable to mental health issues than others. According to estimates, 70 per cent of adults experience serious trauma during their lifetime, but only 6 per cent of the population develops post-traumatic stress disorder (PTSD).[9] It's possible that those who suffer more are the people who struggle to adapt when the evidence changes. And since that inflexibility to changing inner sensations shows up not only in anxiety-related disorders but also in eating disorders, depression and chronic fatigue, it raises the possibility that we could use this kind of test to find the underlying cause of many mental health disorders, then design targeted interventions to help people rebalance body and brain.

Not regaining a balance can lead to long-term ill health of the body as well as the mind. Whatever the initial cause of the issue, if it goes on for too long it turns into a general prediction of what is needed to survive, and the whole body–brain system shifts accordingly. In anxiety, this can mean a hardening of the arteries to deal with the constant demands of high blood pressure; in the brain, it can lead to lower levels of connectivity in circuits that would otherwise calm things down. In Khalsa's isoproterenol studies, for example, adrenaline-sensitive individuals had a double whammy: hypersensitivity to stress hormones and lower activity in the prefrontal cortex, a brain region that's involved in interpreting body signals and deciding whether to calm things down. The consequence is that body and brain work together to sustain an unhealthy state of affairs. Fighting to stay on an even keel in these circumstances can prove exhausting.

If this situation is left untreated, it could crash the whole mind–body system, resulting in depression. This idea was put forward by the computational neuroscientist Klaas Stephan and his colleagues at the University of Zurich.[10] Stephan and his team suggest that if a mind–body clash isn't resolved after several attempts at action or learning, it reaches a point where further investment of energy and effort starts to seem futile. At this point, the body–brain system shifts into energy-saving mode, which to the person experiencing it feels like fatigue and dejection. Perhaps they have tried to control their anxiety by rationalising that they are safe, but the sense of dread won't go away. After multiple fruitless efforts to solve the problem, the brain starts to predict that the world is inherently unpredictable and that all attempts to regulate the body will fail. Klaas and his colleagues argue that this helps to explain why so many health concerns – physical and emotional – lead to depression and fatigue. The hope is that if we can understand this process better, we might stand a better chance of intervening earlier.

I feel nothing

For some people, then, problems with bodymental health manifest as overwhelming feelings that spiral out of control. For other people, the underlying problem is almost the opposite: they are unusually insensitive to their body signals, and have trouble making the link between sensations and emotions.[11]

This tendency is known as alexithymia* and it affects around 10 per cent of the population. It is defined as a personality trait rather than a clinical disorder, but it shows up as a common feature of mental health disorders, from eating disorders to depression and obsessive compulsive disorder (OCD).[12] It is also a common feature of autism and ADHD.

A related concept is 'alexisomia', a term coined in 1983 by Yujiro Ikemi of Kyushu University in Japan to describe an inability to notice bodily sensations – or the ability to notice them, but then to ignore them. Ikemi called alexisomia 'a general crisis of the modern era' and warned that many modern diseases, both physical and emotional, are the result of our tendency to fail to heed what he called the 'wisdom of the body'.[13]

The reason that being deaf to our body signals causes us problems is that, regardless of our conscious awareness of them, they still affect our physical health, and our thoughts, feelings and decisions. Without having a direct line to them, life can get confusing. Did I eat too much, or is it hot in here? Am I hungry or tired? In OCD, it might account for the nagging feeling that something isn't quite right, but it isn't clear what that thing might be. In diabetes, a lack of awareness of a link between blood sugar levels and symptoms such as thirst and fatigue, can make it challenging for some people to manage their condition. With alexithymia and alexisomia, people can be perpetually left in the dark about what they are feeling and why.

* An online self-test for alexithymia can be found at https://www.alexithymia.us/test-alexithymia

One important question that researchers are still trying to figure out the answer to is: what is a good amount of interoceptive sensitivity? We know that it is possible to have too much interoceptive focus: people who are diagnosed with heart arrhythmias that they previously knew nothing about, for example, often become preoccupied with their heartbeat, and become anxious when they feel even the slightest change in its rhythm. Increasing interoceptive focus in some conditions (such as chronic pain, chronic fatigue and PTSD) can lead to more anxiety and suffering. What is less clear is where to draw the line between too much interoceptive sensitivity and too little.

This is something that Sarah Garfinkel and Hugo Critchley have been working on for over a decade. Critchley's studies were hugely influential in the early days of interoception research in the early 2000s; his brain imaging studies provided hard data to support the burgeoning idea that body signals were important in building the mind, and provided evidence to back up the idea that the insula is an important brain region for putting bodily signals into context. He had already shown that interoceptive signals are important for memory,[14] the self, and emotions, particularly fear,[15] both consciously and unconsciously. When Garfinkel joined his lab in 2011, having previously worked with PTSD patients, she was curious about whether the heart–brain link might offer new avenues for the treatment of mental health disorders.

Having established that the heart plays a huge role in mental and emotional processing, Critchley and Garfinkel made the surprising discovery that what was most important in determining a person's risk of mental distress was not how accurately they could detect their heartbeat, but to what extent their ability to feel it matched how sensitive they thought they were to changes in their bodies, or how aware they were of any changes. The healthiest combination is when people think they are good at detecting their own heartbeat, and tests show they are right. On the other hand, a person who thinks they are sensitive to their body signals but turns out not to be is more likely to have anxiety, depression and a host of other bodymental health issues. 'It's the discrepancy between the subjective belief and accuracy that corresponds to symptoms,' says Garfinkel.

This got Critchley and Garfinkel wondering whether it would be possible to close the gap between what people *think* they feel and what they *actually* feel. Garfinkel had spent a lot of time in the lab, testing the equipment before using it on study participants, and had noticed that, with practice, the discrepancy between her accuracy score and her confidence began to narrow. This led to a clinical trial to investigate whether interoceptive training could reduce anxiety in a group of people with autism who experience anxiety related to their condition.

The training is a variation on the standard heartbeat detection task. Volunteers are hooked up to electrodes that monitor their heart in real time, and are asked to start counting their heartbeat silently. When told to stop, the volunteer reports how many they felt, and how confident they are about whether they are right. Then the person's heartbeat is played back to them through speakers, either in real time or slightly out of time with their actual heartbeat. Their job is to say whether it was in time or out of time and, again, to rate their confidence.

In the training study, volunteers first did light exercise for two minutes, to raise their heart rate so it was easier to feel. They were given feedback on their accuracy after each bout, and they had six training sessions over two months, each thirty minutes long.

So far, the data strongly suggest that the training works.[16] The intervention not only improved participants' accuracy, but it also had a real effect on their anxiety. A third of the volunteers improved to the point where they were no longer considered clinically anxious, and the benefits remained a year later. Similar studies in non-autistic people with anxiety showed similar results, as did a study in people with joint hypermobility, led by Eccles, which was combined with therapy to help them understand the link between hypermobility and a racing heart. 'If you understand that about yourself, you can think to yourself, "Actually, I stood up too quick. It'll go back to normal in a few minutes. My heart's not going to explode, it's not out of control,"' says Eccles.

The good news is that a small amount of embodied knowledge seems to go a long way. Jane Green, who took part in one of the early training studies and also has hypermobile joints, says that the training helped her to make sense of what she calls 'whoosh attacks': sudden bouts of anxiety that occur when she is under stress and that can quickly become overwhelming. 'I realised when I'm having a whoosh attack that I'm reacting in a physical way. I think knowing about it helps – I can't stop it, but I know what's happening. It doesn't escalate,' she says.

Garfinkel, Critchley and Eccles are working on bringing this technology out of the lab and into the hands of anyone who wants to get to know their body from the inside. They are about to test an app-based set-up, to see if the same benefits can be achieved without a trained therapist. If it works as well outside the lab as it does in studies, it might be available to buy before the end of the decade.

In the meantime, it's easy to follow at least part of the Sussex study protocol. Doing gentle exercise to raise the heart rate and then paying close attention to how it feels as it returns to normal is one way to get better at connecting with your heart in a safe, non-anxiety-inducing way. A similar approach is emerging in body-based therapies for anxiety disorders, including PTSD. Getting people used to the feeling of a raised heart rate or changes in breathing rate in a safe environment, whether through exercise, biofeedback or mindfulness, is already being found to help speed recovery.[17]

It may also be possible to train people to regulate their stress response, to prevent mental health issues developing in the first place. One such intervention is being pioneered by researchers at Radboud University in the Netherlands, in collaboration with the Dutch police force and a team of computer game designers.

Policing is a notoriously stressful occupation, which often requires overriding natural fight-or-flight responses and remaining calm in situations that go against all our instincts for self-protection. The resulting stress has been shown to take its toll on officers' mental health, and to affect their ability to make life-or-death decisions under pressure. Meanwhile, while stress-reduction strategies such as meditation or breathing exercises can help in a classroom, the same state of calm can be difficult to find in the heat of action.

The Radboud team wanted to know if it would be possible to train police officers to regulate their stress responses in a realistically stressful virtual environment. They created an immersive virtual reality game called *DUST* (Decision Under Stress Training), in which players find and shoot zombies in a dark car park. Players wear a virtual reality headset and brandish a replica gun, and they are wired into the game via a sensor strapped to their chest. When a player's heart rate and breathing rate rise, their field of vision gets darker and narrows, making the zombies harder to distinguish from innocent bystanders. But when players manage to control their stress response by slowing their breathing, their field of vision lightens and broadens, making the game easier. The idea is that rewarding the players for controlling their responses while they are stressed, will help them to learn strategies they can apply in real-life situations.

In these ongoing studies,[18] 80 per cent of police officers wanted to continue to play the game after the study ended. Practice in steadying their emotions also led to improved scores on a police shooting-range test. The next step is to roll out the game as part of the Dutch Police Academy training programme and to expand the game to university students, for whom stress and anxiety are also major problems. The early results are encouraging, and the hope is that it could one day help young people develop vital stress-regulation skills while doing something they find enjoyable and engaging.

This work chimes with other research that suggests that as well as studying people's ability to feel their body signals – what psychologists call their 'trait' level tendencies – it's important to consider how they experience their bodies from one moment to the next. This 'state measure' doesn't always match with the trait tendency, according to Jenny Murphy at the University of Surrey. And, she argues, what's more important than whether you *can* feel your body signals is *how* you feel when you do. This might vary among groups and at different times. In the case of the police officers, for example, an awareness of how they are breathing may help them feel in control of their stress response. In people with PTSD, it may trigger a panic attack, while for others it may not. The one thing everyone agrees on, though, is that our relationship with our body signals can no longer be ignored in the search for solutions to bodymental health in general – and stress and anxiety in particular.

Putting the 'me' into meaning

Both Garfinkel's training and the police officers' training in the Radboud study helped participants to regulate their body signals in the wider context of what's happening around them. This helped them build a more complete picture of how they were, and what action needed to be taken to cope better. In other words, it helped them build a strong sense of self, along with the confidence that they could act to change their experience for the better. As we saw in Chapter 1, our sense of self is constructed from within: these findings suggest that trying to master the construction process can give us a sense of agency – that we can act to change our own destiny.

The importance of visceral signals for building a unified sense of self – the sense that there is one 'me' that experiences the world through one body – has led to considerable interest in how interoception might be involved in disorders such as schizophrenia, where the sense of self is disrupted. Recent research suggests that people who have experienced psychosis had less insight into their own heart signals,[19] while other research has found that treating people in the early stages of schizophrenia with statins, which regulate heart rate, among other things, can reduce rates of psychiatric hospitalisation.[20]

Manos Tsakiris, a philosopher and neuroscientist at Royal Holloway University in London, has also investigated how interoceptive ability affects the self-building process in healthy people. In experiments, he tested people's heartbeat-detecting abilities and asked them to complete psychological questionnaires probing their relationship with their own bodies – specifically, whether they think of their body as 'me' or 'it'. The results showed that people who were less able to sense their bodies from within were more likely to perceive their body as a separate 'object' from themselves, and to have lower body satisfaction.[21]

According to a large survey of body satisfaction, the disconnect between sense of self and body ownership is extremely common. Up to 60 per cent of adults[22] admit to having a difficult relationship with the size or shape of their bodies, and that rises to nearly 80 per cent in adolescent girls.[23]

It's difficult to trace where the problem began, but the tendency to objectify our bodies – to analyse them from the outside and judge them as worthy of admiration only if they conform to the current ideal – has been present for a long time. And despite the rise of body positivity movements, this doesn't seem to be changing. The idea of moving and feeding our bodies to feel good from the inside doesn't seem to occur to us – and this is to our collective detriment.

Extreme body dissatisfaction is expressed in eating disorders; while it is far from the only issue, it is one of the most difficult aspects of the disorder to treat. Current treatments include asking people with eating disorders to confront the reality of their body shape in a mirror and learning to assess it more positively. While this does seem to help in the short term, other studies by Tsakiris have shown that it further reduces people's ability to sense their body from the inside, taking them further from what they need to feel better about their bodies in the long run.[24] Since as many as 50 per cent of people with anorexia relapse within a year of treatment, this seems like an important thing to fix.

Researchers at the Laureate Institute for Brain Research, including Khalsa and the clinical psychologist Emily Choquette, are trying a different approach. Instead of asking people with anorexia to confront their bodies in a mirror, they are using floatation therapy, in which the only bodily information comes from within.

Today floatation tanks can be found in high-end spas and specialist float centres, but they were originally designed as a tool for neuroscience research. In the 1950s, scientists assumed that the brain was only active when responding to the outside world – and that without any form of external stimulation, consciousness would simply shut down.

John C. Lilly, a neuroscientist at the US National Institute of Mental Health (NIMH), built the first 'sensory deprivation tank' to test this theory. In his early float tanks, volunteers were suspended in deep water in the dark, wearing a diving helmet to allow them to breathe. Surprisingly, people remained fully conscious throughout, and found the experience relaxing and liberating.

In the 1970s, Lilly left the NIMH and immersed himself in American counterculture, using LSD to explore the limits of consciousness and attempting to communicate with dolphins.[25] He remained interested in sensory deprivation. After he gave a talk on floatation therapy he met a man called Glenn Perry, who suggested adding Epsom salts to the water so that people could float easily on the surface without needing an oxygen mask. Working together, the pair designed a float tank that, with only a few modifications, remains in use today.

Although studies were carried out on floatation and relaxation in the 1980s and 1990s, it wasn't until the early 2010s that floatation was taken seriously again as a tool for neuroscience research. A notable shift came in 2015, when LIBR opened its floatation research centre to study the effects of floating on the brain and on mental health. Having shown that floatation reduces stress, blood pressure and muscle tension, and has measurable effects on the insula and other brain regions, they turned their attention to clinical disorders including anxiety, PTSD and eating disorders. The anorexia studies were inspired, in part, by Emily Noren,[26] who wrote a book about the role floating played in her recovery from anorexia and bulimia. Many people with eating disorders are over-sensitive to interoceptive signals from the gut, and tend to interpret sensations such as fullness as uncomfortable or upsetting. Part of the reason that Noren found floating so helpful was that, as she put it, 'If I followed a meal with a float … I could allow my food to digest without the discomfort of fullness. Lying in the float tank, free from gravity … I didn't feel "fat" or feel the weight of my food.'

Hindy Friedman, a participant in Choquette's study in 2018, found something similar. For her, the experience was like taking a holiday from her body – and from the intensity of her inpatient anorexia treatment. 'You don't feel anything,' she told me. 'And when you don't feel all those sensations, you're calmer. You feel more at ease. More comfortable in your own skin.'

These accounts make it sound as if floatation took Hindy and Emily even further away from their bodies, but the data so far suggests otherwise. In the study, people reported being less aware of their gut sensations after spending an hour in the tank. But almost everyone said that they felt their heartbeat more strongly than usual.

In my experience, being in a floatation tank provides a rare chance to feel my heart beating without any stress or exercise-related baggage. For at least half the session, my heart was so quiet that I didn't feel it beating at all. But when I could feel it, it felt totally different to any way that I'd felt it before. It didn't thud, it didn't hammer. It didn't even flutter. It was just there, gently doing its thing; a comforting and reassuring presence. I have never felt more relaxed and at ease.

The results of Choquette's study support this finding, and show a significant – and long-term – boost to body image.[27] People with anorexia felt calmer after their floatation experiences, and they felt significantly better about their bodies – and the boost in body satisfaction was still there six months after the end of the experiment. By comparison, the group with anorexia who had standard therapy showed no such change. It isn't clear how it works, but Choquette and her colleagues speculate that because floating focuses attention to the body from within, while in a state of calm, it may help to counteract the distortion of body image that some people feel when looking in a mirror.

The next phase of the research will be to give people with eating disorders, who tend to be less sensitive to their heartbeat, a session of body-focused mindfulness before they get in the tank. Choquette offered to let me test the study protocol while I was in Tulsa; it super-charged my body awareness before I entered the tank, leaving me able to find my 'heartbeat happy place' more quickly. And although I don't have any particular issues with my body image, based on the standardised tests I completed before and after the float, the float had a measurable effect on how I perceive my body. The tests involve choosing which body, out of a line-up of faceless bodies, most closely matches my current body shape, then choosing the one that represents my ideal shape. Before the float there was a slight difference – my ideal body shape had slightly slimmer thighs than the real me. Afterwards, when I did the test again, I was perfectly happy with the body I've got, and I picked the same shape for my current and ideal. During the float I was conscious that, while my limbs were weightless, I could feel the strength of my muscles and bones from the inside. When I emerged, I was perfectly happy with my thighs.

As well as having the potential to treat disorders, researchers hope that correcting heart–brain signals might even prevent problems from occurring in the first place. If errant heart–brain signalling could be detected in childhood or adolescence, critical windows for the development of mental health issues, it might be possible to intervene early, preventing anxiety from becoming fixed in the circuitry that links body and brain. And it stands to reason that teaching young people to experience – and appreciate – their bodies from the inside, perhaps through dance or other forms of mindful movement, such as martial arts, rock climbing or yoga, could help to prevent problems associated with body image.[28]

Other researchers are taking a more radical approach: using psychedelic drugs to reset the sense of self. The idea is that the drug, at least when taken in a controlled setting and under medical supervision, will dramatically disrupt the signals between body and brain: when they settle, the pathways will reset to a healthier baseline.[29] A recent brain imaging study suggests that it's mostly the brain end of the interoceptive conversation that is affected by ketamine. Afterwards, when the brain reconnects, it seems to have rebooted the system. People who have taken part in such studies report not only a change in their outlook on life, but also a feeling of being more connected with their bodies.[30] It's worth pointing out here that these results come from studies carried out under medical supervision, where the purity and dose of the drugs are regulated. The same can't be said for street versions of these drugs, or for any form of self-experimentation outside a clinical setting.

Hindy, the woman with anorexia we met earlier, tried psychedelic therapy after she was discharged from hospital following treatment. She said that, even though her psilocybin trip involved crying and discomfort, it made her feel similarly about her body to the way she'd felt in the float tank. 'It was completely visceral in my body,' she says. 'The whole experience was within the body, and it was so beautiful, getting to explore how your body's giving you these sensations. I realised that all these sensations are my body giving me messages.'

Target practice

As well as these more holistic brain–body approaches to rebalancing body–mind connections, some researchers are selecting a single input into the system to see if changing just one part can reset the whole.

Most of the work so far that has involved the body end of the equation has been done on the heart. It's a good target, not just because it's available to conscious awareness – at least sometimes – but because of its central role in the autonomic nervous system. The heart is a key hub in the switch between 'fight or flight' and 'rest and digest', and in more subtle changes in arousal that we may not notice, but which still affect how we think and feel.

One way to target the heart is to use drugs to reduce our heart rate while people are tackling emotional triggers during therapy. The beta blocker propranolol, for example, has been used in this way in the treatment of PTSD, while people are accessing traumatic memories. In theory, fewer heartbeats while remembering a traumatic event should disrupt the heart–brain pathways that sustain the fear reaction, helping people to more quickly unlearn the associations formed during a traumatic event. A recent review concluded that, while this treatment is in its early days, propranolol does indeed reduce the severity of PTSD symptoms when administered in this way.[31]

The heart–fear connection has also been used in the opposite way – to boost fear in a controlled setting, with the aim of helping people to recover faster. In a 2019 study, Hugo Critchley developed a version of exposure therapy for arachnophobia, in which images of spiders were timed to appear on a screen at the exact moment that a person's heart was contracting. Compared to people who saw the images when their heart was relaxed or at completely random intervals, the contraction-exposure group were less terrified by images of spiders at the end of the treatment.[32] Their anxiety levels were also much lower, and their bodily responses were triggered less intensely. People who already had good awareness of their heartbeat did best of all: perhaps heartbeat detection training followed by timed exposure might help people who are not as interoceptively well endowed.

At the brain end of the conversation, the key target is the insula, tucked away deep within the folds of the brain. This means it isn't easily accessible via brain stimulation (in which an electrical signal is applied to the outside of the head in the hope that it will affect nerve firing on the inside of the skull).

The importance of the insula in understanding our body–brain circuitry has meant that scientists have been on the hunt for solutions to this problem. A paper published in

2024 showed that highly focused, low-intensity ultrasound that reaches deep into the brain can stimulate the human insula, and can also change its activity and reduce the subjective experience of pain.[33] This study was swiftly followed by another, which showed that low-intensity ultrasound to the insula reduces the strength of the heartbeat evoked potential, a signal that represents the brain's view of the heart.[34] Both studies were greeted with great excitement by interoception researchers. By tweaking the brain end of the interoceptive conversation and measuring what effect this has on how people think and feel, the hope is that we will start to get a sense of whether heartbeat evoked potential can be used as a biomarker that can distinguish between healthy and disrupted interoception. The next few years are likely to see a flurry of research along these lines.

Insula-targeted neurofeedback is also a work in progress. Back at LIBR in Tulsa, Masaya Misaki puts me through my paces using real-time functional MRI scanning. This, he tells me, provides 'a live stream of brain activation' focused on my insula – specifically, a portion of the left insula, where activity has been shown to differ in people with psychiatric disorders and those without.[35]

When I am in the scanner, Misaki pinpoints the insula in my brain, then produces a graph on a screen in front of me, along with a small heart icon. My job is to feel my heart beating, while focusing on the graph and heart icon. When the brain scan shows that I'm successfully tuning in (based on increased activity in my insula and changes in my heart rate), the line on the graph rises and the heart icon gets larger. When I lose focus (which is often), the line falls and the heart icon shrinks.

During the test, it felt as if the line spent more time plummeting towards the baseline than soaring upwards, but when Khalsa talks me through the data afterwards, it's clear that I was able to tune in to my heart, and that this did indeed change the levels of activity in my insula. The next question for researchers is whether conducting this kind of training over a period of weeks improves interoceptive accuracy, and whether it has any impact on how we feel. In a previous study, Masaki showed that targeting the amygdala, a part of the brain that processes emotions and which is connected to the insula, significantly reduced symptoms in people with depression and post-traumatic stress after just three sessions.[36]

There are a few hurdles to get over before this approach can be used in therapy, one of which being that functional MRI (fMRI) scans, which track blood flow in the brain as a measure of brain activity, are expensive and not easily accessible. But Khalsa says that, one day, this kind of targeted neurofeedback could be used either during therapy sessions, to give the therapist or the patient a window into how particular triggers affect the patient's body and brain, or as a 'before and after' test to show just how far they have come. 'At this point it's theoretical,' says Khalsa. 'Whether or not it adds something – that's what further studies are for.'

While some of these interventions are a long way off being used in the clinic, others are closer to being introduced alongside standard care. More generally, the hope is that as interoceptive research moves into the mainstream, bodymental health will become the basis of joined-up medicine. We might not have all the tools yet, but this sort of approach to health is definitely on the rise.

It takes a village

In the meantime, what we *do* have is other people, and there is a growing understanding that our relationships can regulate our internal world in ways that are good – not just for our health and happiness, but also for the wellbeing of humanity in general.

We are, and always have been, social creatures. Living in groups and cooperating is what allowed us to survive in the early days: as relatively puny top predators, working together allowed us to take down prey much larger than ourselves. Even now, social interactions bind us together as groups, and even though we no longer need to hunt and gather, we need each other as much as we ever did to feel safe and connected.

This became painfully obvious during the Covid-19 pandemic, which drastically reduced opportunities for human interaction. The pandemic illustrated how resilient and adaptable the human mind can be when faced with sudden change. It also demonstrated that it doesn't take long for us to accept a level of isolation that can be devastating for our mental health – and that these changes don't necessarily correct themselves when things return to normal.

Kay Tye at the Salk Institute of Biological Studies in California has studied what happened during the pandemic through the lens of social homeostasis – the ways we adapt our behaviour to find the right amount of social interaction.[37] Previous studies have shown that a body–mind system ensures that we feel a craving similar to hunger following a short period of isolation, which drives us to seek out company. But if isolation goes on for too long, our predictive brains tweak the point at which we get the urge to seek out company. The upshot of this is that, over time, we get used to solitude; what previously felt like the right amount of social contact now feels overwhelming. And once that happens, we respond by seeking solitude, further reinforcing the 'new normal'.

This would be fine if we were happy and healthy on our own, but research suggests otherwise. Isolation disrupts our interoceptive pathways in ways that lead to an increased sensitivity to emotional and physical pain, and sets off a wave of inflammation as if we have been physically injured. Inflammation, in turn, communicates to the brain that all is not well, and that the safest course of action is to conserve energy until the threat has passed. This response is known as 'sickness behaviour' and it can lead to depression if it's not resolved.

Sick and tired

The link between inflammation and depression has sparked a flurry of research into drugs that target inflammation in people with depression. The jury is still out on whether they work; a major review in 2023 concluded that there has been too much variability in studies to draw any general conclusions.[38] Various approaches to tackling inflammation have been tried experimentally, including artificially increasing inflammation further – either by the injection of harmless toxins or via a short, sharp bout of exercise. Then there is whole-body hyperthermia, in which a person lies down in a bed-sized tent with their head poking out. The tent is then heated by infrared lamps until the body reaches 38.5°C (101.3°F), mimicking a fever, and kept at that temperature for an hour.

Such interventions might sound like they would make matters worse, but early results suggest that they might actually help. One study from 2016 found that a single session of whole-body hyperthermia significantly reduced symptoms of depression within a week – and that the effects lasted for up to six weeks.[39] It's unclear how it works, but one possibility is that it stimulates the body's inflammatory pathways, forcing the body–brain loop to dampen inflammation in response. Once the inflammation clears, the system has reset to a healthier baseline. The process of using a short, sharp physiological shock to reset, and potentially retrain, the stress response is called hormesis, and it might explain why cold-water swimming could be used to treat depression and other mental health issues. Debbie, the woman with hypermobility-related anxiety we met earlier, calls it 'the best thing' for her mental health. 'It makes me feel grounded,' she says. 'I come home with a big smile on my face.'

Hormesis might also explain why exercise so reliably improves our mental health. Any safe, temporary stress may serve as an internal lesson about how well our bodies can cope with short periods of stress – and Jonathan Savitz at LIBR is about to begin a study of people with depression to test this out.

Inflammation is only involved in a subset of cases of depression, while others stem from glitches elsewhere in the body–brain interoceptive loop. In depression and other problems with bodymental health, there's a lot of research still to be done before we will fully understand how to tweak interoceptive signals to improve things. But we do know we need to think of emotional problems as a mind–body breakdown in communication to stand any chance of helping people: the 25 per cent of people who struggle with mental health and everyone who finds that modern life often leaves them feeling overwhelmed.

The avoidance of pain, and other difficult feelings, and the pursuit of pleasure or relief lies at the heart of many aspects of interoception. This is why, as we'll see in Chapter 6, many interoception researchers are beginning to see both extremes of our conscious experience as two sides of the same coin – embodied experiences that are intricately linked with our thoughts and emotions. This expanded body–brain understanding of pleasure and pain is leading to holistic treatments for disorders such as chronic pain and addiction, and to new ways of navigating life's ups and downs.

6

Pleasure and pain

Riding the waves of feeling – and trying not to fall in

I love surfing. Actually, that's not quite true. I love bobbing around in the ocean, sitting on a surfboard with my feet in the water. Catching waves is fun, but the thrill of the ride never quite outweighs the fear of being dragged beneath the surface.

We all vary in our tendency to seek thrills and avoid pain. As boring as it may be, I lean towards the latter. When actual avoidance isn't possible, I have another strategy: zone out or (if I can get away with it) go to sleep. My ability to sleep through a crisis is a superpower of sorts, although one that would make me a terrible superhero.

Mentally disconnecting from the here and now is a common strategy when dealing with overwhelming feelings, particularly stress. It's one of the reasons we watch TV, read novels, and scroll mindlessly on social media. Yet while it can be an effective way to take a break from modern life, it has its downsides. For one, it distances us from bodily sensations that signal stress and discomfort – and from life's pleasures. And it disconnects us from the embodied sense of self that is key to us feeling that we are in control of our own destiny. According to a study of social media scrolling carried out at the University of Washington, this disconnect often sets in unintentionally. Often, participants intended to simply check their notifications, only to emerge much later, with a vague sense of shame and no idea what they'd been reading.[1]

Whether you're a pleasure-seeker or a more cautious pain-avoider, some degree of pleasure and pain is unavoidable. They are each key motivators of behaviour that have been honed over millions of years, to prompt us to look for what will benefit us and to avoid what will do us harm. In theory, it's straightforward: our feelings about whether something is pleasurable or painful drive us to approach what is good for us and avoid what will hurt. Then, with our needs met, we can settle back to a comfortable middle ground.

But with human beings, these things are never quite so simple. As we evolved to become the complex creatures we are today, pleasure and pain became entwined – not only with each other, but also with our thoughts, feelings and emotions, in ways that can make them difficult to read and manage.

We're beginning to gain an understanding of the complex body–brain interactions that underlie our strongest homeostatic feelings. This is important for general wellbeing, but also to help us navigate life without the need for potentially harmful coping strategies, such as dissociation, comfort eating, or other forms of emotional numbing that involve alcohol and drugs. For that reason, a better understanding of the ways that pleasure and pain are intertwined is crucial – and not just for the many people with disorders of the pleasure–pain system, including chronic pain and addiction.

Survival signals

We might understand how pleasure and pain overlap if we recall why interoception exists: to maximise our chance of survival by predicting what's coming, adapting accordingly, and using live sensory signals to update any errors in our predictions.

To some extent, pleasure and pain feed into our every feeling and decision. Feelings exist on a spectrum that ranges from positive to negative (in scientific terms, they have positive or negative valence). They can also be measured on a second sliding scale that registers the urgency of a situation. The two come together so that things you need make you feel good when you get them, and bad when you don't. The more urgent or important they are, the bigger the feeling.

The basic system is a good one, but as we evolved to become more complicated, our brains developed so that we could predict what would benefit us or cause harm, and adapt in advance. As a result, the way we experience either end of the hedonic spectrum as pleasurable or aversive, and how strongly that feeling manifests from one moment to the next, is far from simple.

The complex relationship between the body's signals and the brain's prediction and interpretations of them is most obvious in the case of pain. One route to pain is when damage to our bodily tissues triggers receptors that can detect physical, chemical and temperature-related threats. When triggered, these nociceptors fire a message to the brain, but this isn't enough to cause the conscious perception of pain. These signals can be ignored, blocked or deferred depending on what else is happening at the time; the conscious experience of pain can be temporarily put on the back burner, but most of the time it pushes to the front of our conscious awareness.

Pain doesn't only result from signals of tissue damage being carried from sensory nerves to the brain. It's perfectly possible to feel pain without any tissue damage. One classic example comes from a report published in the *British Medical Journal* in 1995,[2] which explored the case of a construction worker who had accidentally jumped on a nail. Even though he was wearing protective boots, the nail went right through. When the man arrived at hospital, the nail was poking out from the top of his boot and he was in extreme pain. After he'd been given strong painkillers, doctors removed the nail and then the boot. When they did, the report notes, 'a miraculous cure appeared to have taken place'. His foot was entirely undamaged: the nail had passed between his toes.

This isn't to say that pain is imaginary – nail or no nail, the man's suffering was real – but it illustrates that pain is about more than sensation. The same can be said for pleasure. Both are complex emotions that emerge from body–brain processes that can be either dialled up or down, or can become disconnected, leaving our experience unbound by the usual checks and balances.

The connection between pure sensation and the experience of pleasure or pain is complicated further by the fact that the circuitry was at some point co-opted to help manage social and emotional relationships, as well as physical danger and opportunity. Evolution often adapts the body's circuitry for a new purpose – in this case, using the pleasure–pain pathways to inform physiological and social homeostasis. As a result, physical and emotional pain processing are dealt with in the same regions of the brain, including the all-important insula. And while positive emotions can reduce the pain we feel, negative emotions can make it even worse. This has been shown in research into the so-called 'nocebo' effect – the dark side of the placebo effect, in which expectations lead to harm rather than cure. In experiments, when people are told to expect pain and become anxious about what is coming, they show increased pain-related brain activity and rate pain as being more severe than a comparison group who weren't told to expect any pain.

The link between pleasure, pain and social relationships makes sense when you think about the extent to which early humans depended on each other for survival. Living in a group provides obvious advantages for fending off predators and pooling resources to share food and childcare. Maintaining these groups is much easier if being together feels good and being alone feels bad – and if members of the group feel each other's pain and are motivated to help.[3] As humans evolved, groups that cared about each other were more likely to survive and pass on their genes to us, their distant descendants. For them, just as for us, love and support provide feelings of pleasure, comfort and safety, while isolation and social rejection feel painful.

One important part of the puzzle regarding this overlap between pleasure, pain and social emotions was found in the late 1970s, when the neuroscientist Jaak Panksepp showed that bonding between baby animals and their mothers depended on the release of natural opioids in the brain. Blocking these endorphins in a rat that had recently given birth made her less attentive to her young, while infant animals that had been separated from their mother became less distressed when they were given a low dose of opiates.[4] At the time, the idea that a mother's love was comparable to an opioid addiction was highly controversial. Since then, the results of this experiment have become widely accepted. There is also evidence that our system is calibrated in our earliest relationships and has a lifelong impact on the way we experience pleasure and pain in our relationships.

Since Panksepp's research, further studies have shown that, as well as in mother–baby bonding, endorphins are involved in other types of social bonding. Endorphins are released during social touch, for example, and when a group of people laugh together. If all is well, these chemicals can provide pleasure, safety and comfort – and they can reduce pain where it occurs. Experiments have shown that people can endure more pain if they have the support of a romantic partner,[5] and that people with larger social networks tend to have a higher pain tolerance.[6] It seems that the warm feelings we get from loved ones really can make life a little easier to bear. In a similar way, exercise can improve our mood: endorphins released during intense exercise can help deal with injuries or pain. The famous 'runner's high' is a bonus dose of pain relief that is provided just in case. Strong relationships do something similar – perhaps because when we know we're not facing life alone, our body can afford to dial back on the intensity, and urgency, of pain as a signal for action.

Interestingly, studies in which people were asked to mark where they feel certain emotions on an outline of a body have shown that there is considerable overlap between where we experience pleasure and where we feel love, togetherness and social closeness. In one study of over 1,000 volunteers by Lauri Nummenmaa, a psychologist at the University of Turku in Finland, all of these feelings showed up throughout the torso and in the front of the head. If you add this to the knowledge that social relationships help to reduce pain, this suggests that the people around us bring us pleasure and are our best ally against pain.

The way that pleasure, pain and emotion are intricately intertwined also explains the recent finding that painkilling drugs such as paracetamol blunt not only physical pain but also the emotional pain of rejection.[7] On the flip side, though, there's evidence that painkillers blunt feelings of pleasure as well as pain, by reducing the intensity of emotions in general.[8] Painkillers also seem to reduce our capacity for empathy – our ability to imagine someone else's pain, and to embody it and feel it from within our own bodies. Both of these studies suggest that painkillers, while vital for many people, are not without their downsides.[9]

The endorphins – our natural opioids – aren't the only natural chemical that links physiological changes to our experience of pleasure or pain. Several others are produced in the body, including dopamine, serotonin and oxytocin.

Nevertheless, understanding opioids has become increasingly urgent as a result of the opioid crisis, which has seen powerful synthetic opioids cause devastation across the world.

Until the mid-1990s, opioid medications were usually restricted to short-term use following surgery and for cancer-related pain. Then a new form of slow-release opioid painkiller called oxycodone (trade name OxyContin) came onto the market, sold as a safe solution for chronic forms of pain. Even though it was chemically similar to heroin, its maker Purdue Pharma marketed the drug as safe, and claimed that less than 1 per cent of patients became addicted.

As prescriptions soared, it quickly became apparent that these new opioids were more addictive than had been claimed – but by this time, many people taking them were hooked.[10] Meanwhile, drugs that had previously existed only in medicine cabinets began to find their way into the hands of recreational users, many of whom also found themselves hooked, thanks to the feelings of safety, warmth and love that opioids provide. Overdose rates more than quadrupled in a decade, and when the inevitable crackdown on prescription opioids came, some of those who were addicted turned to heroin and other illegal opioids instead.[11]

Never felt better

Not everyone gets an intense rush of pleasure when they take an opioid drug, but for those who do, the feeling can be hard to beat. Maia Szalavitz knows this from experience: she spent her late teens and early twenties addicted to heroin, from the first moment it flooded her body with feelings of unconditional love and security.

That was in the mid-1980s. Nowadays, Szalavitz has long been abstinent from drugs, and has carved out a career as a neuroscience journalist and the author of several best-selling books. In her work she argues that if we understand addiction as a social and emotional problem rather than a failure of moral character, we will stand a much better chance of helping people to recover.

When we meet online, the first thing Maia wants me to understand is that addiction has nothing to do with pleasure, even if it starts out that way. She points to the official definition laid down by the American Psychiatric Association in its diagnostic manual. 'Addiction is "compulsive behaviour that occurs despite negative consequences",' she says. 'It's not having fun.'

Whatever leads to the first dose, the route to pain follows a depressingly familiar trajectory, as tolerance to the drug's effects reduces the highs and withdrawal adds to the lows. This process has long been understood in terms of changes in the brain: the dopamine system in the brain manages how much we want something, and how motivated we are to work for it. Pleasure, on the other hand, is more opioid-based and reinforces the link between the initial good feeling and the effects of the drug. In normal circumstances we don't notice the difference between wanting and liking; the two pathways integrate seamlessly as part of the same experience.[12] But in addiction, these circuits can become disconnected, and this helps to perpetuate the cravings long after the rewards have stopped.

This is all well understood, but it misses a vital piece of the puzzle. From the perspective of the person with the addiction, the wanting, craving and using of a drug doesn't happen in their head. As far as they are concerned, the feelings that drive addiction are very much embodied. This much is clear from the way that people with substance use disorders describe their cravings in physical terms: as a burning sensation in the throat for alcohol, perhaps, or as the feeling of cigarette smoke moving towards the lungs. For opioids, the feeling of warmth and safety that we are hardwired to seek is experienced as a full body sensation. If interoceptive sensation is all about helping us to fulfil important homeostatic needs, addiction is best understood as homeostasis gone wrong: a situation in which the body signals associated with the drug have hoodwinked the body and brain into treating it as a life-giving elixir.

Until recently, no one had thought to consider interoception as a driver of addiction – or a potential target for treatments designed to aid recovery. In 2007, the neuroscientist Nashir Naqvi published what has become a classic study. He had noticed that images of the brain often showed activation in the insula when people with addiction issues were shown pictures related to their substance use. The insula, as you will recall, is also known as the interoceptive cortex – a region of the brain where bodily sensations meet top-down predictions to generate feelings. These feelings form the basis for our sense of self, as a person living in the here and now, with wants and needs. They also form the basis of our emotions, which in turn guide our actions. Naqvi wanted to know what activity in the insula had to do with maintaining addiction, and what would happen if it was removed from the equation.

To find out, he went in search of a specific group of people – smokers who had recently had a stroke that had damaged their insula. A control group consisted of smokers who had had a stroke that had damaged other brain regions. Many of the stroke patients in both groups were able to quit smoking after their health scare, but only those with damage to the insula did so immediately and easily, with no cravings or relapses. One of the people with insula damage, a thirty-eight-year-old man who had not planned to quit his forty-a-day habit, told the researchers that his sudden change of heart had nothing to do with wanting to be healthier. It was simply because his 'body forgot the urge to smoke'.[13]

Naqvi's findings put interoception on the map as an important aspect of addiction, raising the possibility that addiction is driven not by a lack of impulse control but by errant homeostatic drives. It could be that a new sensation becomes tied to the pleasure of the drug and makes an unnatural sensation feel like a basic physiological need. Or it could be that the substance provides an embodied answer to a homeostatic need that isn't being met.

In this view, the drive that keeps us going back for more – despite negative consequences – is an extension of the biological system that helps us fall in love – and stay in love against the odds. It's what allows us to overlook our partner's flaws, and it's what keeps us loving our children through sleepless nights, toddler tantrums and the roller coaster of the teenage years. 'If we couldn't persist despite negative consequences, nobody would be able to be a parent,' Maia Szalavitz says.

Szalavitz suggests that the connection between unconditional love and the sensations evoked by opioids may explain why not everyone who takes them goes on to become addicted. This is true even for heroin: a study that followed over 1,000 first-time users for up to a year found that roughly a third of them went on to develop a full-blown addiction.[14]

One potential risk factor, Szalavitz says, is whether a person has other ways to access the feelings of safety that we are hardwired to need. She points out that lots of people are prescribed opioids after surgery and don't become addicted, even if they do experience feelings of euphoria. 'Most people in that circumstance who have a job or a partner, or other things in their life, they think: "I better not touch that again, because I could get in trouble".' On the other hand, she says, 'People who don't have good things in their life, who are depressed, anxious or economically despairing, they get this insanely pleasurable experience and they are like "Oh heck, yeah – I'm getting more of this".'

In wider society, addiction is easy to dismiss as a lack of self-control or some kind of moral malfunction, but Szalavitz emphasises that we must remember that there are often deeper issues at play. 'If you just think of addiction as this overwhelming experience of pleasure, you'll think that people with addiction are horrible, selfish people; in fact, they tend to be sad people,' she says.

This much is clear when you appreciate how much factors such as unemployment, social exclusion,[15] deprivation and poverty[16] matter for a person's likelihood of developing both addiction and the risk of death from overdose. Trauma and neglect in early life are also among the biggest risk factors for addiction, perhaps because the need to feel safe and supported in early life wasn't met.

There may be other internal drivers, too. For Maia, recovery followed her discovering that she was on the autism spectrum and gaining an understanding of how this contributed to her depression. 'A lot of the early recovery process was creating a life for myself where I could feel OK in my skin without the aid of opioids,' she says.

A better understanding of how neurodivergence can affect the processing of bodily signals could further help to identify people who might be at risk of addiction. According to recent studies, ADHD at least doubles the risk[17] – a fact that is usually explained by a problem with our brain's circuitry relating to impulse control, but which could also stem from a need for physiological arousal that is lacking in those with the disorder. One of the paradoxes of using stimulants in ADHD treatment is that they calm people down, reducing the urge to go sensation-seeking.

To understand what drives different people to seek out drugs, we need to take into account not only their genetic make-up and their life history but also their inner world. Are sensations intense and overwhelming to them, as is often found in people with autism, or not intense enough, as in people with ADHD? Were their needs met when they were infants – and if they weren't, how has that affected their pleasure and pain circuitry? Has trauma been a part of their experience? And have they ever become so overwhelmed that they dissociated from inner sensations, for their own protection?

Body–brain pain

Taking this kind of full-person approach is just as important when dealing with chronic pain – which, like addiction, is intimately intertwined with emotions and early life experiences. Both conditions are significantly more likely in people with a history of trauma, particularly in childhood.[18] People with PTSD are also significantly more likely to experience chronic pain, which can occur alongside emotional dissociation and create a situation where people have a higher threshold for pain but, when they do feel it, they tend to experience it more intensely.[19]

Chronic pain, which is defined as pain that lasts three months or beyond an injury's natural healing time, used to be thought of as a longer-lasting version of the acute pain that follows injury and involves communication between body and brain along the spinal cord pathway. Now, though, it is understood that the problem is, in many cases, a communication breakdown between what the brain predicts is going on in the body and what is actually happening. Cut off from the regulatory checks and balances, the pain takes on a life of its own.

This is important for a particular kind of pain that was only officially recognised in 2016. Until then, there were only two types: nociceptive, which involves bottom-up signalling after tissue damage, and neuropathic, when damage to the signalling pathways between body and brain causes them to fire in error. The third type, nociplastic pain, exists without any clear evidence of damage to tissue or the nerve pathways. In nociplastic pain, the evidence that all is well either doesn't get through, or any sensation is misinterpreted as evidence of imminent or ongoing injury.

The classic example of nociplastic pain is fibromyalgia, a condition that causes pain all over the body, often with no clear physical cause. Nociplastic pain also features in migraine, irritable bowel syndrome and chronic back pain. It can set in after injury or develop alongside a chronic condition such as osteoarthritis, endometriosis or IBS. Sometimes it happens for no discernible reason. Whatever the trigger, it has a tendency to feed itself, as the person suffering becomes hypersensitive to their body sensations. Meanwhile, the brain becomes hypervigilant to signs of threat, whether physical or emotional, and interprets them all as pain. This 'central sensitisation' cements the connection between negative emotions and physical pain until they are deeply entrenched.

For this reason, early diagnosis of the type of pain a person is experiencing is crucial. Treatments that work well for nociceptive pain, including opioids, either aren't effective or make matters worse in nociplastic pain, wasting valuable time that could be used to retrain errant body–brain pathways before they become entrenched. This was made heartbreakingly clear to me when I talked to a long-time colleague whose wife ended her life in 2022 after an intense battle with nociplastic pain over many months. What began as a relatively minor injury gradually spiralled out of control; at its worst, it felt like somebody had pushed two hot swords between her ribs and was prising them apart. The pain was unrelenting, with no diagnosis and no treatment that didn't make matters worse.

In hindsight, doctors missed a window of opportunity to intervene. When a large dose of intravenous morphine brought no relief from the pain, it should have been a major red flag: when opioids fail to work, it would suggest that there is no bottom-up nociceptive signal to dampen. And the fact that benzodiazepines, used to treat severe anxiety, managed to take the edge off her distress should have been a clue that central sensitisation was part of the problem. When caught early, nociplastic pain often responds to treatment well enough to significantly improve quality of life. But thanks to a lack of awareness of nociplastic pain, even among doctors, and a lack of whole-person treatments for pain conditions, no one was able to spot the signs until it was too late.

Awareness of the unique challenges of nociplastic pain is beginning to spread, albeit slowly, and new treatments are starting to trickle through. Many of them fall within the biopsychosocial model of pain, which recognises that a person's experience depends on physical, psychological and social factors. Pain reprocessing therapy (PRT) involves helping people to reinterpret their pain as a brain-generated false alarm rather than evidence of damage or threat. Guided movement reconnects the body sensations with an interpretation of comfort and safety rather than the fear of pain, while talking therapy helps people to understand how stress and negative emotions increase our experience of pain, and how positive experiences can relieve it.

In a recent randomised clinical trial in fifty people with chronic back pain, 66 per cent of them were pain-free (or nearly pain-free) after four weeks of PRT, compared to 10 per cent of an equal-sized control group who received standard care.[20] Interestingly, a third group – who were given an injection of saline solution and were told that it was a placebo – did significantly better than those who received standard care: 20 per cent of this group were nearly or totally pain-free afterwards, making it twice as effective as standard care.

The placebo result is interesting – and not just as an indictment of standard care, which so often leaves people suffering from chronic pain and searching in vain for answers. It's also evidence in favour of a full-person approach to pain and health in general, in which social and emotional factors are taken into account at every stage of diagnosis and treatment. The group that received the placebo were injected with it during what the researchers described as 'an empathic, validating clinical encounter', and were then shown videos explaining the science of how placebo treatments can stimulate the body's healing response.

In other words, treating people with kindness and respect and providing them with support and comfort is beneficial in their experience of pain, even if you do nothing else to help them. If this approach was made widely available as the first line of treatment for unexplained pain, it could have a real impact on suffering for people with conditions for which little else is available.

Cynthia Price, a psychologist at Washington University in St Louis, Missouri, has spent decades working on this kind of treatment for physical and emotional pain. Based on her background in somatic psychology and body-focused therapy, she developed Mindful Awareness in Body-oriented Therapy (MABT) to help people with dissociation who had experienced severe trauma. 'I've worked a lot with people with severe trauma histories who really felt as if they were cut off from the head down,' she told me. 'They came to see me to learn how to be reconnected with their bodies.'

Price's treatment involves working with a therapist to help the person practise holding mindful attention in different parts of the body, and working through the feelings that arise. It's usually done as an eight- to ten-week hands-on intervention, but the idea is that the effects of the treatment last much longer than that. 'We are really teaching people skills and then helping them integrate them into their daily life,' she says. When I suggest that her techniques could be helpful for everyone, whether or not they've experienced trauma, she agrees wholeheartedly. 'Absolutely! You don't have to have a severe trauma history to benefit from this approach.'

Price has used the same approach in clinical trials for people with addiction, who have a history of interpersonal trauma and often self-medicate with drugs or alcohol. 'Not knowing how to cope with reactivity and stress when you are triggered, due to having a high level of trauma, is enormously uncomfortable,' she says. 'People who feel unable to manage their stress responses are at more risk of addiction, as a way to manage the pain of their abuse.' Ironically, in many cases drug addiction results not from people being out of control, but from a desperate attempt to *gain* control over their bodies and lives.

So far, MABT has been shown to reduce stress and improve mood, while increasing people's awareness of how their body feels from within. In a series of randomised, controlled trials in women being treated for drug addiction, MABT reduced cravings and helped people to stay abstinent for longer than those receiving standard treatment. It also reduced symptoms of PTSD and pain, and was easy enough that people could keep practising outside the clinic. 'We have seen a remarkable response. People find this kind of work so helpful that they keep doing it multiple times a week, a year later,' says Price.

Help, or do no harm

All these approaches share a view of addiction not as a moral deviance to be frowned upon and punished, but as an extension of the basic human needs we all have. And recovery is much more likely to succeed if people are able to find another way to meet those needs.

As Maia Szalavitz tells me, there's no quick fix. 'It's like asking about the cure for love. It's different for different people – and it's always going to be. But that doesn't mean we can't do a heck of a lot better. One of the critical things is just to be nice to people – help them feel like decent people, that we value them, whether they are using or not.'

She argues that we should concentrate on treatments founded on the principle of harm reduction: those that keep people safe, whether by providing drug testing, clean needles or a safe space to use drugs while they are accessing support to help them recover.

One way to apply harm reduction using an interoceptive approach is to ask people with substance use disorders about their embodied experiences. Studies in alcohol addiction have shown that when compared to non-addicted binge drinkers, people with addiction issues feel the physical sensations of craving as negative rather than as the promise of a release from stress.

These kinds of studies can then inform new interventions, which provide people with positive embodied experiences, in which they are encouraged to tune in to pleasurable physical sensations without the use of substances. One idea is to use floatation therapy as a short cut to positive emotions and relaxation. Jennifer Stewart, a clinical psychologist at LIBR, and her colleagues have recently completed a pilot study using floatation as treatment for a group of women recovering from drug addiction, alongside the usual care. An important part of the study was asking the volunteers what the experience felt like, whether it reminded them of any previous experiences from their lives, and whether it was a positive or negative memory. This revealed some potentially important insights. There are two float tanks at LIBR: one is enclosed, and the other is open in the centre of a room. When asked, several people said that they preferred the open tank because the closed one reminded them of being in prison, says Stewart. Other participants also said that the experience reminded them of prison, but in a positive way – it provided a rare opportunity to be alone and to reflect. This sort of information is important if you are trying to give people an embodied sense of freedom rather than something else to feel trapped by.

Interestingly, one of Price's recent studies, in collaboration with the neuroscientist Norman Farb at the University of Toronto, included the use of brain imaging to track changes in the insula, and its connectivity to brain regions involved in emotional processing and motivation.

The study found that healthy – but stressed – people who received MABT had a higher level of response in their insula at the end of the intervention. When asked about their tendency to notice body sensations and use them to regulate their emotions, those who received MABT were significantly more likely to listen to their body than were controls who didn't receive MABT.[21] This finding is intriguing, given that research has found insula abnormalities in people who are addicted to various kinds of drugs, including alcohol, cocaine, heroin, methamphetamine and cannabis, and in people who have behavioural addictions, such as gambling.

The details of these abnormalities are still being worked out. While some studies have found that addiction correlates with a smaller insula and lower-than-average activity in response to body signals, others have reported unusually high insula sensitivity. This variation might be explained by the possibility that people were at different stages of their addiction. One recent study imaged the brains of a group of university students who dabbled with stimulants, some of whom later become addicted. Those who did, had stronger insula activity for pleasure-related signals than their peers who stopped after university.[22] Another group who had been addicted to stimulants for many years had almost no insula response to pleasure. 'It's like they have blown out their pleasure circuits already, and there's nothing left,' says Stewart.

Changes to the way the insula is connected to other brain regions involved in pleasure and emotion is also seen in chronic pain conditions, including nociplastic pain. There's also evidence that in this sort of pain, changes in the way networks in the brain are connected to each other may explain why pain signals that would usually be ignored or dampened get boosted.[23]

It's early days, but the hope is that, as we learn more about which brain circuits go awry in people with addiction or chronic pain, it may be possible to target the insula directly with brain stimulation. The insula is difficult to target because of its position, deep in the folds of the brain. However, a group of researchers at the Fralin Biomedical Institute at Virginia Tech has found a way to reach it using low-intensity, focused ultrasound that can precisely target different regions of the insula and related regions. In two studies published in 2024, healthy volunteers had a hot probe held against their hand while they received stimulation to the posterior insula in the brain (where bottom-up nociceptive inputs come in) or to the anterior insula (where top-down predictions and expectations are added into the mix). Stimulation to both parts of the insula significantly reduced pain ratings, but only stimulation to the anterior insula, where context is added, had the effect of reducing stress.

Wynn Legon, who led that study, is conducting further research to test the same technique in people with chronic pain. Meanwhile, a number of clinical trials are under way to investigate whether ultrasound stimulation of the insula affects cravings in various kinds of addiction, including opioids and cocaine.[24] There's also the potential for insula-targeted neurofeedback of the kind I road-tested during my visit to Tulsa. If people could learn to regulate their own insula activity, perhaps it could have a similar effect as stimulating the insula artificially.

A broader body–brain understanding of how our interoceptive pathways go wrong in chronic pain and addiction is, slowly but surely, changing the way we understand and treat these disorders. The main stumbling block in both medicine and wider society is a lack of awareness of just how much interoception has to do with these disorders, which have long been presumed to be either 'all in the mind' or the result of bad choices. Whether we like to admit it or not, we are all wired to avoid pain and seek pleasure – in our body as well as in our brain. And while some people may be more vulnerable than others to glitches in these pathways, none of us is immune to their influence.

Most of us, it's fair to say, occasionally resort to unhealthy coping strategies to move along the pain–pleasure spectrum when things get tough. Whatever the strategy, whether it's scrolling on our phones, binge-watching TV or indulging in some form of substance abuse, while it provides short-term relief, it also makes us feel worse in the long run. Happily, though, interoceptive research is working on solutions for these situations too. One of these offers relief from pain and discomfort, and promises warm, fuzzy feelings of safety and support, and comes with no downsides whatsoever. It's safe, free, doesn't require any specialist equipment, training or even a doctor. And its effectiveness is supported by a growing pile of evidence.

The intervention in question – gentle touch – might sound a little far-fetched, but there are reasons to take it seriously. For one, it is based on a known body–brain pathway that plays an important role in regulating the pleasure and pain we experience. And for another, it seems to work.

Healing touch

This important interoceptive pathway is found in the skin: our largest organ and the interface between our insides and the outside world. Because of the skin's outward-facing role, until about twenty years ago it was thought to be completely unconnected to interoception. Recently, that view has changed. Research has shown that our skin monitors not only what touches us and where, but it also carries information that is relevant to the healthy functioning of the whole body in relation to homeostasis and survival. For example, our skin detects damage that could lead to infection, or an irritant from a toxic plant or biting insect. The skin also keeps track of more positive signals, such as touch-related signs that we are in the company of people who support us and keep us safe.

Touch, it turns out, isn't just one sense, but several. The sense we learn about at school should actually be called discriminative touch, which relies on fast-conducting nerves that allow us to interact with our surroundings – for example, to grasp and manipulate objects without squashing or dropping them.

Another, less well-known, aspect of touch, called affective touch, relies on the skin's smallest and slowest-conducting sensory fibres. These, the so-called C fibres, are less good at noticing where and when the skin is being touched, but they are great at relaying signals that are relevant for homeostasis, such as temperature, pressure and tissue damage.

Affective touch relies on a family of C fibres that was discovered in humans in 1999, having been known to exist in cats for more than fifty years. These C-tactile (CT) fibres are tuned to fire most strongly in response to slow, gentle touch, at speeds of between one and ten centimetres (between half an inch and four inches) per second. The sweet spot at which they fire most enthusiastically is about three centimetres (or just over an inch) per second, and in response to something that is at, or close to, human body temperature. In other words, they are perfectly set up to detect being gently stroked by another human being. When activated, these stroke-sensitive nerves don't make us purr, but they can make us feel similarly content. Studies in humans have shown that this kind of stroking is associated with the release of endorphins and oxytocin, and feels pleasant and relaxing. Studies have found that the more activity that fires along the nerves, the more pleasant people say the touch feels.[25] This kind of touch also calms the nervous system, synchronising the heart and breathing rates of the giver and receiver, and it seems that we intuitively know how to do it. In studies where people were asked to stroke their partner's arm or their baby's arm, they naturally selected the right speed to activate CT fibres.[26]

Aikaterini Fotopoulou from University College London suggests that the affective touch system forms a key part of how babies learn to 'mentalise' their homeostatic state – in other words, how they derive meaning from their interoceptive signals. She argues that babies are born hardwired to need gentle touch, and not just as a means of staying warm and fed. Affective touch, such as gentle caresses during play or feeding, also provides a signal that tells the baby's brain, via the C tactile fibres, that its homeostatic needs for love, food and warmth are being met. This allows the baby to shift its inner sense of 'how I feel now' from 'bad, it's urgent' to 'warm, calm and contented'. These formative relationships set the tone of the body–brain conversation between pain, pleasure and loving care. If these early lessons go well, gentle touch becomes a short cut to feeling safe and supported that can last a lifetime. If they don't, or if the baby's basic needs are provided without the love and care a baby's brain is hardwired to expect, it could explain why a traumatic upbringing is so strongly connected to disorders of pleasure and pain.

The discovery of affective touch has led to research into its potential as a tool to improve wellbeing, both as a stress-buster and as a new way to treat pain, whether physical or emotional. Most studies into pain relief have been conducted by subjecting healthy people to a harmless but painful stimulus. In adults, several studies have shown that affective touch reduces pain when a heated probe is placed on the skin, whereas faster stroking and vibration do not. Interestingly, the pain-reducing effect in one study was strongest when the stroking came directly before the pain, suggesting that the touch provides something other than a distraction.[27]

In studies conducted on babies who were pricked in the heel to collect a blood sample, the results were similar: babies who were gently stroked ten seconds before the procedure grimaced for half as long as those who weren't. Measurements of their brain activity taken at the time showed that pain-related activity was reduced by affective touch by about the same amount as has been seen in studies where numbing cream was applied prior to the heel prick.[28]

Chronic pain is a trickier issue to remedy. Affective touch does seem to work for some people – in one 2020 study of fifty people with fibromyalgia, chronic back pain, headaches and nerve injuries, just ten minutes of affective touch reduced pain ratings by an average of around 23 per cent – or one point on a ten-point pain rating scale. One point might not sound like much, but there was a lot of variability in how people responded. Some people got no relief, others dropped by two or three points, and two of the participants' pain was reduced to zero.[29] One 2023 case study reported that a man with Parkinson's disease who also experienced chronic pain was pain-free after seven days of affective touch on his forearm from his partner, twice a day for fifteen minutes. The pain was still gone two months later.[30]

These early successes are encouraging, but we don't yet fully understand why some people respond better than others. It could be that the pain relief is driven by the way affective touch boosts the bottom-up pleasure signals, which change the brain's interpretation from 'unsafe' to 'safe'. It could be that the incoming signals from C-tactile fibres drown out those from nociceptive, pain-sensing fibres, or short-circuit the pain signal at the spinal cord on the way to the brain. It could be any or all of these things in varying combinations, depending on the type of pain and the person. Getting to the bottom of this is important, not least because some chronic pain conditions involve allodynia: a condition in which, due to nerve damage or central sensitisation, harmless touch – even gentle stroking – is experienced as pain.

One research group is using virtual reality to get around this problem. Based on the finding that people are able to recognise affective touch as pleasurable when they see it happening, a group of Italian researchers has developed a visual illusion in which people 'see' their skin being stroked through a VR headset, without it actually being touched. The hope is that this may reduce pain by changing our emotional processing and undoing the errant connections between pain, stress and fear.

Everyday levels of stress and discomfort can be tackled more directly using the skin's interoceptive pathways. Affective touch from a romantic partner has been shown to not only feel good but also to reduce heart rate. The same study found that stroking your own arm has some benefits, but without the bonus of reducing heart rate. Some researchers have designed prototypes of wearable arm-stroking machines that consist of a soft brush attached to a motor that moves the brush along the skin at the right pressure and speed to stimulate CT fibres. One such device, which its inventors hope will one day become a wearable stress-reliever, was found to reduce anxiety caused by public speaking; volunteers described it as a 'warm, fuzzy feeling', like 'a calm heartbeat' and 'a loving sensation' that reminded people of stroking a dog, cat or teddy bear.[31]

For those who experience it, the pleasant tingling sensation that has become known as ASMR (autonomous sensory meridian response) may be another way to get the same feeling. In ASMR, around 20 per cent of people experience a pleasant tingling sensation on their scalp and neck in response to certain sounds or sensations, such as the sound of whispering or slow brushing. ASMR videos have become popular online over the past decade or so, leading to a number of studies exploring what the phenomenon has to do with our interoceptive pleasure–pain circuitry. A couple of studies have suggested that people who are sensitive to ASMR are more sensitive to their own bodily sensations in general, including those that are interoceptive.[32] One possible explanation is that the way in which gentle sound, touch and comfort come together in early childhood causes them to develop a connection between sounds and the circuitry of affective touch.[33] This could make it useful as a stress- and pain reliever in those who are sensitive and for whom affective touch is not readily at hand. Other alternative remedies include the presence of pets: a recent study found that having a dog present while receiving a painful cold stimulus helped people withstand more pain than they could without company. The dog was more effective than a close friend. It didn't even have to be their own pet: even an unfamiliar dog proved to be better than a friend. Researchers suggest that dogs offer emotional support without the fear of judgement or having to reassure a friend that you are OK.[34]

On the other hand, some people hate dogs, while some find ASMR rage-inducing and some find affective touch to be ticklish or annoying. We all have different sensory preferences. And context matters a lot – such as who is doing the stroking and whether you are somewhere where you feel safe and relaxed. Attempting ASMR in the middle of a busy office would be unlikely to work.

In the right context, though, skin-based interoceptive pathways are an important tool in our arsenal for staying physically and mentally healthy, and for feeling strong, safe and supported from within. The skin, as the border between the internal and external worlds, is the perfect place to start to rebalance how we feel on the inside with what we need to do to adapt to the challenges of life. Having a healthy relationship with your inner signals is not just about being able to tune in; it's also about learning to understand what's being said, solve any problems, and get back to living your life. In the final chapter, I'll explore how we can do this when we're facing some of the most common issues that modern life throws at us, from stress, to a lack of vim and vigour, and the tricky task of knowing when to eat, how much to eat and when to stop. And I'll look forward to a future in which body, brain and mind are finally reunited in a whole-person view of what it means to be healthy and to thrive.

7

Tune in

Keeping the body in mind, and the mind in the world

Genuinely new perspectives in science are rare – and those that are both relevant to everyday life and easily applied are rarer still. But the emerging science of interoception is one such perspective.

First, though, a disclaimer. Despite the way it is often portrayed in popular culture, science does not operate as a fact-generating machine. Science is a process of asking questions and then working towards the most likely explanation, while ruling out what doesn't fit the evidence. When we apply science to everyday life, then, it's a good idea to remember that 'the latest research' is very much a work in process.

This is especially true for the most interesting and important questions, such as 'What makes humans tick?' and 'Why do we feel, think and act the way we do?' In nearly a quarter of a century as a science journalist, I've met hundreds of scientists, from Nobel Prize-winners to fresh-thinking PhD students, and the one thing they have in common is an openness to being wrong. In my experience, anyone who tells you that they have all the answers is either fooling themselves or trying to sell you something.

That said, as science makes progress, it sometimes makes sense to consider whether innovations that are coming out of the lab could be useful. The growing consensus that the mind does not end inside the skull but rather emerges from a dynamic conversation between body and brain is an important shift that can make our thoughts and feelings easier to understand.

Know thy baseline

When trying to incorporate a new understanding of the mind into your everyday life, it can be tricky to know where to start. It doesn't help that many of our interoceptive signals exist at the borders of consciousness, feeding into feelings, motivations and assumptions in ways that we aren't aware of, and which might drive us to behave in ways that are not in our best interests, such as avoidance, numbing or self-medicating.

Because of this, we might begin by bringing some of our implicit assumptions into the light. The Multidimensional Assessment of Interoceptive Awareness questionnaire (MAIA)[1] is a scientifically validated test that is widely used to measure people's interoceptive tendencies, such as their tendency to notice their body signals and trust them as an accurate source of information. Other questions aim to determine whether they are experienced as a source of worry or calm. This is useful for recognising your tendencies and knowing what to work on, but it also provides a benchmark for where you are now compared to, say, in a year's time. For example, when I first did the MAIA questionnaire, I scored in the normal range on the subscales for 'noticing' and 'trusting' my interoceptive signals, but below average on 'self-regulation'. This suggests that my energy would be best spent on learning how to calm my body when I notice signs of stress, and perhaps how to rev things up when I feel lethargic.

Once you have your baseline, the next step is to decide which parts of your life could benefit from a re-evaluation of the body–brain connection. You might be looking for new ways to deal with stress and anxiety, or to develop a healthier approach to food, rest and exercise. You might want to break free from unhealthy coping strategies that are causing more problems than they solve. Or you might want to feel more comfortable in your own skin, more confident and better placed to maintain healthier relationships.

I'll tackle each of these issues in this chapter, but first it is worth briefly exploring what healthy interoception looks like. As we've seen, it is possible to be both too insensitive to your body and to be too 'tuned in'. Unfortunately, there's no straightforward test for interoceptive ability, but results from recent research suggest that we shouldn't necessarily be aiming for 20:20 interoceptive vision. In an ideal world, we should be aiming for the ability to check in, address any problems, then to check out again and live in the wider world. For that, we need to master four fundamental skills:

Precision – the ability to detect your body's signals, ideally in a variety of situations.

Discrimination – the ability to distinguish between similar physical sensations, depending on the context.

Interpretation – the ability to understand what caused this feeling, and what it means.

Flexibility – the ability to turn your attention inwards for long enough to work out what's happening and fix the problem, before getting on with your life.

If that sounds like a challenge, it is worth remembering that almost everyone has mastered this already for at least two common interoceptive signals. Anyone who has been potty-trained has learned to sense a physiological need, identify what action is required, take appropriate action, then get on with their day. In principle, we should be able to do something similar for sensations and signals that are tied up with our thoughts, feelings and sense of self.

The rest of this chapter will consider what the research so far can offer in terms of advice on how to make this a reality. First, it will give a handful of general-purpose strategies that make interoceptive signals easier to detect, and then it will focus on a few specific examples where the realities of modern life mean that we need to take extra measures to work out what we need. I also list a few tech-based short cuts that have the potential to help us tune in to our signals or tweak them, to change the way we think and feel.

General-purpose interoceptive strategies

Body-based mindfulness

Tuning into the body doesn't always come naturally. Around fifteen years ago, a yoga teacher managed to undo the calm she'd instilled in me during a class by suggesting that for the final pose we do 'whatever our bodies are calling for'. I was stumped, not to mention irritated. Surely it was her job to tell me what my body needed?

I now understand that she was asking us to focus on how our bodies felt from the inside, to find any parts that were stiff or sore, and to move them in a way that made them feel better. In other words, to mindfully peer inside our bodies and look for any tension that hadn't been wrung out in the rest of the class, and then to fix it and move on.

Mindfulness is now fully in the mainstream. Millions of people around the world use it for stress relief or self-care, and it has become widely taught in schools and workplaces to promote emotional wellbeing. Research into how meditation changes the brain over time has not only shown that it works, but has provided some clues to how. Practising noticing when your mind is wandering and directing your focus back to where you intended to place it strengthens attention-related connections in the brain, as if building a muscle.[2] Many forms of meditation use breathing-related sensations as an attentional anchor, making them forms of interoceptive training. Some types of meditation take this further and focus almost entirely on tuning into the body. These body-focused – or somatic – approaches direct attention to how bodily sensations feel emotionally, and how emotions feel physically. The aim is to develop the skill of being able to flexibly shift attention around the body, so that you can tune into the relevant signals, deal with any issues, then tune out again, hopefully with the problem solved and a calmer body and mind.

Somatically focused guided meditations are less common than mindfulness-based options, but they do exist – it's worth looking around online to find one that works for you. Another option is to try some form of mindful movement: yoga, martial arts, tai chi and Pilates all combine movement and breath combinations while focusing on the body and noticing how it feels. There's a small but growing body of evidence that these kinds of mindful movements improve both physical and mental health. Yoga, for example, has been found to reduce stress and boost mood, while tai chi reduces depression and anxiety and improves sleep. This has led some researchers to design interventions that attempt to extract the 'special sauce' from these practices and use it in targeted mental health programmes. In a small pilot study published in 2024, a team of researchers from the University of Perugia in Italy combined mindfulness, team games, self-massage, dance and breathing exercises with education about the body–mind connection. Early results found that an eight-week intervention using their 'Movimento Biologico' programme improved the ability of university students to recognise their body sensations and to use them as a trusted source of information to help them regulate their emotions.[3]

In principle, any kind of movement can have a similar impact: weightlifting can be mindful, as can rock climbing, swimming, surfing or dancing. However you choose to connect with your body from the inside, the usual principles of mindfulness apply: notice sensations in your body, focus your attention on them, be curious about what they mean – then let them go. For some people, particularly those with a history of trauma, it's probably a good idea to do this with guidance from a therapist.

Random check-ins

Another way to practise tuning in and out from your body is to check in throughout the day. You might want to set an alarm, or you could download an app that will ping at random intervals throughout the day.[4] When the time arrives, notice how you are breathing and how your muscles are feeling. Are you clenching your jaw? If so, what might you do to change that? Sometimes the answer will be that you just need to stop sitting at a screen and take a quick break to stretch, walk around the block or put the kettle on. At other times, there will be a real work or life problem bubbling under the surface that could benefit from some attention. Making time to check in can ensure that what's most important sees the light of day, allowing you to address it and then move on.

Another useful way to practise tuning in, and to develop the skill of discrimination, is to be open to the possibility that a feeling in your body isn't signalling what you immediately assume. This suggestion comes from Lisa Feldman Barrett, the neuroscientist and author of *How Emotions Are Made*. She says, for example, that hunger can easily be confused with fatigue, and vice versa. 'You have a lifetime of experiencing that after you chew and swallow you feel energised, but if people are eating because they feel hungry, when what they are is fatigued, the fatigue won't be alleviated by the food because it's not the cause,' she says. 'It's about being curious.'

Being more curious in daily life will also allow you to notice when you're leaning into an unhelpful coping strategy: perhaps hiding from the world, opening a bottle of wine or squashing your own feelings to please others. It might not be easy – or comfortable – at first, but with practice this can help you to recognise changes in your body that provide a trusted guide to what you really want and need.

Once you've mastered the art of tuning in and being curious, it can prove useful in all kinds of scenarios when you aren't sure what to think, feel or do. When you've been invited to a social event, does the thought of going make your heart sink, or do you feel lighter at the prospect? How do you feel when you listen to different kinds of music or consume certain kinds of media? Get curious about that, too – maybe look at how the same news story is reported by a variety of different media outlets with different political leanings. Does one report make you feel angry while another makes you feel sad? Perhaps one telling of the story makes you feel motivated to donate to a relevant charity? Which interpretation of events rings true to you? Do you inherently trust one reporter over the other, and why might that be?

Manos Tsakiris, a philosopher and interoception researcher, recently founded the Centre for the Politics of

Feelings at the University of London to study the way that emotions affect our politics and how political decisions affect our mental and physical health. He suggests trying 'critical feeling' when we have a strong response to a political issue: ask yourself, what am I feeling right now? Is this feeling in response to the message, the way it is delivered, or my pre-existing beliefs and opinions? Getting curious about what's driving your feelings about the state of the world might help to reduce the feelings of overwhelm and hopelessness that can come with twenty-four-hour access to global news.

Change the signal

While our feelings can, at times, be overwhelming, it's worth remembering that they are not fixed – they change, depending on what is happening outside of the body, but also on what we're doing at the time. Or, perhaps, what we're not doing.

Interoceptive signals evolved to flag the need for physical action to put things in the body back in balance. Low on energy or dehydrated? Go out and find what you need. Stressed? Run, fight or hide. Cold? Light a fire. Whatever the signal, taking action sets the wheels in motion to rebalance body and mind.

In modern life, we rarely need to physically move to meet our homeostatic needs; quite apart from the fact that we don't have to work to catch our own food or find warmth and shelter, technology has made it easy to keep in contact with friends, shop and be entertained sitting in front of a screen and without moving anything other than our fingers and eyes. Yet the fact remains that our body–brain connections evolved to expect movement to be part of the solution. Running from danger, for example, helps to burn off the glucose released from storage to fuel the necessary action. If we get stressed and don't move, that fuel doesn't get used up. Without an action to provide the necessary closure, the biological stress response can hang around longer than it should. More generally, if we are sedentary most of the time, our bodies save energy by shrinking our muscles and not bothering to invest in stronger bones. At the same time, the mitochondria in our muscles becomes less efficient at releasing energy. All of these things make us feel as if we're firing on too few cylinders – because as far as our bodies are concerned, that's exactly what's happening.

That doesn't necessarily mean that we need to start hitting the gym every day. A growing body of evidence suggests that regular light to moderate exercise, such as walking or taking the stairs instead of the lift, keeps our body and mind in decent working order. Adding some form of weight-bearing exercise is even better (carrying shopping works just as well as weights), as is moving regularly in ways that take the body through its natural range of motion. This might involve a programme of stretching, but it can also be as simple as practising various ways of getting down onto the floor and back up again. One method is to work on getting into and out of a deep squat, using a door or sturdy chair for support at first.

Movement can also be used as a short-term fix to a problematic state of mind; it can, for instance, help us snap out of lethargy. Our perception of time is increasingly thought to emerge from the way that rhythmic bodily signals, such as heartbeat and breathing rate, are represented in the insula. If we want to stop time from dragging, the quickest solution is to activate the body. If you walk around the block or do a few stretches, the kickstart to your heart, lungs and muscles should change the internal record so that your internal perception of time is reset to something that feels more comfortable.

Moving around also provides the all-important connection between the world inside the body and the one that's around us. You can't move without changing something on the inside and interacting with your surroundings, even if that's only by breathing a little deeper and watching where you are going. So, if there's one simple change that everyone can make to their lives to bring body, mind and world together, it would be to actively explore the world whenever possible, while keeping one ear open for the subtle guiding signals from within.

Tech-based short cut #1: Heart rate variability

Given the subtlety of interoceptive feelings, it can be difficult to be sure whether what you need most is to move or rest. One way to help work this out is to track heart rate variability using a smart watch or other wearable device. This is a measure of how evenly the heart beats over a particular period, and is an indicator of how well your body is responding to stress.

A low heart-rate variability (HRV) is a sign that the heart is beating at an even pace, with little fluctuation in the gap between one beat and the next. Perhaps surprisingly, this is not an indicator of good stress control. A low HRV score suggests that your sympathetic nervous system – the one that revs the body up in times of stress, increasing heart rate and breathing and releasing glucose from storage ready for action – is dominant. In contrast, a higher HRV score is a sign that the parasympathetic, 'rest and digest' system is in charge and that everything is under control. Several wearables translate HRV into a score that indicates whether your body is rested and capable of tackling challenges (higher HRV), or that your body is dealing with some kind of physiological stress (infection, over-exertion, mental load) and that you should rest and recover.

I tested three off-the-shelf devices: an Apple Watch™, which takes snapshots throughout the day and during exercise; a WHOOP fitness band, which takes an overnight average and computes a daily stress score and a readiness score; and a Polar H10 chest-mounted heart-rate monitor, linked to the Elite HRV app. When tracking this process via HRV measurements from a smart watch or other wearable, there are a few things to remember. HRV reflects a dynamic process, and most wearables provide snapshots rather than a twenty-four-hour overview of your ups and downs. They also vary in terms of which aspects of HRV they take into account when generating a score. What counts as a 'good' score also varies depending on your age and fitness level, and while there are averages available online, the most important thing is what's normal for you.

After trying these three wearables, my main conclusion was that one measure of HRV is better than three. Comparing the results from three devices quickly became confusing, not least because they provided very different estimates based on snapshots taken at different times. On the other hand, when each dipped noticeably from its own normal, there was usually a reason for it: illness, stress or the aftermath of a night out. Over time, I have found that a combination of paying attention to how I feel and the numbers the wearables provided has helped me learn to distinguish between when my body is telling me to take a break and when I am lethargic and need to get up and move.

Body reading in the modern world

The above strategies can provide a powerful way to begin to shift your mindset away from seeing the mind as disembodied or locked in the brain to a more integrated understanding that includes the body and the wider world.

But on their own, they aren't quite enough. The modern world, packed with mental and emotional stressors, highly processed foods that hoodwink our appetite-control and pleasure-seeking circuitry, and not nearly enough physical activity, doesn't always make this easy. That's why the next section suggests ways that you can work around these challenges and feel what really matters.

Stress and anxiety

Stress is not always a bad thing. Humans are a species of explorers and risk-takers, and we thrive on the challenge of making progress. If this wasn't so intrinsic to human nature, we'd probably still be sitting around fires, whittling arrowheads and marking cave walls with our handprints. In the grand scheme of human evolution, doing new and scary things has been the making of us.

On the other hand, stress is a major cause of mental and physical health issues, and it is at the heart of a huge amount of human suffering. And since there are no signs that life is going to get any less stressful, it's a good idea to learn new ways to handle it.

Stress comes down to uncertainty over whether you have the resources to deal with an approaching challenge. Anxiety is another symptom of uncertainty about what might happen, and whether you can cope. The difference is that, in this case, stress occurs in response to a threat that may never materialise.

Whether the stress is triggered by the brain or the body, the physiological consequences are similar: stress hormones release glucose into the blood, your heart rate rises, your pupils dilate, your muscles tense and you begin to breathe more quickly.

Interoceptive training studies, such as those by Sarah Garfinkel, have helped people to recognise and read stress-related signals, such as elevated heart rate or breathing rate, so they can interrupt this process before it spirals out of control. In the training studies, boosting these signals in the lab with light exercise between bouts of training also helped. This is easy enough to replicate outside the lab, by doing jumping jacks or running on the spot. However you raise your heart rate, what's important is to notice how it feels, and to stay tuned in to the sensation as it returns to normal.

In theory, if you can get used to feeling your heart beating in a variety of situations where you are safe, this should generate the embodied knowledge that changes in heart and breathing rates are normal – and temporary. The benefit of staying tuned into these signals as they calm down is that it shows what it feels like when the heart, lungs and muscles return to normal. And it does seem to work: after taking part in Garfinkel's studies, participants said that they were better able to notice when their heart rate was rising, and that this knowledge was enough to interrupt the spiral of anxiety. It also helped them to feel in control of their reaction to stress – *and* they were still feeling the benefits a year later. Interestingly, once participants had gained greater 'precision' at noticing their heart and lung signals, they reported noticing them less often. Garfinkel speculates that this might mean that having learned that changes in heart rate are not necessarily urgent, small changes were less likely to be escalated into consciousness and experienced as anxiety.

Other evidence suggests that being able to feel your heart and lung sensations while in an extreme state of relaxation is helpful in the fight against stress and anxiety. The best place to achieve this state is in a floatation tank: the darkness, quiet and lack of external sensations mean that interoceptive signals are the only ones that reach the brain. Studies by Sahib Khalsa and the team at LIBR in Tulsa have shown that people with anxiety were able to feel and hear their heartbeat and breathing more clearly than usual[5] in the tank, but that these sensations felt positive and relaxing rather than negative. This suggests that just as you can learn to fear and avoid your body signals, you can also learn to use them as a sign of safety and comfort.

Having learned to feel my heart beating over the course of six sessions in a floatation tank, I can now tune into it much more easily while I'm at rest, and to experience it as comforting and soothing. I have even got into the habit of deliberately tuning into it as I fall asleep at night. The sensation, and the feeling of calm, is not as intense as when I'm in the tank, but it's close enough. Floatation tanks are springing up all over the USA and Europe, but they aren't yet commonplace or affordable. Outside a tank, the closest I have got to the same feeling is lying in 'corpse pose' at the end of an intense yoga class, on my back with my arms and legs flopped to the sides. I've also felt similarly calm while doing a guided somatic meditation. Another option is to try progressive muscle relaxation, where you lie quietly and focus on tightening and then releasing muscles in the soles of your feet and then work slowly up your body to your neck, face and forehead. As the muscles relax, they update the interoceptive signals from your muscles to report that all is well.

However you find that feeling of calm, it's important that you notice how your body feels when it's safe and relaxed. Then you can begin to build up the knowledge and trust that, whatever happens, your body is a safe haven. With luck, over time, the constant surprise will be replaced with the knowledge that you can deal with any situation, however challenging.

Tech-based short cut #2: Vagus nerve stimulation

Now that the role that the vagus nerve plays in calming the body is more widely known, several companies have developed products to stimulate it non-invasively. Some of them claim to target the parasympathetic branch of the nervous system, and to improve health by increasing heart rate variability. They are small and relatively unobtrusive, comprising of an ear-clip roughly the size of in-ear headphones and a handset smaller than a smartphone, so you can find your calm while replying to emails and attending virtual meetings, without attracting strange looks.

I experimented with one of these (a Nurosym™ device, lent to me by its manufacturer Parasym) during some of my more stressful moments. According to the company's internal data (which have been neither independently verified nor peer reviewed),[6] a 2022 'clinical trial' in ten healthy people showed a small increase in heart rate variability – a marker of stress that can be measured on many smart watches – by an average of four points after five minutes of stimulation. It's difficult to tell how important this is, not least because the 'before' and 'after' HRV scores varied from person to person by between two and three points in either direction; a change of just four points is difficult to interpret without seeing the original data.

In my own mini-experiments, I found no detectable changes in my subjective stress level or my HRV after an hour of stimulation, despite using the device on multiple occasions over several months. Overall, until there is more evidence from much larger trials, I remain open-minded about whether this technology will offer meaningful health benefits.

DIY vagus stimulation (breathe)

There is, however, an easier – and free – way to activate the vagus nerve, which directly harnesses the interoceptive signals from the heart, lungs and blood vessels in the chest. We know this thanks to the work of the Russian engineer turned physiologist Evgeny Vaschillo, who discovered a physiological sweet spot when we breathe at a rate of six breaths per minute (in for five seconds, out for five seconds), which maximises HRV. Vaschillo called this 'resonance breathing'.

It works because of how the vagus nerve regulates heart rate, based on pressure changes in the chest. When we inhale, the space inside the chest expands, reducing pressure on the blood vessels.

This allows them to expand, sending more blood to the heart. This, too, is reported to the brain via the vagus nerve, and the brain responds by increasing the heart rate. On an exhale, the opposite happens: pressure in the chest increases and blood flow slows, as does the heart.[7] This constant fluctuation provides a flexible baseline from which we can increase blood and oxygen flow quickly in an emergency and conserve energy the rest of the time by not pumping blood faster than it's needed.

When there's an active stress response on the go, though, heart rate, breathing rate and blood pressure all rise together and this fine balance is temporarily put on hold. This is no problem if the stress passes quickly, but when it becomes chronic it becomes a drain on the body's resources.

Resonance breathing can help put things back in balance. It works because it takes around five seconds for a change in blood pressure to translate into a change in heart rate, and vice versa. If we slow our breathing down to match this rate, breathing in for five seconds and out for five seconds, it gives our body a helpful nudge in the right direction – a little like when you push a child on a swing at just the right moment to send them higher. Sure enough, studies of resonance breathing have found that it reduces symptoms of stress, anxiety, depression and chronic pain. It has also been found to reduce blood pressure, increase athletic performance, and even improve concentration.[8]

Hunger, energy, and mood food

The crossed wires that lead us to overeat certain foods and to snack when we're stressed or tired are often framed as a lack of self-control. But in many cases it's a simple case of interoceptive mistaken identity – tiredness mistaken for hunger, for example, or fullness mistaken for comfort and safety. Over a lifetime, these interoceptive errors can become entrenched, but there are ways to change your habits and relearn what these signals mean.

It's not easy – not least because the ubiquity of ultra-processed foods makes fullness in particular an imperfect signal. Nevertheless, it is worth trying to get to know these physical signs a little better. You don't have to switch to a 100 per cent wholefood diet, but picking one day a week to prepare a meal from scratch, using whole, minimally processed ingredients, can be a good start. The trick is to take the time to eat slowly, without distractions, and to pay attention to when you start to feel full.

Preliminary results from an ongoing study offer an intriguing suggestion on how to make fullness sensations easier to feel. In a study of forty healthy adults, half were asked to wear a shapewear top (a kind of tight vest that is worn as underwear) while they ate, while the remaining volunteers ate while wearing a baggy T-shirt. The results showed that those wearing the shapewear were more accurate at judging their own body size, and better at sensing their fullness signals. The effect was stronger in women than in men, and most effective after around twenty minutes of wearing the top. People who wore the top for longer seem to have got used to the sensations, and were able to tune them out and keep on eating. The study, which is yet to be published, suggested that such clothes could be a wearable form of 'training wheels' for anyone looking to learn how much they should eat in a sitting.

Once you've identified when you are full, the important question becomes: do you still want to eat? If the answer is yes, why is that? Is it because you were taught that it was rude to leave food on your plate? Are you craving something sweet? Once you have identified what is driving the urge to eat, you can decide what to do. If you choose to eat a sweet treat, that's fine. Life is short, and pleasure is an important sensation, too.

In fact, pleasure is one of our best weapons against physical and emotional pain, and against a lack of energy and motivation. If motivation isn't forthcoming, knowing that it's because your brain and body have concluded that something isn't worth your time, you can start to work out where the problem is coming from, and how you might fix it. Is it stress? A draining or toxic work environment? Or are you struggling to find the meaning in a task? Once you've established the cause, you can tackle the problem. Do you need a day off? An early night? A laugh with some good friends? Do you need to rethink your career, or can you find meaning elsewhere in your life? Once you've identified the energy drain, you stand a better chance of working out how to plug the holes, or at least make the time you spend not in that situation as pleasurable as possible.

Tech-based short cut #3: Continuous blood glucose monitoring

Continuous blood sugar monitors were designed to help people with diabetes manage their condition, but they are now available over the counter. They are small and unobtrusive plastic discs that stick to the back of the arm, with a flexible sensor that dips into the fluid that bathes the skin cells and is a close approximation of the sugar levels in the blood. This data is beamed to a smartphone app, providing near-instant insight into real-time data.

Having a constant measure of your blood sugar is a potentially useful interoceptive signal with which you can learn how blood sugar, mood and energy levels are connected. I used a Lingo sensor, made by the healthcare company Abbott, for three weeks, while logging my food intake, mood and energy levels.

Surprisingly, even when the app showed that my blood sugar was 'spiking', I didn't feel any kind of 'sugar rush', and nor did I feel happier or full of energy. When I was hungry, tired, or even when I felt shaky, I would normally assume that my blood sugar had crashed, but there was no evidence that my level was anything other than normal. This was useful information: with evidence that my blood sugar was fine, I deduced that the real cause of my shakiness was almost certainly anxiety that I might be on the wrong bus while I was already running late. Being able to rule out low blood sugar also meant that I didn't need to stress about needing to find food too.

The only time when my energy and blood sugar were aligned was one afternoon when, after enjoying a chocolate bar, I woke up on the sofa half an hour later, dazed and slightly confused. When I checked the app later, I noticed that my blood sugar had dipped below the lower limit of 'normal' at about the time I nodded off.

Overall, monitoring blood sugar can be interesting, but it's worth remembering that it's one food-related signal of many, and there's little evidence that people without diabetes benefit from tracking their blood sugar. Also, in my experience, it is easy to get caught up in the game and try to 'beat' yesterday's blood sugar score, even if your levels are perfectly healthy. For that reason, perfectionists and people with a history of disordered eating should avoid this technology altogether.

Inner strength, outer support

A lack of energy and motivation may have nothing to do with food and everything to do with a suspicion that you can't handle what's been asked of you. According to some estimates, 70 per cent of people experience imposter syndrome – the nagging feeling that they are not as capable as they are pretending to be or are thought to be. Many of these people are highly qualified and talented; some are at the top of their profession. Many more hold themselves back from challenges they are capable of tackling, while less able but more confident people are promoted above them.

Imposter syndrome can act as a motivator for some people, but a lot of the time it is a huge waste of energy. On the other hand, if the way we feel about ourselves is based on signals that originate within the body, it opens up the possibility that if we can change those signals, we can look at ourselves more positively.

One important line of communication between the body and the brain comes from what Antonio Damasio has described as the body's 'musculoskeletal division' – messages from the bones, muscles and connective tissues that provide an overview of what the body is capable of at any given time.[9] We aren't usually aware of these feelings; they are 'in between' feelings that aren't necessarily conscious, but that still have an impact on our experience, such as whether we feel uneasy or confident. Several decades of research suggests that our physical strength has an important impact on how capable we feel.

Studies in which people increase their physical strength – either through weight training or other forms of exercise – have shown that becoming physically more capable boosts self-confidence, self-esteem and what psychologists call 'self-efficacy' – the implicit sense of being able to meet life's challenges. Interestingly, a study in young people found that strength training had a greater impact on their self-worth and confidence than on their perception of their own attractiveness.[10] In an age where social media encourages people to show off their strength by flexing their muscles in 'gym selfies', this seems like something everyone should know: upgrade the body's musculoskeletal hardware, and inner strength should follow. Other people might not be able to see it, but you'll be able to feel it – and that's what matters.

No matter how strong you are on the inside, though, everyone needs the support of others. We've already seen that when we feel safe and supported, our bodies respond with hormones that make us feel good: natural painkillers and access to reserves of energy and motivation.

There's no easy 'life hack' to finding your tribe, but a good place to start is with your friends and family. Pay attention to how you feel in your body when you are with them. Do you feel safe, relaxed and supported, or on edge and fearing rejection or ridicule? Similarly, how do you feel when you are on your own? At what point do peace and solitude tip over into loneliness, and how does your body feel in each scenario? Again, there are no hard-and-fast rules; some people need others around them all the time, while other people need time to decompress after socialising. But if you've never thought about it, now might be a good time to start. By focusing on how your body feels in the company of others, you might gain an appreciation for the special people in your life – and a reason to make more time to see them. Alternatively, you might find that you are getting too much – or too little – social contact than you need to feel comfortable in your skin.

Our skin, as a large organ that forms the border between our insides and the outer world, is perfectly positioned to keep tabs on how things are going for us. Touch, as we've seen, is an important way in which interoceptive pathways in the skin help us feel supported, and there's evidence that you can tap into it on your own. In a recent study, just twenty seconds a day of compassionate self-touch, which in this study involved putting one hand on the heart, the other on the belly, and focusing on feeling compassion and kindness towards yourself, reduced stress levels, improved mood, and led to greater self-compassion after a month, compared to a control group.[11] The researchers point out that this method isn't the only way to achieve the same result – they suggest that gently stroking your arms or giving yourself a hug would do something similar, as long as it's combined with positive feelings about yourself and some kind words of support.

The future

In a few short years, interoception has gone from being an interesting idea on the fringes of neuroscience to a field that has the potential to revolutionise our understanding of the human mind. Reframing the body as the joint architect of our mental experiences presents us with opportunities to intervene when evolutionary 'factory settings', which were calibrated for hunting and gathering, clash with the world we live in.

This understanding is starting to change the way in which medical research is conducted. For centuries, specialisms were divided based on which body parts or anatomical systems they involved. The growing understanding that brain and body collaborate in everything we think, feel and do has begun to feed into research that extends beyond one body part or disease, and instead sees the body and brain as part of one interconnected system.

In 2021, the US government's medical research body, the National Institutes of Health, announced $18.5 million of funding into interoception research. Helene Langevin, director of the NIH's National Center for Complementary and Integrative Health, says that interoception research is the perfect way to encourage people from across the specialities to work together: 'Interoception talks to all the body systems and the connections between them, and that has a tendency to get people together.' For the past two years, the NIH has hosted an annual research conference on interoception, bringing together scientists and doctors from the fields of psychiatry, metabolic science, pain, psychology and molecular biology, who often discover that they are asking similar questions. A similar realisation is spreading through wider society. From the rise of mindfulness as a method of controlling stress to the toll that the Covid-19 pandemic took on our mental and physical health, there is a growing understanding among those who are interested in 'wellness' that health is not about either the body or the mind, but about both.

As the world continues to change, getting a better handle on our inner sense will be increasingly important.

Climate change is just one of the challenges ahead. According to some climate projections, by 2070, up to 3 billion people will be living in regions hot enough to endanger life. A preliminary study by Charles Verdonk, a neuroscientist at the French Armed Forces Biomedical Research Institute, suggests that people with poor interoception skills are more likely to suffer heat exhaustion, partly because they miss the vital signals to rest, drink and seek shade. Verdonk and his colleagues suggest that interventions such as body-focused mindfulness may help people to notice, and respond to, their bodily warning signals.[12]

Other researchers suggest that better interoceptive awareness can help us to navigate the ever-changing social climate too. Being more aware of subtle internal changes might help us to trust our gut when we are targeted by online scammers, or might make us stop to think twice about whether a political argument is based on emotion alone, or whether it has a basis in fact. Having a better handle on what we are feeling and why is a useful skill in a world where social discourse, particularly online, has become more emotionally driven than ever before. Complex social issues are increasingly being simplified into polarised debates where insults fly and strangers can stir strong emotions that have nowhere to go. As we spend more of our lives online, it is starting to feel like crunch time. Either we take a fresh look at why we think, feel and act the way we do, or we may find ourselves being dragged through life by emotional reactions that feel out of control.

The obvious place to start is with the youngest in society.

The vital role that our early life experiences play in setting the tone for our lifelong body–brain connections suggests that early interventions are key. Recent evidence suggests that interventions that teach parents how to recognise and respond to their children's emotional and physical needs, and to see 'bad' behaviour as the communication of an unmet need, not only improve children's behaviour but also protect them from poor mental health later in life. There is also some evidence that this approach helped to reduce parents' stress levels.[13] This suggests that properly funded support for parents, particularly those who may not have received the comfort they needed in their early life, could help them to improve their mental health – and parenting skills.

There is also an urgent need for interventions that might help young people regulate their emotions in our education system. As mindfulness has become more common as a stress-reduction tool for adults, it has begun to be taught in schools, with the intention of teaching children how to self-regulate. Recently, though, its effectiveness in children has been called into question. A large study of mindfulness interventions in UK schoolchildren published in 2022 concluded that mindfulness didn't improve children's mental health and, for some young people with existing mental health issues, it made matters worse.[14] With the search now on for better interventions, it seems sensible to try more body-focused strategies – particularly when combined with teaching young people that moving around is the easiest way to self-regulate from the inside out.

There is already a precedent. Kelly Mahler is an

American occupational therapist who has designed an 'Interoception Curriculum', a series of guided exercises, games and lesson plans for children with autism and ADHD. The approach has been tested in a series of small studies. Initial results are promising, with significant improvements in both interoceptive awareness and emotional regulation in middle-school children,[15] and Mahler is in the process of expanding the programme more broadly.[16] Mahler's programme inspired Emma Goodall from the Department of Education in South Australia to produce an 'interoception kit' for schools.[17] This, too, is aimed primarily at students with special educational needs, but could easily be adapted for use more broadly. In the not too distant future, interactive computer games, like the one we heard about in Chapter 5 that's being trialled by the Dutch police force, could be adapted for schools, to help young people to recognise bodily signals associated with stress – and learn to regulate them.

For those of us who have left full-time education, help is also on the way. As we wait for today's science to trickle into tomorrow's education, medicine and evidence-based lifestyle advice, there is plenty we can do to foster an understanding of ourselves as fully integrated mind–body beings. As we explore the signals we receive from within our own bodies, we might find that they are not always right, but they always have something important to say about our place in the world, and we owe it to ourselves to listen. When we understand ourselves as more than a biological machine run by a disembodied mind, we can start to live a life that is richer and more connected. Then, as the father of psychology William James put it over a century ago, we can finally 'realise more deeply than ever how much of our mental life is knit up in our corporeal frame'.[18]

Acknowledgements

The seed for this book was planted in a dark corner of a London pub in April 2023. It made it into the light thanks to many people, not least my agent Peter Tallack, who not only arranged the pub gathering and provided the beer but, more importantly, assured me that I wasn't the only person who cared about a mysterious sense that hardly anyone had heard of. Thanks, Peter, for your enthusiasm and advice and for telling me to get on with it when I was dithering.

The same goes for the amazing team at Profile Books, notably Nick Humphrey, who has been a cheerleader from day one, and also Georgina Difford, Alex Elam, Sinem Erkas, Jeff Edwards (for the diagrams) and Jon Petre, who have helped it hugely along its way. Thanks, too, to Jennifer Croll and Lucy Kenward at Greystone Books for your enthusiasm and guidance, and also to Jane Hammett for not only spotting all the 'not onlys', but also for letting me keep a few. Thank you all for caring about the finished product as much as I do.

Of course, there wouldn't be anything to care about without the scientists doing the ground-breaking work and their willingness to give up their time to tell me about it.

Huge thanks go to Sahib Khalsa, who so generously invited me to his lab and pulled out all the stops so that I could get a full interoceptive immersion – literally. Thanks, Sahib, for being so encouraging and positive about this book from start to finish, and to all at the Laureate Institute for Brain Research for making time for me while I was in Tulsa: in particular, Emily Choquette, Jennifer Stewart, Ryan Smith, Masaya Misaki, Jonathan Savitz and Robin Aupperle. Big thanks, too, to Martin Picard and Kathryn Whyte for hosting me at Columbia University, and to Naveen Jayaprakash, Stavros Zanos, Ibrahim Mughrabi and Kevin Tracey for showing me around the Feinstein Institutes for Medical Research. Also massive thanks to Hugo Critchley, Jessica Eccles and Lisa Quadt at Brighton and Sussex Medical School; Sarah Garfinkel at University College London and Jenny Murphy at the University of Surrey for always being willing to chat, meet, experiment on me and share their wisdom and experience. Also to Helene Langevin, Lisa Feldman Barrett, Stephen Liberles, Cynthia Price, Ardem Patapoutian and Antonio Damasio for some really interesting and thought-provoking conversations along the way.

I am equally grateful to the many people who helped me better understand how the science coming out of the lab matters in everyday life. Chris White, John Coates, Bob Arnot, Maia Szalavitz, Sam Keen, Graham, Debbie, Hindy, Jane and Colin: thank you so much for sharing your stories and for trusting me to tell them.

In the gaps between all of these enlightening conversations, writing can get lonely, so I feel fortunate to have found the lovely co-working community at Well & Good in Godalming. Thanks to Charlie and Chelley for the tea, biscuits and sympathy, and to Annette for reminding me to shut up and write at regular intervals. I'm also hugely grateful for the support of the UK's finest science writers and editors over many years: Gaia Vince and Jo Marchant, whose festive party is the best science writer's therapy group in town, Helen Thomson, Alison George, Cat De Lange, David Robson, Michael Brooks, Richard Fisher, Sally Adee and Rowan Hooper, to name a few. A special mention goes to Graham Lawton, who has been putting my writing-related neuroses into perspective for a quarter of a century now. 'It's only a book' was something I really needed to hear in the run-up to my deadline.

Finally, if one thing has come out of my research for this book it has been the importance of surrounding yourself with the right people. Susie, Janine, Sole, Helen, Kate, KC, Sally, Al and Jaz, Jo, Jo and JoJo, you are all fabulous human beings and I'm very lucky to have you. Ditto Mum and the extended Williamses and Fildeses. And, of course, my big two: Jon and Sam – thank you for putting up with me over the last year and sorry to have been head down and frowning for so much of it. Just to be clear, when I'm describing warm fuzzy feelings in my belly that feel like love, comfort, safety and home, I'm thinking of you.

Notes

Introduction

1 Hoemann K, Gendron M, Crittenden AN, et al. (2024). What we can learn about emotion by talking with the Hadza. *Perspectives on Psychological Science* 19(1): 173–200.

2 Sherrington CS (1906). *The Integrative Action of the Nervous System*. Yale University Press.

3 Wray B (2022). *Generation Dread: Finding Purpose in an age of Climate Crisis.* Knopf

4 S Korean dies after games session. BBC website, 10 August 2005.

5 Kuperczko D, Kenyeres P, Darnai G, et al. (2022). Sudden gamer death: Non-violent death cases linked to playing video games. *BMC Psychiatry* 22: 824.

6 Gupta AH (2023). Checking email? You're probably not breathing. The *New York Times* website.

7 Martínez Steele E, Baraldi LG, Louzada ML, et al. (2016). Ultra-processed foods and added sugars in the US diet: Evidence from a nationally representative cross-sectional study. *BMJ Open* 6: e009892.

8 Pahwa R, Goyal A, Jialal I. (2024). *Chronic inflammation.* (Updated 7 August 2023.) In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing.

9 Knafo M, SHamay-Tsoory S (2024). 'Empathic immunity' – how we feel about others may contribute to how well we feel. Behavioural and biological preliminary results. Poster #15,

ESCAN 2024, 23 May. Abstract: https://escan2024.com/wp-content/uploads/2024/05/escan2024_booklet-4.pdf
10 Fotopoulou A, Tsakiris M (2017). Mentalizing homeostasis: The social origins of interoceptive inference. *Neuropsychoanalysis* 19(1): 3–28.
11 Harris E (2023). Meta-analysis: Social isolation, loneliness tied to higher mortality. *JAMA* 330(3): 211.

1. An inside story

1 'I'll be just fine,' says Earth. The Daily Mash website, 13 October 2024.
2 Choi, CQ (2012). How the first life on Earth struggled to survive. Live Science website.
3 Lane N, Martin W (2010). The energetics of genome complexity. *Nature* 467: 929–34.
4 Arakaki Y, Toyooka H, Hamamura Y, et al. (2013). The simplest integrated multicellular organism unveiled. *PLOS ONE* Online Edition.
5 Albert DJ (2011). What's on the mind of a jellyfish? A review of behavioural observations on *Aurelia sp.* jellyfish. *Neurosci. Biobehav. Rev.* 35(3): 474–82.
6 Pezzulo G, Parr T, Friston K (2022). The evolution of brain architectures for predictive coding and active inference. *Phil. Trans. R. Soc.* B37720200531.
7 Sterling P, Eyer J (1988). Allostasis: A new paradigm to explain arousal pathology. In S. Fisher and J. Reason (eds), *Handbook of Life Stress, Cognition and Health*. John Wiley & Sons, pp. 629–49.
8 Sterling P (2012). Allostasis: A model of predictive regulation. *Physiol Behav.* 106(1): 5–15.
9 Zoom call, 13 April 2023.
10 Craig AD (2003). Interoception: The sense of the physiological condition of the body. *Curr. Opin. Neurobiology* 13: 500–05.
11 Damasio A, Damasio H (2023). Feelings are the source of consciousness. *Neural Comput.* 35(3): 277–86.

12 Christov-Moore L, et al. (2023). Preventing antisocial robots: A pathway to artificial empathy. *Sci. Robot* 8: eabq3658.
13 Plath S (1963). *The Bell Jar*. Heinemann.
14 Suzuki K, Garfinkel SN, Critchley HD, et al. (2013). Multisensory integration across exteroceptive and interoceptive domains modulates self-experience in the rubber-hand illusion. *Neuropsychologia* 51: 2909–17.
15 Maister L, Tang T, Tsakiris M (2017). Neurobehavioral evidence of interoceptive sensitivity in early infancy. *Elife* 6: e25318.
16 Pollatos O, Schandry R (2004). Accuracy of heartbeat perception is reflected in the amplitude of the heartbeat-evoked brain potential. *Psychophysiology* 41: 476–82.
17 Rebollo I, Devauchelle AD, Béranger B, et al. (2018). Stomach–brain synchrony reveals a novel, delayed-connectivity resting-state network in humans. *Elife* 7: e33321.
18 Chan PS, Lee LY, Davenport PW (2024). Neural mechanisms of respiratory interoception. *Auton. Neurosci.* 253: 103181.
19 Smith B (2017). The uncommon senses. Series 1. Interoception. BBC Sounds website.
20 Kandasamy N, Garfinkel S, Page L, et al. (2016). Interoceptive ability predicts survival on a London trading floor. *Sci. Rep.* 6: 32986.
21 Coates J (2013). *The Hour Between Dog and Wolf: How risk taking transforms us, body and mind.* Penguin.
22 Gefter A (2023). What are dreams for? The *New Yorker* website.

2. The interoceptive superhighway

1 Porges SW (1995). Orienting in a defensive world: Mammalian modifications of our evolutionary heritage. A polyvagal theory. *Psychophysiology* 32(4): 301–18.
2 Tolkien JRR (1991). *The Fellowship of the Ring*. HarperCollins.
3 Libassi M (2022). Feinstein awarded $6.7M NIH grant to create first human vagus nerve anatomical map. Northwell Health website.

4 Jayaprakash N, Song W, Toth V, et al. (2023). Organ- and function-specific anatomical organization of vagal fibers supports fascicular vagus nerve stimulation. *Brain Stimul.* 16(2): 484–506.
5 Badran BW, Austelle CW (2022). The future is noninvasive: A brief review of the evolution and clinical utility of vagus nerve stimulation. *Focus (Am. Psychiatr. Publ.)* 20(1): 3–7.
6 Wade G (2023). Unravelling the secrets of the vagus nerve will revolutionise medicine. *New Scientist* website.
7 Vagus nerve stimulation for moderate to severe rheumatoid arthritis (RESET-RA). ClinicalTrials.gov.
8 Silberstein SD, Calhoun AH, Lipton RB, et al. (2016). Chronic migraine headache prevention with noninvasive vagus nerve stimulation: The EVENT study. *Neurology* 87(5): 529–38.
9 Diener HC, Goadsby PJ, Ashina M, et al. (2019). Non-invasive vagus nerve stimulation (nVNS) for the preventive treatment of episodic migraine: The multicentre, double-blind, randomised, sham-controlled PREMIUM trial. *Cephalalgia* 39(12): 1475–87.
10 Butt MF, Albusoda A, Farmer AD, et al. (2020). The anatomical basis for transcutaneous auricular vagus nerve stimulation. *J. Anat.* 236(4): 588–611.
11 Stavrakis S, Stoner JA, Humphrey MB, et al. (2020). TREAT AF (transcutaneous electrical vagus nerve stimulation to suppress atrial fibrillation): A randomized clinical trial. *JACC Clin. Electrophysiol.* 6(3): 282–91.
12 Stavrakis S, Elkholey K, Morris L, et al. (2022). Neuromodulation of inflammation to treat heart failure with preserved ejection fraction: A pilot randomized clinical trial. *J. Am. Heart Assoc.* 11(3): e023582.
13 Nayak G, Zhang KX, Vemaraju S, et al. (2020). Adaptive thermogenesis in mice is enhanced by opsin 3-dependent adipocyte light sensing. *Cell Rep.* 30(3): 672–86.e8.
14 Kinany N, Pirondini E, Micera S, et al. (2020). Dynamic functional connectivity of resting-state spinal cord fMRI

reveals fine-grained intrinsic architecture. *Neuron.* 108(3): 424–35.e4.
15 Vahdat S, Khatibi A, Lungu O, et al. (2020). Resting-state brain and spinal cord networks in humans are functionally integrated. *PLoS Biol.* 18(7): e3000789.
16 Kashkouli Nejad K, Sugiura M, Thyreau B, et al. (2014). Spinal fMRI of interoceptive attention/awareness in experts and novices. *Neural Plast*. 2014: 679509.
17 Kinany N, Pirondini E, Micera S, et al. (2023). Spinal cord fMRI: A new window into the central nervous system. *Neuroscientist* 29(6): 715–31.
18 Jin H, Li M, Jeong E, et al. (2024). A body–brain circuit that regulates body inflammatory responses. *Nature* 630(8017): 695–703.

3. Power up
1 Maisel P, Baum E, Donner-Banzhoff N (2021). Fatigue as the chief complaint – epidemiology, causes, diagnosis and treatment. *Dtsch Arztebl Int*. 118(33–34): 566–76.
2 Yoon JH, Park NH, Kang YE, et al. (2023). The demographic features of fatigue in the general population worldwide: A systematic review and meta-analysis. *Front. Public Health* 11: 1192121.
3 Picard M (2022). Why do we care more about disease than health? *Phenomics* 2(3): 145–55.
4 Garmany A, Yamada S, Terzic A. (2021). Longevity leap: Mind the healthspan gap. *NPJ Regen. Med.* 6: 57.
5 Wallace DC. (2008). Mitochondria as chi. *Genetics* 179(2): 727–35.
6 Picard M, Trumpff C, Burelle Y (2019). Mitochondrial psychobiology: Foundations and applications. *Curr. Opin. Behav. Sci.* 28: 142–51.
7 Pontzer H (2021). *Burn: The misunderstood science of metabolism.* Allen Lane.
8 Karamanou M, Androutsos G (2013). Antoine-Laurent de

Lavoisier (1743–1794) and the birth of respiratory physiology. *Thorax* 68: 978–79.
9 West JB (2013). The collaboration of Antoine and Marie-Anne Lavoisier and the first measurements of human oxygen consumption. *Am. J. Physiol. Lung Cell Mol. Physiol.* 305(11): L775–85.
10 Muoio DM (2014). Metabolic inflexibility: When mitochondrial indecision leads to metabolic gridlock. *Cell* 159(6): 1253–62.
11 Diniz MS, Tocantins C, Grilo LF, et al. (2022). The bitter side of sugar consumption: A mitochondrial perspective on diabetes development. *Diabetology* 3: 583–95.
12 Lionetti L, Mollica MP, Donizzetti I, et al. (2014). High-lard and high-fish-oil diets differ in their effects on function and dynamic behaviour of rat hepatic mitochondria. *PLoS One* 9(3): e92753.
13 Melaku YA, Reynolds AC, Gill TK, et al. (2019). Association between macronutrient intake and excessive daytime sleepiness: An iso-caloric substitution analysis from the North West Adelaide Health Study. *Nutrients* 11(10): 2374.
14 Mantantzis K, Schlaghecken F, Sünram-Lea SI, et al. (2019). Sugar rush or sugar crash? A meta-analysis of carbohydrate effects on mood. *Neurosci. Biobehav. Rev.* 101: 45–67.
15 Bobba-Alves N, Sturm G, Lin J, et al. (2023). Cellular allostatic load is linked to increased energy expenditure and accelerated biological aging. *Psychoneuroendocrinology* 155: 106322.
16 Bernardi L, Sleight P, Bandinelli G, et al. (2001). Effect of rosary prayer and yoga mantras on autonomic cardiovascular rhythms: Comparative study. *BMJ* 323(7327): 1446–49.
17 Noble DJ, Hochman, S (2019). Hypothesis: Pulmonary afferent activity patterns during slow, deep breathing contribute to the neural induction of physiological relaxation. *Frontiers in Physiology* 13(10): 1176.
18 Bhasin MK, Dusek JA, Chang BH, et al. (2017). Relaxation response induces temporal transcriptome changes in energy

metabolism, insulin secretion and inflammatory pathways. *PLoS One* 8(5): e62817. Erratum in: *PLoS One* (Feb 2017, 12(2): e0172873).

19 Wood C (1993). Mood change and perceptions of vitality: A comparison of the effects of relaxation, visualization and yoga. *J. Royal Soc. Medicine* 86(5): 254–58.

20 Davis AJ, Crittenden B, Cohen E (2021). Effects of social support on performance outputs and perceived difficulty during physical exercise. *Physiol. Behav.* 239: 113490.

21 Picard M, Prather AA, Puterman E, et al. (2018). A mitochondrial health index sensitive to mood and caregiving stress. *Biol. Psychiatry* 84(1): 9–17.

22 Hoemann K, Gendron M, Crittenden AN, et al. (2024). What we can learn about emotion by talking with the Hadza. *Perspectives on Psychological Science* 19(1): 173–200.

23 Sayre MK, Pontzer H, Alexander GE, et al. (2020). Ageing and physical function in East African foragers and pastoralists. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 375(1811): 20190608.

24 Pontzer H (2018). Energy constraint as a novel mechanism linking exercise and health. *Physiology (Bethesda)* 33(6): 384–93.

25 Bautmans I, Knoop V, Beyer I, et al. (2024). The relationship between self-perceived fatigue, muscle endurance, and circulating markers of inflammation in participants of the Copenhagen aging and Midlife Biobank (CAMB). *Eur. Rev. Aging Phys. Act.* 21(1): 2.

4. Gut reading for beginners

1 Geliebter A (1988). Gastric distension and gastric capacity in relation to food intake in humans. *Physiol. Behav.* 44(4–5): 665–68.

2 van Dyck Z, Vögele C, Blechert J, et al. (2016). The water load test as a measure of gastric interoception: Development of a two-stage protocol and application to a healthy female population. *PLoS One* 11(9): e0163574.

3 Levine MS, Spencer G, Alavi A, et al. (2007). Competitive speed eating: Truth and consequences. *AJR Am. J. Roentgenol.* 189(3): 681–6.
4 *Hack Your Health: The Secrets of Your Gut*. Netflix.
5 Granström L, Backman L (1985). Stomach distension in extremely obese and in normal subjects. *Acta Chir. Scand.* 151(4): 367–70.
6 Hellström PM, Geliebter A, Näslund E, et al. (2004). Peripheral and central signals in the control of eating in normal, obese and binge-eating human subjects. *Br. J. Nutr.* 92 Suppl. 1: S47–57.
7 Mayeli A, Al Zoubi O, White EJ, et al. (2023). Parieto-occipital ERP indicators of gut mechanosensation in humans. *Nat. Commun.* 14(1): 3398.
8 Herbert BM, Blechert J, Hautzinger M, et al. (2013). Intuitive eating is associated with interoceptive sensitivity. Effects on body mass index. *Appetite* 70: 22–30.
9 Monteiro CA, Levy RB, Claro RM, et al. (2010). A new classification of foods based on the extent and purpose of their processing. *Cad. Saude. Publica.* 26(11): 2039–49.
10 Monteiro CA, Cannon G, Lawrence M, et al. (2019). *Ultra-processed foods, diet quality, and health using the NOVA classification system*. Rome, FAO.
11 According to Walkers Crisps' FAQ page: 'It can depend on the size of the potato, but usually it is around one good quality potato, thinly sliced, that makes one bag of Walkers Crisps!'
12 Hall KD, Ayuketah A, Brychta R, et al. (2019). Ultra-processed diets cause excess calorie intake and weight gain: An inpatient randomized controlled trial of ad libitum food intake. *Cell Metab.* 30(1): 67–77.e3.
13 Latorre R, Sternini C, De Giorgio R, et al. (2016). Enteroendocrine cells: A review of their role in brain-gut communication. *Neurogastroenterol Motil.* 28(5): 620–30.
14 Bohórquez DV, Shahid RA, Erdmann A, et al. (2015).

Neuroepithelial circuit formed by innervation of sensory enteroendocrine cells. *J. Clin. Invest.* 125(2): 782–6.

15 Kaelberer MM, Buchanan KL, Klein ME, et al. (2018). A gut–brain neural circuit for nutrient sensory transduction. *Science* 361(6408): eaat5236.

16 Kaelberer MM, Rupprecht LE, Liu WW, et al. (2020). Neuropod cells: The emerging biology of gut–brain sensory transduction. *Annu. Rev. Neurosci.* 43: 337–53.

17 Beutler LR, Corpuz TV, Ahn JS, et al. (2020). Obesity causes selective and long-lasting desensitization of AgRP neurons to dietary fat. *Elife* 9: e55909.

18 Lorch CM, Hayes NW, Xia JL, et al. (2024). Sucrose overconsumption impairs AgRP neuron dynamics and promotes palatable food intake. *Cell Rep.* 43(2): 113675.

19 Tan HE, Sisti AC, Jin H, et al. (2020). The gut–brain axis mediates sugar preference. *Nature* 580(7804): 511–16.

20 Edwin Thanarajah S, DiFeliceantonio AG, Albus K, et al. (2023). Habitual daily intake of a sweet and fatty snack modulates reward processing in humans. *Cell Metab.* 35(4): 571–584.e6.

21 van Galen KA, Schrantee A, Ter Horst KW, et al. (2023). Brain responses to nutrients are severely impaired and not reversed by weight loss in humans with obesity: A randomized crossover study. *Nat. Metab.* 5(6): 1059–72.

22 Todd J, Cardellicchio P, Swami V, et al. (2021). Weaker implicit interoception is associated with more negative body image: Evidence from gastric-alpha phase amplitude coupling and the heartbeat evoked potential. *Cortex* 143: 254–66.

23 Wilding JPH, Batterham RL, Calanna S, et al. (2021). STEP 1 study group. Once-weekly semaglutide in adults with overweight or obesity. *N. Engl. J. Med.* 384(11): 989–1002.

24 Couzin-Frankel, J. (2023). Breakthrough of the year. *Science* 382(6676).

25 Hall KD (2024). Physiology of the weight-loss plateau in

response to diet restriction, GLP-1 receptor agonism, and bariatric surgery. *Obesity (Silver Spring)* 32(6): 1163–68.
26 Richards JR, Khalsa SS (2024). Highway to the danger zone? A cautionary account that GLP-1 receptor agonists may be too effective for unmonitored weight loss. *Obes Rev.* 25(5): e13709.
27 Behary P, Miras AD (2015). Food preferences and underlying mechanisms after bariatric surgery. *Proc. Nutr. Soc.* 74(4): 419–25.
28 Apovian CM, Shah SN, Wolfe BM, et al. (2017). Two-year outcomes of vagal nerve blocking (vBloc) for the treatment of obesity in the ReCharge trial. *Obes. Surg.* 27(1): 169–76.
29 Johannessen H, Revesz D, Kodama Y, et al. (2017). Vagal blocking for obesity control: A possible mechanism-of-action. *Obes. Surg.* 27(1): 177–85.
30 Ousey J, Boktor JC, Mazmanian SK (2023). Gut microbiota suppress feeding induced by palatable foods. *Curr Biol.* 33(1): 147–157.e7.
31 Strang S, Hoeber C, Uhl O, et al. (2017). Impact of nutrition on social decision-making. *Proc. Natl Acad. Sci. USA* 114(25): 6510–14.
32 Falkenstein M, Simon MC, Mantri A, et al. (2024). Impact of the gut microbiome composition on social decision-making. *PNAS Nexus* 3(5): 166.
33 Pollan M (2007). Unhappy meals. The *New York Times Magazine* website.
34 Reddit forum: https://www.reddit.com/r/GlobalTalk/comments/ep78do/question_how_do_you_saytalk_about_gut_feelings_in/
35 Dunn BD, Galton HC, Morgan R, et al. (2010). Listening to your heart. How interoception shapes emotion, experience and intuitive decision-making. *Psychol. Sci.* 21(12): 1835–44.
36 Pollatos O, Mönkemöller K, Groppe K, et al. (2023). Interoceptive accuracy is associated with benefits in decision making in children. *Front. Psychol.* 13: 1070037.

37 Nummenmaa L, Hari R, Hietanen JK, et al. (2018). Maps of subjective feelings. *Proc. Natl Acad. Sci. USA*. 115(37): 9198–203.
38 Herman AM, Zaremba D, Kossowski B, et al. (2022). The utility of the emBODY tool as a novel method of studying complex phenomena-related emotions. *Sci. Rep.* (1): 19884.
39 Porciello G, Monti A, Panasiti MS, et al. (2024). Ingestible pills reveal gastric correlates of emotions. *Elife* 13: e85567.
40 Nord CL, Dalmaijer ES, Armstrong T, et al. (2021). A causal role for gastric rhythm in human disgust avoidance. *Curr. Biol.* 31(3): 629–634.e3.
41 Margolis KG, Cryan JF, Mayer EA (2021). The microbiota-gut-brain axis: From motility to mood. *Gastroenterology* 160(5): 1486–501.
42 Koloski NA, Jones M, Talley NJ (2016). Evidence that independent gut-to-brain and brain-to-gut pathways operate in the irritable bowel syndrome and functional dyspepsia: A 1-year population-based prospective study. *Aliment. Pharmacol. Ther.* 44(6): 592–600.
43 Hoban AE, Scott L, Fitzgerald P, et al. (2016). Transferring the blues: Depression-associated gut microbiota induces neurobehavioural changes in the rat. *J. Psychiatr. Res.* 82: 109–18.
44 Zucker NL, LaVia MC, Craske MG, et al. (2019). Feeling and body investigators (FBI): ARFID division. An acceptance-based interoceptive exposure treatment for children with ARFID. *Int. J. Eat. Disord.* 52(4): 466–72.
45 Khalsa SS, Berner LA, Anderson LM (2022). Gastrointestinal interoception in eating disorders: Charting a new path. *Curr. Psychiatry Rep.* 24(1): 47–60.

5. Bodymental health

1 Garfinkel SN, Minati L, Gray MA, et al. (2014). Fear from the heart: Sensitivity to fear stimuli depends on individual heartbeats. *J. Neurosci.* 34(19): 6573–82.
2 Harrison OK, Köchli L, Marino S, et al. (2021). Interoception of

breathing and its relationship with anxiety. *Neuron.* 109(24): 4080–4093.e8.

3 Suksasilp C, Garfinkel SN (2022). Towards a comprehensive assessment of interoception in a multi-dimensional framework. *Biol. Psychol.* 168: 108262.

4 Eccles JA, Beacher FD, Gray MA, et al. (2012). Brain structure and joint hypermobility: Relevance to the expression of psychiatric symptoms. *Br. J. Psychiatry*. 200(6): 508–9.

5 Bulbena A, Agulló A, Pailhez G, et al. (2004). Is joint hypermobility related to anxiety in a nonclinical population also? *Psychosomatics* 45(5): 432–37.

6 Grimes PZ, Kampoureli CN, Rae CL, et al. (2023). The neural correlates of autonomic interoception in a clinical sample: Implications for anxiety. Preprint.

7 Teed AR, Feinstein JS, Puhl M, et al. (2022). Association of generalized anxiety disorder with autonomic hypersensitivity and blunted ventromedial prefrontal cortex activity during peripheral adrenergic stimulation: A randomized clinical trial. *JAMA Psychiatry* 79(4): 323–32.

8 Lavalley CA, Hakimi N, Taylor S, et al. (2023). Transdiagnostic failure to adapt interoceptive precision estimates across affective, substance use, and eating disorders: A replication study. *MedRxiv: the preprint server for health sciences* 2023.10.11.23296870. Update in *Biol. Psychol.* 31 May 2024, 191: 108825.

9 Joshi SA, Aupperle RL, Khalsa SS (2023). Interoception in fear learning and posttraumatic stress disorder. *Focus (Am. Psychiatr. Publ.)* 21(3): 266–77.

10 Stephan KE, Manjaly ZM, Mathys CD, et al. (2016). Allostatic self-efficacy: A metacognitive theory of dyshomeostasis-induced fatigue and depression. *Front. Hum. Neurosci.* 10: 550.

11 Brewer R, Cook R, Bird G (2016). Alexithymia: A general deficit of interoception. *R. Soc. Open Sci.* (10): 150664.

12 Roh D, Kim WJ, Kim CH (2011). Alexithymia in

obsessive-compulsive disorder: Clinical correlates and symptom dimensions. *J. Nerv. Ment. Dis.* 199(9): 690–95.
13 Oka T. (2020). Shitsu-taikan-sho (alexisomia): a historical review and its clinical importance. *Biopsychosoc Med.* 26;14:23.
14 Garfinkel SN, Gould van Praag CD, Engels M, et al. (2021). Interoceptive cardiac signals selectively enhance fear memories. *J. Exp. Psychol. Gen.* 150(6): 1165–76.
15 Critchley HD, Wiens S, Rotshtein P, et al. (2004). Neural systems supporting interoceptive awareness. *Nat. Neurosci.* 7(2): 189–95.
16 Quadt L, Garfinkel SN, Mulcahy JS, et al. (2021). Interoceptive training to target anxiety in autistic adults (ADIE): A single-center, superiority randomized controlled trial. *EClinicalMedicine* 39: 101042.
17 Wald J, Taylor S (2005). Interoceptive exposure therapy combined with trauma-related exposure therapy for post-traumatic stress disorder: A case report. *Cogn. Behav. Ther.* 34(1): 34–40.
18 Michela A, van Peer JM, Brammer JC, et al. (2022). A deep-breathing biofeedback trainability in a virtual-reality action game: A single-case design study with police trainers. *Front. Psychol.* 13: 806163.
19 Jeganathan J, Campbell MEJ, Legrand N, et al. (2024). Aberrant cardiac interoception in psychosis. *Schizophrenia Bulletin* sbae078.
20 Nord CL, Garfinkel SN (2022). Interoceptive pathways to understand and treat mental health conditions. *Trends Cogn. Sci.* 26(6): 499–513.
21 Ainley V, Tsakiris M (2013). Body conscious? Interoceptive awareness, measured by heartbeat perception, is negatively correlated with self-objectification. *PLoS One* 8(2): e55568.
22 Frederick DA, Peplau LA, Lever J (2006). The swimsuit issue: Correlates of body image in a sample of 52,677 heterosexual adults. *Body Image* 3(4): 413–19.
23 Kearney-Cooke A, Tieger D (2015). Body image disturbance

and the development of eating disorders. Chapter 22 in Treasure J, Schmidt U, van Furth E (eds) *The Wiley Handbook of Eating Disorders: Assessment, Prevention, Treatment, Policy, and Future Directions*. John Wiley & Sons, Ltd.

24 Pollatos O, Herbert BM, Berberich G, et al. (2016). Atypical self-focus effect on interoceptive accuracy in anorexia nervosa. *Front. Hum. Neurosci.* 10: 484.

25 Communication between man and dolphin: A summary. Dr John C. Lilly's website.

26 Noren E (2015). *Unsinkable: My story of discovering float tanks and reaching full recovery from anorexia and bulimia*. CreateSpace Independent Publishing Platform.

27 Choquette EM, Flux MC, Moseman SE, et al. (2023). The impact of floatation therapy on body image and anxiety in anorexia nervosa: A randomised clinical efficacy trial. *EClinicalMedicine* 29(64): 102173.

28 Duberg A, Möller M, Sunvisson H. (2016). 'I feel free': Experiences of a dance intervention for adolescent girls with internalizing problems. *Int. J. Qual. Stud. Health Well-being* 11: 31946.

29 Watts R, Kettner H, Geerts D, et al. (2022). The Watts Connectedness Scale: A new scale for measuring a sense of connectedness to self, others, and world. *Psychopharmacology (Berl.)* 239(11): 3461–83.

30 Maqueda AE, Valle M, Addy PH, et al. (2015). Salvinorin-a induces intense dissociative effects, blocking external sensory perception and modulating interoception and sense of body ownership in humans. *Int. J. Neuropsychopharmacol.* 18(12): pyv065.

31 Young C, Butcher R (2020). Propranolol for post-traumatic stress disorder: A review of clinical effectiveness [Internet]. Ottawa (ON): Canadian Agency for Drugs and Technologies in Health.

32 Watson DR, Garfinkel SN, Gould van Praag C, et al. (2019). Computerized exposure therapy for spider phobia: Effects of

cardiac timing and interoceptive ability on subjective and behavioral outcomes. *Psychosom. Med.* 81(1): 90–99.

33 Legon W, Strohman A, In A, et al. (2024). Noninvasive neuromodulation of subregions of the human insula differentially affect pain processing and heart-rate variability: A within-subjects pseudo-randomized trial. *Pain* 165(7): 1625–41.

34 Strohman A, Isaac G, Payne B, et al. (2024). Low-intensity focused ultrasound to the insula differentially modulates the heartbeat-evoked potential: A proof-of-concept study. *Clin. Neurophysiol.* 19:S1388-2457(24): 00265-7.

35 Nord CL, Lawson RP, Dalgleish T. (2021). Disrupted dorsal mid-insula activation during interoception across psychiatric disorders. *Am. J. Psychiatry* 178(8): 761–70.

36 Misaki M, Phillips R, Zotev V, et al. (2019). Brain activity mediators of PTSD symptom reduction during real-time fMRI amygdala neurofeedback emotional training. *Neuroimage Clin.* 24: 102047.

37 Lee CR, Chen A, Tye KM (2021). The neural circuitry of social homeostasis: Consequences of acute versus chronic social isolation. *Cell* 184(6): 1500–16. Erratum in: *Cell* (May 2021, 184(10): 2794–95).

38 Simon MS, Arteaga-Henríquez G, Fouad Algendy A, et al. (2023). Anti-inflammatory treatment efficacy in major depressive disorder: A systematic review of meta-analyses. *Neuropsychiatr. Dis. Treat.* 19: 1–25.

39 Janssen CW, Lowry CA, Mehl MR, et al. (2016). Whole-body hyperthermia for the treatment of major depressive disorder: A randomized clinical trial. *JAMA Psychiatry* 73(8): 789–95.

6. Pleasure and pain

1 Baughan A, Zhang MR, Rao R, et al. (2022). 'I don't even remember what I read': How design influences dissociation on social media. In Proceedings of the 2022 CHI Conference on

Human Factors in Computing Systems (CHI '22). Association for Computing Machinery, New York, Article 18, 1–13.

2 Fisher JP, et al. (1995). *BMJ* 310: 70. (Article not available online. It appears in the printed journal as a photo of the boot and nail, with the following caption: 'A builder aged 29 came to the accident and emergency department having jumped down on to a 15cm nail. As the smallest movement of the nail was painful, he was sedated with fentanyl and midazolam. The nail was then pulled out from below. When his boot was removed a miraculous cure appeared to have taken place. Despite entering proximal to the steel toecap the nail had penetrated between the toes: the foot was entirely uninjured.' J.P. FISHER, senior house officer, D.T. HASSAN, senior registrar, N. O'CONNOR, registrar, accident and emergency department, Leicester Royal Infirmary.)

3 Dimitroff SJ, Kardan O, Necka EA, et al. (2017). Physiological dynamics of stress contagion. *Sci. Rep.* 7: 6168.

4 Panksepp J, Nelson E, Siviy S (1994). Brain opioids and mother–infant social motivation. *Acta Paediatr. Suppl.* 397: 40–6.

5 von Mohr M, Krahé C, Beck B, et al. (2018). The social buffering of pain by affective touch: A laser-evoked potential study in romantic couples. *Soc. Cogn. Affect. Neurosci.* 13(11): 1121–30.

6 Johnson KA, Dunbar R (2016). Pain tolerance predicts human social network size. *Sci. Rep.* 6: 25267.

7 Dewall CN, Macdonald G, Webster GD, et al. (2010). Acetaminophen reduces social pain: Behavioral and neural evidence. *Psychol. Sci.* 21(7): 931–37.

8 Durso GRO, Luttrell A, Way B, et al. (2015). Over-the-counter relief from pains and pleasures alike: Acetaminophen blunts evaluation sensitivity to both negative and positive stimuli. *Psychol. Sci.* 26(6): 750–58.

9 Banwinkler M, Rütgen M, Lamm C, et al. (2023). A pill as a

quick solution: Association between painkiller intake, empathy, and prosocial behavior. *Sci. Rep.* 13: 18320.
10 Jones MR, Viswanath O, Peck J, et al. (2018). A brief history of the opioid epidemic and strategies for pain medicine. *Pain Ther.* 7(1): 13–21.
11 Figure 3 in Drug overdose deaths: Facts and figures. National Institute on Drug Abuse website.
12 Nguyen D, Naffziger EE, Berridge KC (2021). Positive affect: Nature and brain bases of liking and wanting. *Curr. Opin. Behav. Sci.* 39: 72–78.
13 Naqvi NH, Rudrauf D, Damasio H, et al. (2007). Damage to the insula disrupts addiction to cigarette smoking. *Science* 315(5811): 531–34.
14 Santiago Rivera OJ, Havens JR, Parker MA, et al. (2018). Risk of heroin dependence in newly incident heroin users. *JAMA Psychiatry* 75(8): 863–64.
15 Wesselmann ED, Parris L (2021). Exploring the links between social exclusion and substance use, misuse, and addiction. *Front. Psychol.* 12: 674743.
16 Pear VA, Ponicki WR, Gaidus A, et al. (2019). Urban–rural variation in the socioeconomic determinants of opioid overdose. *Drug Alcohol Depend.* 195: 66–73.
17 Fuller-Thomson E, Lewis DA, Agbeyaka S (2022). Attention-deficit/hyperactivity disorder and alcohol and other substance use disorders in young adulthood: Findings from a Canadian nationally representative survey. *Alcohol.* 57(3): 385–95.
18 Bussières A, Hancock MJ, Elklit A, et al. (2023). Adverse childhood experience is associated with an increased risk of reporting chronic pain in adulthood: A systematic review and meta-analysis. *Eur. J. Psychotraumatol.* 14(2): 2284025.
19 Defrin R, Schreiber S, Ginzburg K (2015). Paradoxical pain perception in posttraumatic stress disorder: The unique role of anxiety and dissociation. *J. Pain.* 16(10): 961–70.
20 Ashar YK, Gordon A, Schubiner H, et al. (2022). Effect of pain reprocessing therapy vs placebo and usual care for patients

with chronic back pain: A randomized clinical trial. *JAMA Psychiatry* 79(1): 13–23.

21 Price CJ, Sevinc G, Farb NAS (2023). Within-person modulation of neural networks following interoceptive awareness training through Mindful Awareness in Body-Oriented Therapy (MABT): A pilot study. *Brain Sci.* 13(10): 1396.

22 Stewart JL, Butt M, May AC, et al. (2017). Insular and cingulate attenuation during decision making is associated with future transition to stimulant use disorder. *Addiction* 112(9): 1567–77.

23 Kaplan CM, Kelleher E, Irani A, et al. (2024). Deciphering nociplastic pain: Clinical features, risk factors and potential mechanisms. *Nat. Rev. Neurol.* 20(6): 347–63.

24 Exablate for LIFU neuromodulation in patients with opioid use disorder (OUD) and/or other substance use disorders (SUDs). See https://clinicaltrials.gov/study/NCT04197921

25 Ackerley R, Backlund Wasling H, Liljencrantz J, et al. (2014). Human C-tactile afferents are tuned to the temperature of a skin-stroking caress. *J. Neurosci.* 34(8): 2879–83.

26 Croy I, Luong A, Triscoli C, et al. (2016). Interpersonal stroking touch is targeted to C tactile afferent activation. *Behav. Brain Res.* 297: 37–40.

27 Liljencrantz J, Strigo I, Ellingsen DM, et al. (2017). Slow brushing reduces heat pain in humans. *Eur. J. Pain* 21(7): 1173–85.

28 Gursul D, Goksan S, Hartley C, et al. (2018). Stroking modulates noxious-evoked brain activity in human infants. *Curr. Biol.* 28(24): R1380–R1381.

29 Di Lernia D, Lacerenza M, Ainley V, et al. (2020). Altered interoceptive perception and the effects of interoceptive analgesia in musculoskeletal, primary, and neuropathic chronic pain conditions. *J. Pers. Med.* 10(4): 201.

30 Meijer LL, Ruis C, van der Smagt MJ, et al. (2023). Chronic pain relief after receiving affective touch: A single case report. *J. Neuropsychol.* 17(3): 584–89.

31 Zhao Y, Tao Y, Le G, et al. (2022). Affective touch as immediate and passive wearable intervention. *Proceedings of the ACM on Interactive Mobile, Wearable and Ubiquitous Technologies* 6(4): Article 200.
32 Poerio GL, Mank S, Hostler TJ (2022). The awesome as well as the awful: Heightened sensory sensitivity predicts the presence and intensity of Autonomous Sensory Meridian Response (ASMR). *J. Res. Personality* 97: 1–12.
33 Villena-Gonzalez M, Rojas-Thomas F, Morales-Torres R, et al. (2023). Autonomous sensory meridian response is associated with a larger heartbeat-evoked potential amplitude without differences in interoceptive awareness. *Psychophysiology* 60(6): e14277.
34 Mauersberger H, Springer A, Fotopoulou A, et al. (2024). Pet dogs succeed where human companions fail: The presence of pet dogs reduces pain. *Acta Psychol. (Amst.)* 249: 104418.

7. Tune in

1 Table 5 in Mehling WE, Price C, Daubenmier JJ, et al. (2012). The Multidimensional Assessment of Interoceptive Awareness (MAIA). *PLoS ONE* 7(11): e48230. The questionnaire and scoring system can be found at https://osher.ucsf.edu/research/maia.
2 Malinowski P (2013). Neural mechanisms of attentional control in mindfulness meditation. *Front. Neurosci.* 4: 7–8.
3 Spaccapanico Proietti S, Chiavarini M, Iorio F, et al. (2024). The role of a mindful movement-based program (Movimento Biologico) in health promotion: Results of a pre-post intervention study. *Front. Public Health* 12: 1372660.
4 For example, the Random Reminders app by OneUp App LLC, which allows you to decide what to be reminded of, how many times a day, and on whichever days you choose.
5 Feinstein JS, Khalsa SS, Yeh H, et al. (2018). The elicitation of relaxation and interoceptive awareness using floatation

therapy in individuals with high anxiety sensitivity. *Biol. Psychiatry Cogn. Neurosci. Neuroimaging* 3(6): 555–62.

6 The Parasym device significantly increases parasympathetic activity. The Parasym website.

7 Yasuma F, Hayano J (2004). Respiratory sinus arrhythmia: Why does the heartbeat synchronize with respiratory rhythm? *Chest* 125(2): 683–90.

8 Lehrer P, Kaur K, Sharma A, et al. (2020). Heart rate variability biofeedback improves emotional and physical health and performance: A systematic review and meta-analysis. *Appl. Psychophysiol. Biofeedback* 45(3): 109–29. Erratum in: *Appl. Psychophysiol. Biofeedback* (Dec 2021, 46(4): 389).

9 Damasio A (2000). *The Feeling of What Happens: Body, Emotion and the Making of Consciousness*. Vintage, p. 150.

10 Collins H, Booth JN, Duncan A, et al. (2019). The effect of resistance training interventions on 'the self' in youth: A systematic review and meta-analysis. *Sports Med. Open* 5: 29.

11 Susman ES, Chen S, Kring AM, et al. (2024). Daily micropractice can augment single-session interventions: A randomized controlled trial of self-compassionate touch and examining their associations with habit formation in US college students. *Behav. Res. Ther.* 175: 104498.

12 Verdonk C, Mellier C, Charlot K, et al. (2022). A psycho-cognitive model for exertional heatstroke: Theory and preliminary testing using self-report measures in a case-control study. Preprint. *medRxiv*.

13 Jugovac S, O'Kearney R, Hawes DJ, et al. (2022). Attachment- and emotion-focused parenting interventions for child and adolescent externalizing and internalizing behaviors: A meta-analysis. *Clin. Child Fam. Psychol. Rev.* 25(4): 754–73. Erratum in: *Clin. Child Fam. Psychol. Rev.* (Dec 2022, 25(4): 774–78).

14 Kuyken W, Ball S, Crane C, et al. (2022). Effectiveness and cost-effectiveness of universal school-based mindfulness training compared with normal school provision in reducing

risk of mental health problems and promoting well-being in adolescence: The MYRIAD cluster randomised controlled trial. *Evid. Based Ment. Health* 25(3): 99–109.

15 Mahler K, Hample K, Ensor C, et al. (2024). An interoception-based intervention for improving emotional regulation in children in a special education classroom: Feasibility study. *Occup. Ther. Health Care* 38(3): 636–50.

16 https://www.kelly-mahler.com/

17 https://www.education.sa.gov.au/docs/support-and-inclusion/engagement-and-wellbeing/ready-to-learn-interoception-kit.pdf

18 James W (1890). *The Principles of Psychology*. New York: Holt.

Index

Index

Index