Interoception: The Secret Ingredient

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Your brain keeps you alive and well by running a metabolic "budget" for your body. Our authors, who co-direct the Interdisciplinary Affective Science Laboratory at Northeastern University and Massachusetts General Hospital, explain how these budgetary activities, and the sensations they create inside your body, suggest surprising connections between brain, mind, body, and world.

Right now, as you read this text, it may seem like your eyes are simply detecting words out there in the world. But you're not detecting—you're constructing. In every moment, outside of your awareness, your brain constructs a model of the outside world, transforming light waves, pressure changes, and chemicals into sights, sounds, touches, smells, and tastes. Your brain continually anticipates what will happen next around you, checks its predictions against sense data streaming in from your eyes, ears, and other sensory surfaces of your body, updates the model as needed, and in doing so creates your experience of the world. This covert construction of your senses is called *exteroception*.

Your brain also models the events occurring *inside* your body. In much the same way that your brain sees sights, feels things that touch your skin, and hears sounds, it also produces your body's inner sensations, such as a gurgling stomach, a tightness in your chest, and even the beating of your heart. Your brain also models other sensations from movements that you cannot feel, such as your liver cleaning your blood. The construction of all your inner sensations is called *interoception* and, like exteroception, it proceeds completely outside your awareness.

For a long time, scientists treated interoception and exteroception as completely separate domains of sensation, bounded by your skin. But recent research has revealed that the two might not be as separate as they seem, and their boundary is fuzzy. Perhaps more importantly, the science of interoception reveals some surprising insights about how your brain works and may be a key to better understanding health and illness.

Your Brain Runs a Budget for Your Body

You live in a complex body. With over 600 muscles in motion and dozens of internal organs, your body pumps 2,000 gallons of blood per day, balances dozens of hormones and other chemicals, regulates the energy of billions of neurons, digests food, excretes waste, and fights illness—all of it nonstop throughout your life. Your brain's most important job is to coordinate and control the systems of your body as they burn and replenish energy efficiently. Your brain ensures that the right amounts of salt, glucose, water, and other vital resources are available where and when they're needed, so you can walk, think, learn, innovate, and love. This constant budgeting of your body's needs is called *allostasis*.

Allostasis is a predictive balancing act. Your brain moves your body through a massively complex world full of other brains-in-bodies, so it must constantly guess which of your cells need what resources… and guess well. If your heart rate is too fast or slow for the physical demands you face, or your lungs don't process sufficient oxygen, or your cells become insensitive to the glucose that ultimately powers your muscles, you're not likely to live long. So, your brain is engaged in the constant body-budgeting of allostasis, anticipating your body's needs at every moment while deciding which efforts are worth the metabolic investment. Right now, for example, your brain is using some glucose and other metabolic resources to read these words. Learning and moving your body are some of your brain's most costly operations, metabolically speaking.

Efficient energy regulation, therefore, is a major selection pressure for all living things. Animals live longer and suffer from fewer diseases when their tissues, organs, and systems receive the right nutrients just when they are needed. Such animals are more fit to reproduce. They can explore further for food and better protect themselves from predators, learning all the while and honing their models of the world. The more effectively and efficiently a brain can invest its energy, therefore, the greater the metabolic return.

Sensing the World Around You

Reading this text depends on seeing, which is one form of exteroception. To perform this activity, your brain makes metabolic investments to model the world outside your body. It directs your eye muscles to contract and relax in a pattern that allows your eyes to sweep across a line of text—at each moment predicting what you will see next, based on past experience (see Figure 1). Your brain then directs your eyes to stop and fixate briefly to compare its predictions to the visual data arising from the page. It makes any necessary corrections and then directs the next volley of eye movements.

Figure 1: This optical illusion demonstrates the power of your brain's use of past experiences to construct what you read. Sweep your eyes from left to right, and you'll perceive the central symbol as a "B"; sweep your eyes from top to bottom and it transforms into a "13".

Vision, like other forms of exteroception, operates in the service of movement. Think about it: How do you know how far away to hold this page, so the article is legible? How do you even know where your limbs are in space? How do you manage not to bump into things when you walk, successfully guide your spoon to your mouth, or pick up a cup with the right amount of force? It's all about sensation and its intimate ties to allostasis. Your brain sees, hears, feels physical contact, and constructs other sensations not because these activities are intrinsically fun or valuable, but because sensations are the means by which your brain controls your body's many moving parts. Your movements give your brain the sense data to build its model of the world, and this model guides your actions, ultimately supporting allostasis so you survive, and even thrive, in the world around you.

Exteroception works mostly by prediction. Your brain issues motor commands, say, to move the muscles of your head, eyes, and other body parts (even before you're aware) and simultaneously predicts the sensations likely to result from those movements. When the actual sense data arrives from the sensory surfaces in your eyes, skin, and other sense organs, your brain integrates the data to confirm or correct the predictions to refine or adjust the motor

movements. In constructing your sensations, your brain estimates the state of the world in order to control and coordinate your body's movements.

Sensing the World Inside You

The muscles attached to your skeleton are not the only moving parts of your body. As you read this article, your brain is conducting a mostly silent symphony of movement inside your body, involving your organs, autonomic nervous system, endocrine system, and immune system. Your lungs continually expand and contract to take in oxygen and expel carbon dioxide as your heart beats to pulse blood throughout your body and brain. If what you're reading seems interesting or unexpected, your heart rate and respiration may slow.

Many other things that you might not think of as movements are indeed movements of a sort. For example, the flow of your saliva to aid digestion; the surge of chemicals that create inflammation; and the gush of cortisol from your adrenal glands. (Cortisol has been called a stress hormone, but it is more correct to call it a metabolic hormone; it gets glucose into your bloodstream quickly when your brain predicts your body will need it.) Even conversations between the cells of your intestine and the bacteria that reside there are considered motor movements; this constant chatting aids digestion, and over time can even adjust the length of your intestine to regulate how quickly you digest!

Interoception, like exteroception, operates in the service of movement predictively. Here's the gist: Your brain issues motor commands that adjust the insides of your body, and it simultaneously predicts the sensory consequences of those movements. At the same time, the sensory surfaces inside your body, including dozens of cells that monitor pressure changes, temperature, contractions, stretches, nutrients, gases, toxins, and various chemicals, send a steady stream of sensory signals back to your brain via electrical impulses in your spinal cord and swirling chemicals in your blood. Your brain integrates these sensory signals to confirm or correct the predictions and adjust its predicted movements, if necessary, thereby maintaining allostasis efficiently. In this way, your brain anticipates the needs of your body and proactively coordinates the internal movements that deliver glucose, water, salt, oxygen, and other resources to an infinite amount of cells just in time.

For example, think of the last time you were thirsty and drank a glass of water. Within seconds after draining the last drops, you probably felt less thirsty. This event might seem ordinary, but the water actually takes about 20 minutes to reach your bloodstream, so it can't possibly quench your thirst in a few seconds. What relieved your thirst? Prediction. As your brain plans and executes the actions that allow you to swallow, it simultaneously anticipates the interoceptive consequences of gulping water, causing you to feel less thirsty long before your brain learns from the body about your increased hydration.

New Insights and Deep Implications

There is still much to learn about the mechanisms of interoception and what they mean for health, illness, and basic mental functions. Exteroceptive senses such as vision are relatively better understood—perhaps because scientists are often guided by their experiences, and we don't experience most interoceptive activity. Nevertheless, creative research by those who do study interoception has brought forth some intriguing insights. New ideas are transforming our most basic understanding of brains and bodies and challenging our most basic assumptions of how they work together to create the mind, control actions, and cause illness. We'll share three such insights that blur three fundamental boundaries: what is inside versus outside the body, what is mental versus physical illness, and what distinguishes different mental phenomena.

Inside vs. Outside

The first insight is that the skin, which seems to physically divide body from world, is an illusory boundary when it comes to sensation. Traditionally, interoception is thought to mean sensing the inner body from signals beneath the skin, as we've discussed so far. But some exteroceptive senses, like proprioception (awareness of body position), olfaction (smell), and taste, emerge from signals coming from inside *and* outside the body. And other signals, like wetness, are entirely computed by the brain. Your skin has no wetness receptors, for example; your brain constructs wetness as a combination of touch and temperature.

It might sound bizarre, but your brain doesn't know where your body ends and the world begins. Instead, it approximates a continually shifting boundary. Sometimes the shifts are slow, accomplished by touch, hearing, and watching body parts in action. If you were an ungainly

teenager, or you've been pregnant with an ever-growing belly that unexpectedly whapped into things around you, then you know what we mean. Other times the shifts are quick. Everyone who has driven around town without hitting other cars or the curb has benefited from just how quickly and effectively a brain can expand the boundaries of a body to include the car's perimeter. (Exit the car and the boundaries shrink back just as fast.)

There is another way in which internal and external cannot be neatly bisected. Interoception gives you an extra, fuzzy, exteroceptive sense for free: the gut feeling that something has happened around you. Here's how it works: The light waves that hit your retina and the air pressure changes that reach your cochlea are the outcomes of changes in the world, and your brain guesses, using past experience, what the causes of that sense data might be. Such guesses prompt your brain to prepare for movement internally, such as quickening your breath or secreting cortisol, to support your next actions. These plans for coordinated movement come with predicted sensory consequences.

Evolution did not wire us to feel every interoceptive gurgle, gush, and tug directly, so instead, we often experience them as simple feelings: pleasure or displeasure, idleness or activation, fatigue or energy. Scientists call these simple feelings *affect* or mood. Affect does not reveal what in the world has changed, where the change is, or what to do about it. Rather, it is just a quick and dirty sixth sense that *something* has happened. That particular something may be outside your body and require a rapid and energetically costly response.

But there's a tricky bit: This arrangement allows and maybe even encourages you to search for the causes of your mood in the outside world—in your relationships with other people, or in your responsibilities at home or at work. Feel on edge? Maybe you're late for an appointment. Feel unpleasant? Maybe someone has wronged you. Many internal perturbations have purely internal causes, however, such as lack of sleep, dehydration, or eating too much processed fat and sugar. Just because you feel bad doesn't automatically mean something bad is happening (or is about to happen) to you.

Mental vs. Physical

This brings us to a second insight: Interoception diminishes the boundary between physical and mental. In every moment, your brain transforms something physical—interoceptive predictions (which are neural patterns) and sense data (which are neural or chemical patterns)—into something mental (affect). The same brain circuitry that models the physiological state of your body to create interoceptive sensations also creates the ups and downs you feel every day. Hundreds of studies from laboratories around the world, including ours, have observed this, but scientists still puzzle over the mechanisms that transform physical signals into mental feelings. They remain one of the great mysteries of consciousness.

A particularly permeable aspect of the mental/physical boundary is between mental and physical disease. Obesity is traditionally viewed as a behavioral disorder, heart disease as a physical disorder, and depression as a mood disorder. But the three are highly co-morbid, with any one of them appearing as the so-called "initial" disorder (i.e., depression can precede obesity or vice versa). In addition, the seeds for all three diseases are planted in early life. This confluence of findings suggests that some behavioral, physical, and mood disorders share disruptions in efficient energy regulation, implying disruptions in allostasis and interoception.

Scientists are still unraveling the complex entwining of metabolism, the immune system, and other internal systems of the body. For example, problems with energy regulation, if they go on long enough, produce chemicals and activate receptors that kick the immune system into high gear. Immune responses are incredibly energy-consuming, which further burdens your metabolism, and such cascades often end in serious illness. Exploring and understanding such basic mechanisms may open the door to new strategies for prevention, treatment, and cure.

Some say that the body "keeps score" of adversity and trauma from childhood onwards, making you more vulnerable to illness; but in fact your brain keeps score, and your body is the score card.

Mental Phenomena

The more we learn about interoception, the blurrier a third presumed boundary becomes: one between different mental phenomena. For example, you'd never confuse your sense of touch with the act of breathing, right? Well, it turns out that the two are more entwined than you may think. When something is touching your skin, you're more likely to take in information about it as you inhale than as you exhale. This finding suggests that the sense of touch, which is traditionally considered exteroceptive, may be entwined with interoception at a basic level.

Similarly, you'd never confuse your eyesight with your heartbeat, but the way that your brain receives visual information from the world may be yoked to your heartbeat. People are more likely to take in visual information during the period of each heartbeat when the heart relaxes and blood fills the ventricles, and less likely to take in visual information when the heart contracts and pushes blood out into the arteries. The latter is like a brief, recurring, visual blind spot in time.

Such findings have surprising implications for understanding how your brain and body create your mind. They imply, for example, that neither the conventional "visual system" nor the conventional "somatosensory system" is solely responsible for the ability to see and to feel touch, respectively, but both are components of larger, more distributed neural assemblies that produce these sensations—assemblies that include interoception. Traditional boundaries between the phenomena of everyday life such as vision and touch may not be respected by the brain.

Observations like these may have practical implications with profound societal impact. Imagine your heart is racing at 180 beats per minute, so rapidly that your brain cannot properly sample sense data from the retina. What will you see? Your brain will construct your visual experience mainly from its predictions—your beliefs—and may go uncorrected by actual events in the outside world. Now suppose your heart is racing because you're a police officer in a high-pressure situation, and you're armed. It is conceivable that your brain's predictions could lead you literally to see things that aren't present.

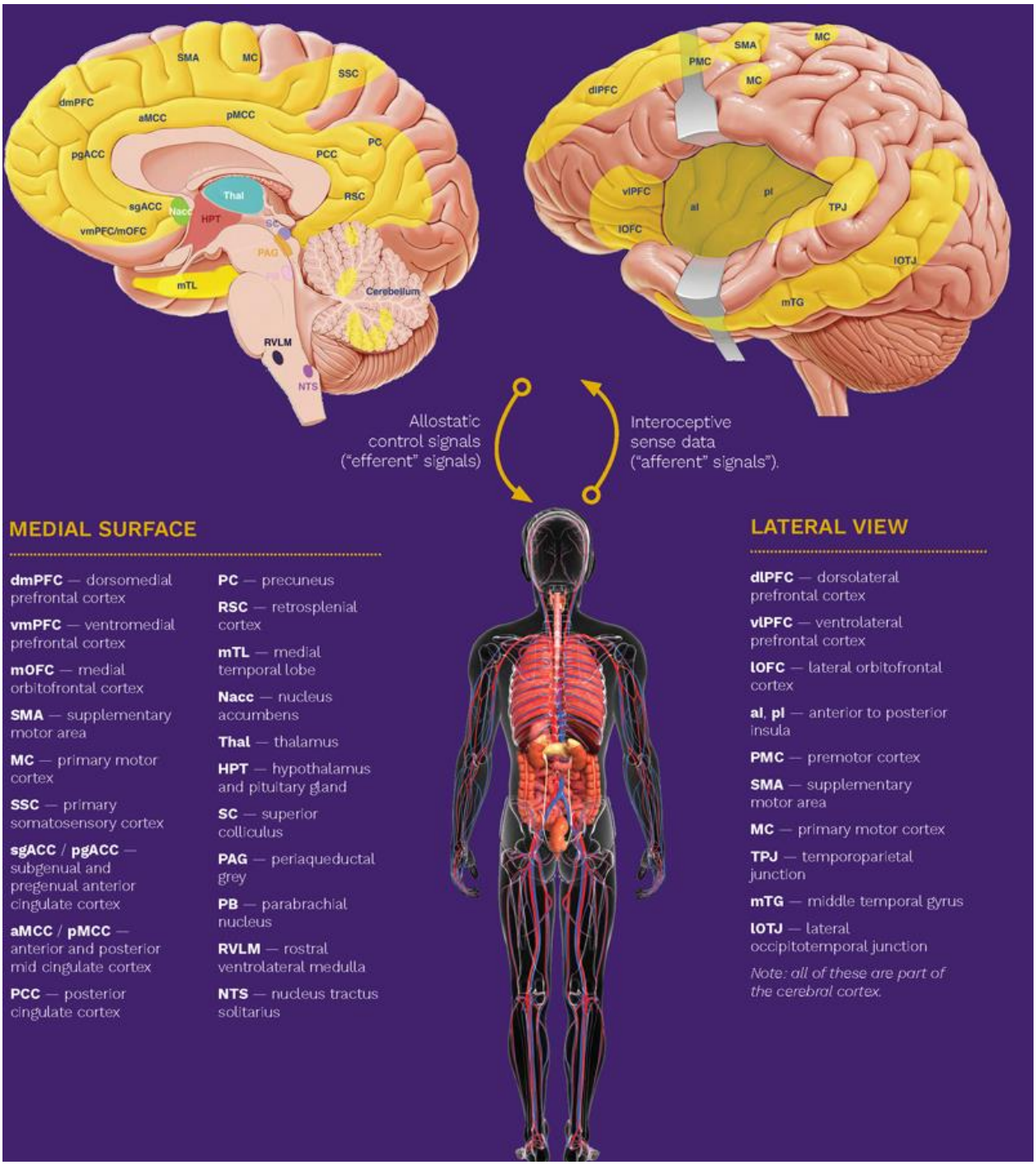
But wait, there's more. Vision, touch, and the sensations of your lungs and heart are just a few of the many mental faculties that scientists study. What about the boundary between cognition and emotion? How about the boundaries between different types of cognition (thinking, decision-making, attention) or different types of emotion (anger, sadness, fear, happiness)? For over a century, scientists typically have assumed that the human mind is made up of different types of mental faculties, each arising from its own dedicated psychological process or mechanism, implemented in its own dedicated set of physical causes in the body and brain. But are they?

Recent evidence suggests we should replace this type-based approach with a more holistic one to better understand how your whole brain, in constant conversation with the various systems in your body, creates your mind at any given moment. If we consider the brain circuitry that is important for allostasis and examine its connectivity to the rest of the brain, we see two well-known brain networks (see Figure 2). The networks overlap in a set of hubs in the cerebral cortex that serve as the brain's backbone for neural communication and have extensive projections to subcortical regions that control the autonomic nervous system, immune system, and endocrine systems. These networks are implicated in various types of sensation and perception, including interoception, and participate in phenomena as diverse as memory, emotion, affect, language, reward, social affiliation, pain, alcohol craving, stress, mental illness, diabetes, and moral judgments of other people. They also converse with groups of cells, deep in the brainstem, that give rise to neurochemicals—dopamine, serotonin, and norepinephrine—that help neurons fire and therefore play important roles in attention, learning, and consciousness. Interoception, it seems, may be at the core of mental phenomena that don't seem interoceptive at all.

Even when we focus on individual brain structures, we can learn how interoception dissolves traditional psychological boundaries. Consider the hippocampus, a structure deep in the temporal lobe of your brain that is typically thought to be crucial for certain types of memory. Exciting scientific evidence now indicates that the hippocampus is bathed in interoceptive information and plays a key role in estimating the physiological state of the body. A rodent's

hippocampus, for example, receives signals about energy availability in the gut that regulate how much the animal eats in a given meal. But the hippocampus can override these signals, causing animals to eat substantially more food than they otherwise would. Therefore, calling the hippocampus a "memory" structure may be far too limiting.

The impact of interoception reaches far beyond what its conventional definition would suggest. Who would have thought that your heartbeat is linked to what you see and how well you see it? To understand something as fundamental as vision, therefore, we must recognize the importance of interoception. To understand health and illness, and even consciousness and mood, we also must appreciate that metabolism, and therefore interoception, plays a central role. Interoception is a secret ingredient in some of the most important and intimate parts of your life.



TWO VITAL NETWORKS: The brain system that supports allostasis and interoception is composed of two large-scale, intrinsic networks. They are conventionally called the "default mode" network and "salience" network, though scientists use several other names in published research. Brain images: Ken Hub Images and Lisa Feldman Barrett; full-body image: Shutterstock

Bios

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