

# **Sensing Machines**

**How Sensors Shape Our Everyday Life**

**Chris Salter**

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## Prologue

The alarm rings at 6:00 a.m. sharp. The clock's built-in atomizer perfumes the air with scent and makes wireless contact with the wrist tracker you wore during sleep. Based on how much you moved and snored during your last six hours of hibernation, a playlist is quickly assembled. While you shower, the blasting strains of Madonna, Rihanna, and Taylor Swift are heard. As you enter your kitchen, a smart speaker announces the temperature and asks if it should turn on the espresso maker, turn off the hall light, and adjust the toaster settings.

You look at your phone's newsfeed. The state of the world on the other side of the globe while you were dormant flashes by. Singapore is requiring its 5.7 million citizens to download a contact-tracing smartphone app to monitor crowd proximity. China is deploying delivery drones armed with thermal sensors, microphones and speakers, ultrasonic emitters, and disinfectant atomizers to enforce the world's biggest quarantine against a newly emerging supervirus. Over the Indian Ocean, radar sensors are strapped onto 169 albatross to detect illegally operating fishing boats.

You scroll. Accusations that your new furniture is sending names, IP addresses, and persistent identifiers to third-party marketers. Plans from a Silicon Valley corporation to turn abandoned US suburbs into smart cities called CleverZones, which have been derailed by community activists who claim the new urban utopia is a gigantic data collection machine. A news item about how pulse oximeters that measure oxygen in the blood exhibit racial bias since they have problems projecting light through darker skin. A Reddit post that a Japanese game company's wearable hoodie that tracks temperature and brainwaves to detect a player's mood has been hacked, with data from millions of teenagers' brainwaves stolen.

Your self-driving car provides that ever-more-important extra hour of work preparation during the endless commute. The front door opens upon approach. The custom-installed AI system scans your pupils and adjusts the climate control and the loudness of the financial news blaring from the digital sound system based on your nervousness.

As the car pilots through the streets and onto the overcrowded expressway, your smart watch buzzes and beats on your wrist, one email flooding in after another. A sea of scrolling numbers and graphs animates the watch's face: heart rate; respiration; sweat levels; NASDAQ rises and falls; DMs from friends; temperature, air pressure, and moisture readings. At one point, lost in a daydream, you briefly gawk at a billboard in the near distance advertising web-based security services. Moments later, ads for security services pop up in your browser.

At work you glare into the screen for the next hours, only interrupted by lunch DoorDashed to your desk. The day passes. The colored mood lighting in the office seamlessly shifts from warm to cold based on how long you occupy your chair and the sequences you type. Every click of the keyboard and movement of the mouse is captured and fed back to you in the form of vibrations on the skin from the smart watch when you miss your benchmark. Online consumption breaks the monotony of contracts, emails, spreadsheets. You download an app that tracks how long it takes you to make decisions in the supermarket, purchase a new fitness tracker, update a social media feed to enable others to locate you. Briefly logging into a banking website during a break results in a strange glitch: the cursor suddenly vanishes during the session.

Some eight hours later, after the routine flurry of calls and online meetings with far-flung project teams in distant locales, a rhythmic pattern pulsed from your watch comes through from a friend you'll soon meet. Before rendezvousing at the gallery, you go for a run to discharge your daily stress. The exercise is punctuated by your smart watch's continual readout of your steps, breathing, and heart rate. As you change your running speed, the biometric sensors built into your earbuds adjust the rhythm and tempo of the electronic beats being piped into your ears.

After showering away your sweat, upon arrival at the newest immersive experience space (another one) with your friend, the gallery attendant places a clear wristband on the arm not occupied by your smart watch and smart disease-tracking armband. You meander through endless labyrinths of light

and sound. In one place, a sign asks you to enter a narrow passage and stand in the center. As you follow the instructions, life-sized projections of animated creatures, floating characters, and abstract bursts of light swim on the walls. Colossal 24K, ten-billion-pixel projections of anemone-like flowers follow your movements as changing scents are diffused from the walls and the floor.

Hunger takes over. The new experience restaurant is waiting past the gallery exit. The gastronomic “journey” is designed to last three hours, and the attendant scans you and your friend to gather data to customize the meal. You are paraded through a series of different rooms, one for each course. Cocktails arrive that steam and smell. Tastes extracted from now-extinct flora and fauna are served up as foams, sprays, and spheres. The main courses appear in a space plunged into total darkness, with each dish accompanied by tactile and sonic signatures. Dessert arrives in another space hung with mammoth plastic strawberries and watermelon slices and flashing videos on a dozen wall-mounted screens. Liquid nitrogen-treated ice cream. Popsicles wrapped in gels. A one-meter-tall Manchego cheese-cake pumped with air closes out the gastronomic overload.

Dancing is finally on the agenda, in the accompanying club housed in the bowels of the gallery. Your wristband allows entrance. You dance in the sweating crowd; the floor beneath you palpitates, changing color and rhythm with your moves. Moving lights in the ceiling zero in on different groups of dancers. Their tracked wristbands light up in dozens of colors that pulse and glow in sync with the DJ’s rhythms. The air is tinged with haze and smoke, the afterimages of strobe lights and the pounding beat. Ecstasy after the long lockdowns.

Arriving home two hours later, you wind down. Donning the latest headset that senses and records brainwaves, you glance at the readout on your phone—digitally scrawled waveforms that ceaselessly fall up and down on the screen. Closing your eyes, you alter the signal by falling into a state of “alert calmness.” Enlightenment nears. More minutes pass. The readout’s sudden jerks and wild oscillations gradually become a smooth, undulating curve. You remove the headset, brush your teeth, set parameters on your wrist sleep tracker, and fall once again into deep slumber.<sup>1</sup>



Welcome to sensory life in the twenty-first century. This story might sound like science fiction. But for an ever-increasing percentage of the planet’s



**Figure 0.1**

Sensory life in the twenty-first century.

socially-economically advantaged populations, it is or will soon be daily reality.

The events in the preceding narrative have something in common. They all involve what I call *sensing machines*—electronic sensors, machine “intelligence,” human labor, and material infrastructures interwoven with our living, breathing, and moving bodies that sense, interpret, and act on the world.

This book tells the story of this world, one where more electronic sensors and computers than people now occupy the planet—some thirty to fifty billion in 2020, and expected to be over a trillion soon thereafter.<sup>2</sup> It explores how we interact with these sensing machines through our long-evolved human senses and how these machines “sense” and act on us.

Sensing machines run the planet. From the intimacy of our homes to the outer reaches of the earth, they shift our understanding of space and time, bodies and machines, self and environment. Sensing machines tell us the espresso maker’s water is the perfect temperature, guide the Roomba vacuum across a dog-hair infested carpet, trigger airbags in the split-second moment of a car crash, change the orientation of an image when rotating a phone, or adjust energy usage to the time of day or the season at hand. They alter our knowledge of the climate and the planet itself, operating across spatiotemporal sites and scales, from the bottom of the ocean and the depths of Earth’s crust to the heights of the thermosphere.

Sensing machines assist in the dramatic transformation of our health, social life, and well-being. They effortlessly reshape and reinvent notions of privacy, personal space, intimacy, and selfhood. Through electronics and mathematics, sensing machines give us new insights about what is happening inside of, outside of, and around our bodies and selves while hiding how this data is captured and used. From architecture and the arts to construction, surgery, security, and travel, their pervasiveness leaves no discipline or practice untouched. In short, sensing machines radically



reconfigure what it means to work, research, build, eat, exercise, socialize, heal, procreate, sleep, and dream in the twenty-first century.



Just reflect for a moment on how *sensors*, basic electronic devices that detect changes in the environment and convert or *transduce* that information into computer readable data, are dramatically reimagining life. In an effort to ward off the COVID-19 pandemic that shut down the world in 2020–2021, governments resorted to contact tracing, using smartphones, electronic wristbands, and the branch of artificial intelligence (AI) called *machine learning* to detect the distances and locations of individuals in order to slow viral spread and thus potentially save millions of lives while also reimagining privacy and personal data.<sup>3</sup>

In the ongoing fight against climate emergency, globally networked biogeochemical sensor arrays are being scattered in the oceans, monitoring whether nations are reducing CO<sub>2</sub> by measuring carbon flux across seasons, under the ice and in surrounding waters.<sup>4</sup> Closer to our bodies, embedded devices in the skin monitor the fluctuation of insulin for diabetics, while ingestible wireless piezoelectric sensors scan stomachs for signs of disease,<sup>5</sup> bringing us a step closer to the cyborg dream of integrating with machines.<sup>6</sup>

Sensing machines reimagine how infrastructures that run cities and economies are conceived, built, and controlled. The Hong Kong-Zhuhai-Macao Bridge, opened in 2018 as the longest private roadway in the world, is breathtaking in the number of sensors it deploys: tilt sensors, high-precision gyroscopes, lasers, displacement sensors, hydraulic load cells, wind speed, temperature, humidity, pressure, air pressure difference, and carbon dioxide detectors.<sup>7</sup>

Set within a strip mall–dotted suburban New Jersey landscape near New York City, the nondescript Equinix NY4 Data Center hosts forty-nine of the world's key stock trading exchanges. Guarded like Fort Knox, with five levels of access security, NY4 utilizes thousands of distributed sensors to monitor temperature, power consumption, and airflow for rows of interlinked servers processing more than a trillion electronic transactions daily.<sup>8</sup> In the building information modeling (BIM) world, systems such as Arup Neuron, a vast AI-driven analytics platform for sensor-augmented building monitoring developed by the global architectural engineering firm Arup, are being compared to the human body. A building's heating, ventilation,

and air conditioning (HVAC) system is seen as the lungs, the blood vessels, the pipes, the bones and skin; the architecture and the Neuron software platform are the brain.<sup>9</sup>

While sensing machines enhance our security and privacy, they also gnaw away at it. Doorbells, thermostats, appliances, and loudspeakers double as surveillance devices. Workers' brainwaves are monitored in offices and on factory floors to detect stress and increase efficiency.<sup>10</sup> New technologies in behavioral biometrics, designed to reduce cybersecurity threats, are able to measure hundreds of parameters based on the common sensors in smartphones and computers: the angle at which we hold the devices; patterns of presses on the surfaces, the speed of rotation (to change things from landscape to portrait) and mouse movement, and how fast applications are opened and closed.<sup>11</sup>

At the same time, supposedly "objective" sensors perpetuate long-engrained human biases. Soap dispensers using infrared (IR) sensing to detect motion under a faucet favor lighter skin. Facial recognition software mainly identifies white faces. Alexa and Google Home's microphones discriminate against Indian and Black English.<sup>12</sup>

With sensors, even our emotional and mental states are up for grabs. Strap on a new wearable "mood tracker" and find out whether you are feeling happy or grumpy based on how much you sweat. Capture something about your mental state with a "brain-computer interface" that senses your brainwaves. Or, be prepared for a future surprise when you book a flight. Seats wired with heart-rate monitors are currently being prototyped that will sense and display a passenger's mood—a useful feature to head off potential altercations with flight attendants if you become an unruly customer.<sup>13</sup>

But while billions of sensors and algorithms are monitoring and calculating our world in opaque and baffling ways, something else is also occurring. New and dizzying relationships are being formed among our bodies, sensing machines, and the environments we inhabit, in which stimuli have been precisely engineered through these very machines in order for us to reach new sensory highs: atomizers spray scents in our homes, offices, and lobbies; sleep machines with light sensors and microphones adjust their output according to our sleep patterns; flicker-based LED relaxation masks reduce our stress; brainwave interfaces that trigger light and sound seek to reveal inner brain states; cars with cameras scan our eye movement

and monitor our nervousness; immersive artworks track and monitor us to create heightened states of audiovisual vertigo and bliss. Even food, which is now put through a scientific regimen of taste modulators, dehydrators, and liquid nitrogen baths under the term *gastronomic engineering*, is being transformed. In other words, ever-new feedback loops emerge between us and technologies that produce new sensations while monitoring and measuring them.

Sensor-based surveillance seems at first to have little to do with brain-wave interfaces for personal transformation or food converted into laboratory experiments. Yet in our contemporary “experience economies,” these things are not opposed. The pleasure of sensation and the ruthlessness of impersonal measurement go hand and hand. To put it bluntly, in contemporary life there is no economy without the senses. In partnership with these machines, our human senses are being jacked up; they are on steroids.<sup>14</sup>



As these examples show, sensing machines have become all-powerful in contemporary life. They devour vast amounts of the world's data while deploying mathematical concepts and models that most people had never heard about until recently, like artificial intelligence, machine learning, and predictive analytics that process and predict at lightning speed, while, at the same time, producing errors and mistakes that reinforce human injustice and capitalist domination. These techniques aim to detect and classify patterns in massive groups of numbers, commonly referred to as *big data*. The purpose is clear: creating rankings, standardizations, population comparisons, better customer profiles, and new kinds of “others” that can be observed, targeted, and controlled.

It is no coincidence that the discovery of new patterns used in the new numerical sorcery we call *data science* is primarily based on statistical methods. Statistics has long been associated with forms of state power. In the late eighteenth and early nineteenth centuries, when the practice first emerged, *statistics* (*Statistik* in German) was literally “data about the state.”<sup>15</sup> Statistics focused on gathering numbers from every imaginable arena of life: birth and death rates, marriage, crime, suicide, and deviancy. In the process, statistical data came to measure the collective behavior of individuals—so-called mass phenomena—to enhance the state's political, economic, and

social knowledge and power over their populations. The individual was quite simply dissolved into the mass.<sup>16</sup>

Statistics evolved to become a rigorous mathematical discipline only in the late nineteenth century, morphing from a descriptive tool into something else: a method of scientific and social scientific analysis that used numbers to quantify, and thus control, the social order by deciding who/what would be classified as “normal” and who/what would deviate from the norm.

In the age of big data, statistical techniques take power to the next step—creating targeted individuals by analyzing mass patterns, not only to count and quantify but also to model and predict. These new quantified prediction cultures based on big data are described by scholars with names such as *surveillance capital*, *dataveillance*, *knowing capitalism*, *datafication*, and *extractive capitalism*.<sup>17</sup> In addition to their destructive political and social effects, all of these paradigms also express a new economic model of experiential extraction—one “that captures our behavioral data and experience and uses it for commercial extraction, prediction and sales.”<sup>18</sup>

The models are all based on a compelling premise. Our *experience* is the new raw material, a resource like oil, gas, or water that can be converted into numbers and mined for indications of future behavior. These predatory techniques depend on the vast digital information infrastructures possessed mainly by the behemoth FAANG corporations (Facebook, Amazon, Apple, Netflix, and Google): mass deployments of sensors, artificial intelligence, server farms, data centers, marketers, and advertising agencies to capture and shape our behavior.

For these firms this is a win-win situation. Deploying algorithms that reinforce likes and dislikes and preferences expressed in our continuously ongoing social media performances gratifies and satiates us. At the same time, FAANG companies and others get immensely wealthy and powerful by using this data to create highly lucrative “prediction products” that imagine the future—not what we will do, but what we *could* do. Hal Varian, Google’s chief economist, cuts to the chase when he writes, “Everyone will expect to be tracked and monitored, since the advantages, in terms of convenience, safety, and services, will be so great. There will, of course, be restrictions on how such information can be used, but continuous monitoring will be the norm.”<sup>19</sup>

Nonetheless, the repercussions of surveillance capitalism are staggering: the total transformation of privacy; continuous monitoring, whether for protection or containment; technical systems whose human-led mistakes lead to discrimination along racial, class, and gender lines; the reconfiguring of human emotions and experience as yet another commodity; the possession of newly gathered knowledge and power in the hands of a few high-tech monopolies on a peninsula south of San Francisco and in the glass towers of Beijing. These effects are already in the news. They are the subject of countless books, articles, podcasts, lectures, policy papers, and discussions within governments, corporations, universities, and homes. We ignore them at our own peril.



But is this the end of the story? True, our human senses, the means by which we see, hear, touch, smell, and taste the world, are now effortlessly captured by artificial sensors and turned into machine-readable data to be exploited by a tiny cluster of the world's most powerful and extractive data corporations. Across literature, film, and even religious practices, however, human beings have long had an almost limitless desire to mold, shape, and share their senses, attention, bodies, and selves with machines: for example, Ismail al-Jazari's thirteenth-century treatise *The Book of Knowledge of Ingenious Mechanical Devices*, which was filled with Islamic visions of automation; seventeenth-century Japanese *karakuri ningyō* mechanical dolls that provide a basis for the Japanese fascination with robots; Mary Shelley's *Frankenstein*; visions of intelligent machines and androids in films like *Metropolis*, *2001: A Space Odyssey*, and *Blade Runner*; and the Hindu practice of offering "puja" (prayers) to kitchen appliances, computers, televisions, cars, and factory machines.<sup>20</sup> Isn't there something deeply seductive about the new kinds of relationships that such sensing machines appear to offer?

In other words, is there something more to sensing machines than just stories of (admittedly) powerful corporations harvesting our behavioral data to maximize their profits? Do we not interact with sensing machines because they enable our desires to go beyond our own human capacities? Do we not find solace in how these machines transform messy human experience into the "objective" ranks of mathematics and statistics? Do we not seek new possibilities in the novel forms of perception and sensation

that these technologies offer? In other words, it may not be only what sensing machines desire from us. It's also what we desire from them.

This book explores these dual and sometimes contradictory dimensions: how our "sensed self" has come to be measured and engineered but also captivated and enthralled by these technologies. Our interaction with sensing machines is complex: multifaceted, contradictory, and ambiguous. My goal here is to convince you that our sensed self did not just appear overnight because of Google or Facebook's predatory data practices. It arose in a much messier way, from a specific set of historically rooted and sometimes conflicting social/cultural/economic contexts and desires.

In these pages, the sensed self emerges through what scholars call *material imaginaries*: the imagined but also realized concepts, ideas, projects, schemes, and devices of scientists, artists, designers, engineers, architects, and entrepreneurs who have sought new ways for our human senses to interact with the "senses" of machines. Moving through research labs and galleries, theaters and restaurants, and the living room, kitchen, and bedroom, I explore key ideas and the protagonists who, inspired by biological systems and mathematics, computer science, and the arts and design, are developing new relations between human and machine senses and how these imaginaries have created new ways for our senses to be mapped and manipulated, quantified and commodified, discriminated against, expanded, controlled, and tantalized. Along the way, *Sensing Machines* investigates how these imaginaries have produced new visions of entanglement and feedback among our senses and bodies, technologies, and the wider environments in which we live.



Why write this book now? At this moment in history, there is much-needed criticism against technological utopias. That the visions of democratization, liberal values, and new forms of community long championed by the computing and information behemoths have led to human and planetary inequity and disaster on a scale previously unimagined must be reckoned with. As one recent book rightfully claims—your computer is literally on fire!

On the one hand, sensing machines make mistakes and are predatory, wielded by powerful corporate interests that have mainly economic concerns in mind. On the other hand, these machines have created new

possibilities and imaginaries between us and our technological “others.” In other words, this book tries to straddle the delicate space between debunking and celebrating sensing machines, by taking specific histories, contexts, interests, needs, and desires into account.

At the same time, there is another motivation to understand how these sensing machines act on our world, and it comes from a very practical position. For more than twenty years, I’ve worked as an artist and researcher. In collaboration with others, I’ve built, programmed, and used such sensing machines, which gives me firsthand knowledge of how these technologies work. I deployed them, however, for an unusual purpose. I’ve used sensors and computers to create large-scale experiential artworks that respond to the movement and presence of visitors. The sensors’ data then orchestrates actions in environments filled with light, projections and sound, intense vibrations and fog, and other things that immerse and saturate people’s senses. These artworks aim to alter the senses of the visitors’ bodies, their perception of time and space, and, perhaps most interestingly, their awareness of their selves.

Through years of making and exhibiting these projects all over the world, I became interested in how *sensors* could be used to answer a central question: How can we design expressive responses in different media to transform a visitor’s attention and their physical presence in a space in order to achieve an artistic or aesthetic experience?

One particular project, called *Just Noticeable Difference* or *JND*, developed in 2010 and toured to museums and festivals around the world, embodies this attempt.<sup>21</sup> The installation takes its name from a well-known concept in psychology: just noticeable difference (JND), the amount that a sensory stimulus must be changed for the difference to be experienced as a sensation. The JND concept was invented by a nineteenth-century psychologist and philosopher named Gustav Fechner, who will play a critical role in this book.

In the *JND* installation, one visitor at a time, alone in a very small, pitch-black room, lying on their back, gradually experienced minute changes of light, sound, and vibration at different levels of intensity. Pressure sensors that the visitors lay upon picked up tiny, almost unnoticed movements as the visitors quietly responded to lack of external stimuli in the environment by minutely fidgeting, moving, or rolling over onto their sides as if sleeping.

In exit interviews, we received enthusiastic responses. People described feelings of ecstasy, of losing the sense of their bodies in space, and seeing, hearing, and feeling things that were not there. Many visitors described powerful sensations: the sense of “losing” themselves; of blanking out, hallucinating, or, most extraordinarily, not knowing who was experiencing the different sensations. The more interviews we did with different and diverse audiences ranging from cab drivers to teachers, artists, and families in China, France, Portugal, Canada, and the United States, the more we realized that the visitors’ perceptions and the sensors, computers, and environment, the machines that enabled these perceptions to take place, were inseparable. Humans and technologies were codependent; they mutually shaped each other.

The turning point in my thinking came almost a year later. I was presenting the project to a distinguished group of scholars who study the interaction between media and science. I had discussed the technical setup and concept behind the installation, as well as the enthusiastic responses of the visitors, when a well-known anthropologist (now a colleague and friend) questioned my motivations. While I implied that the visitors felt liberated because of the sensory experience they encountered, the anthropologist suggested that I was designing or, more bluntly, *engineering* the visitor’s senses and that I should perhaps pay more critical attention to what the social and political repercussions of subjecting people to such sensory manipulation might be. Although this anthropologist didn’t claim that the work was oppressive, they definitely implied that such sensory manipulation walked an ethical fine line between liberation and control.

Taking this criticism seriously, I embarked on several years of research, reading patents, news feeds, and accounts; doing fieldwork in research laboratories; interviewing experts; and studying cultural and technical histories of how computer scientists, engineers, artists, and designers have imagined, designed, and engineered systems that not only intensify our senses but commandeer them as well. While many academic art and cultural historians, anthropologists, and sociologists have written about the latter phenomena,<sup>22</sup> I discovered there has been much less written about why these technologies arose in the first place and the kinds of imaginaries that their inventors or users aimed to stage and realize. This is what this book explores.





The story of *Sensing Machines* comes in eleven short chapters spread across five sections. Each chapter tells a different story of our encounter and interaction with these systems in daily life: playing games, experiencing immersive artworks, driving, eating, exercising, sleeping, and dreaming. Along the way, I draw on examples from computer science, experimental psychology, art history, engineering, anthropology, the histories of technology, science, and psychology, and other disciplines to demonstrate that none of what we are experiencing today is without precedent.

Chapter 1 bounces back and forth between two epochs: the mid-nineteenth century, when the first efforts to quantify the senses through mathematics and machines took place in newly emerging psychology laboratories, and the twenty-first, in which those nineteenth-century techniques are still being used to reimagine and design the latest virtual reality (VR) machines. Chapters 2 and 3, the Playing section, focus on the development of sensor technologies used in music and gaming, in which human bodies were reconceived as new interfaces for expression and play. The two chapters in Immersing, chapters 4 and 5, delve into the use of sensing machines in the arts, from artists' deployment of them in the "programmable art" environments of the 1960s and the immersive installations of collectives like teamLab in today's "experience economies" to a new horizon of autonomous sensing machines that will cooperate with human artists in the not-so-distant future. The Engineering section, with chapters 6 and 7, explores new areas in which our senses are both engineered and intensified—driving and eating. Chapters 8–10, the Monitoring section, open up the black box of sensing machines, examining tracking, pattern recognition, and prediction, as well as the ways in which the technologies of sensors tied to computers are both ubiquitous and hidden, distributed in networks across time and space. Finally, chapter 11, in Enhancing, investigates the larger question of our sensed self: how we attempt to enhance and extend our bodies, minds, and souls through new wearable sensing devices, from brainwave detectors to machines that sense and even shape our deepest sleep and dreams.

Given that this book was completed in the midst of a global pandemic that has had massive political/social/economic/technological repercussions,

I conclude by speculating on the heightened role that sensing machines played during the extremes of the crisis in 2020–2021—one that may potentially bring about a different understanding between ourselves and the technological others that surround and act on and with us.

# 1 Measuring Sensation

When the eye ceases to see, the ear to hear, and the sense of touch to feel, or when our senses deceive us, instruments are like a new sense of an astonishing precision.

—Étienne-Jules Marey

One day in the year 1840, a man opened his eyes and couldn't see. This was it, the "final blow," as he later wrote in his diary.<sup>1</sup> It was as if the man, a renowned German medical doctor turned professor of physics, had inexplicably gone blind overnight. But his condition was not new. It was the dramatic culmination of months of unexplainable symptoms that had befallen this scientist: bursts of light in the eyes, headaches, nausea, lack of appetite, insomnia, and neurosis. Little did the scientist know, however, that his dire situation would eventually result in something remarkable—a startling revelation that would forever change our understanding of the human senses and how they would come to interact with machines.

Between 1839 and 1843, Gustav Fechner, a son of a protestant minister and a trained physician who would soon become a major force in the emerging sciences of psychology and physiology, suffered from a mysterious "malady." The illness had a striking effect on Fechner's work and life. He lost interest in conversing with others. He couldn't see properly, with his eyes continually overwhelmed by flickering artifacts and erratic flashes of light. His head throbbed with dull pain as he wandered aimlessly inside his bedroom, study, and sometimes garden for almost three years, self-isolating and wearing a handmade mask of lead cups that protected his eyes from the blinding daylight. He even painted his bedroom black to stop light from leaking in.<sup>2</sup>

Fechner's eyesight wasn't the only thing that suffered. A growing lack of appetite stretched over months, reducing him to a near skeleton. He stopped speaking in eloquent phrases and sentences. His attempts at healing himself through "animal magnetism" (hypnosis), homeopathy, electric current, and moxibustion (the burning of herbs near the skin) were to no avail.

No one quite knew why Fechner fell ill. Burnout? Too much work, like partially writing and editing a seven-thousand-page, eight-volume encyclopedia? Or turning himself into a human guinea pig in the name of science, damaging his eyesight? Fechner had stared too long into the sun using glasses with only colored filters as he explored the perceptual phenomena of afterimages—the images that stay on the retina long after one stops gazing at a light source. This series of experiments seemed to throw him into a searing, never-ending "light chaos" that he would constantly experience, even with closed eyes.<sup>3</sup>

"Close to insanity," Fechner nevertheless began to slowly recover from his malady. Instead of gradually adjusting his eyes to faint light, he took the brute force route: sudden and intensive short-term exposure to the brightness of the everyday, quickly closing his eyes before the light caused intense pain. He resumed eating, consuming such odd delicacies as raw ham soaked in wine and lemon juice, as well as sour berries and drinks. Although he still experienced "disagreeable sensations" in his head, he finally spoke again.<sup>4</sup>

One October afternoon, Fechner wandered into his garden as he occasionally had done during his illness. This time, however, he took a gigantic step to reintegrate into the visual world. He removed the thick bandages covering his eyes. The light spilled in. As he glanced into his garden, the scientist experienced a miraculous sight. He saw the flowers "glowing." They seemed to speak to him. In this ecstatic moment, Fechner came to an astonishing realization—plants must also have souls.

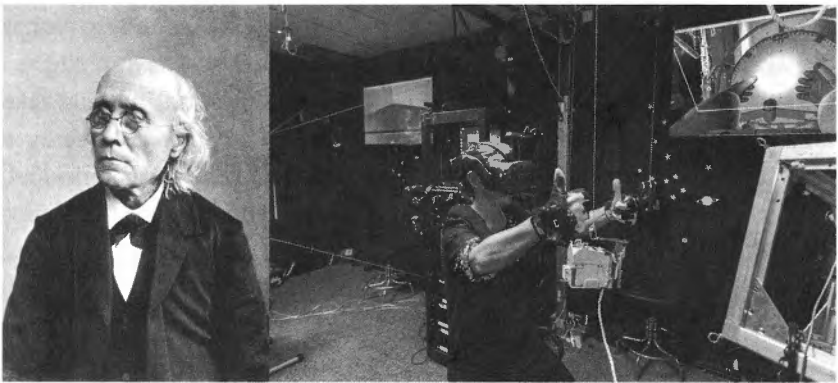


Fast-forward 180 years. In the digital haze of pandemic newsfeeds, you are clicking through pages on LinkedIn. Dozens of jobs in new professions with strange sounding titles appear: vision engineer, applied perception scientist, visual experience researcher, color scientist, and neural interface engineer, the job description of which is to "help us unleash human potential by eliminating the bottlenecks between intent and action."<sup>5</sup>

One career in particular catches your eye: an applied perception scientist, working for Oculus, a once-small start-up that manufactured a lightweight VR headset, which Facebook bought in 2014 for \$2 billion dollars. The job announcement asks for expertise in visual perception, the “computational modeling of vision,” and “experimental and/or modeling approaches” that “help us inform AR/VR display requirements and architectures.”<sup>6</sup> This new career in applied perception science also has another thing in common with the other LinkedIn jobs—it asks for knowledge in an obscure sounding discipline called *psychophysics*.

What does a scientist undergoing a mysterious illness in mid-nineteenth-century Germany have in common with twenty-first century engineers seeking to plumb the depths of human perception? In 2020, Gustav Fechner, physicist, philosopher, and believer in the ever-lasting consciousness of souls, plants, and the earth itself, is a forgotten figure. But he shouldn't be. Fechner is one of first scientists to propose an idea far ahead of its time, one that has had a radical effect on how we view sensing and perception in relationship to man-made machines.

Gustav Fechner asserted that we can measure and calculate how we sense the world using mathematics. Indeed, in the early morning hours of October 22, 1850, just seven years after his malady subsided and the encounter with the flowers in his garden, Fechner had another burst of inspiration. He came to the realization that there must be a relationship between spiritual



**Figure 1.1**

*Left:* Portrait of Gustav Theodor Fechner (circa 1883–1884). Artist unknown. *Right:* NASA training in VR Lab, 2018. Photo by NASA/Robert Markowitz.

and physical energy, *a measurable correspondence between the world external to our sense perception and the internal world of our brain processes.*

But Fechner needed to prove his theory scientifically. He thus invented the almost mystical-sounding discipline that he christened *psychophysics*—a “theory of the relations between body and mind.” In Fechner’s formulation, psychophysics would be an “exact science, like physics” and “rest on experience and the mathematical connection of those empirical facts that demand a measure of what is experienced.”<sup>7</sup> It aimed at no less than to establish a measurable connection between two spheres that had long remained separate: the material, physical universe and the mental, psychological one.

Psychophysics set the European scientific world on fire. It helped advance the newly emerging discipline of experimental psychology, in which there was already a mad rush to translate human thoughts into numbers. The rising hybrid scientists of the period—psychologists, philosophers, mathematicians, and physicists—were eager to escape a nonscientific (e.g., unmeasurable) understanding of how the senses and the mind worked, and Fechner supplied them the ammunition. These scientists began to develop theories to demonstrate mathematical connections between physical phenomena, what are called *stimuli*, and the sensory experience of such phenomena, labeled *sensation* or *perception*. But in the process, they also sought to eliminate the experiencing, subjective self doing the sensing, replacing human sensory experience with “objective” formulas and equations.<sup>8</sup>

Fechner’s ideas would also quickly be materialized in the newly appearing sensing machines of his time—instruments with strange sounding names like *kymographion*, *tachistoscope*, or *chronoscope* and which measured blood pressure; the speed of vision; or response time, the period it would take for a person to react to a stimulus. In the words of the nineteenth-century French physiologist Étienne-Jules Marey, a major inventor of such devices, these new instruments sought to reveal the hidden “language of nature.”<sup>9</sup> Such human sensory measuring devices were to be found in a novel kind of experimental scientific environment: the emerging experimental psychology laboratories in Europe and the United States, whose goal was to create a new kind of human being: quantifiable, calculable, and predictable.

We would assume that psychophysics died a dusty death, relegated to the history books of psychology and the crumbling sets of abandoned scientific instruments that fill up university collections. But this assumption is

an error. As our LinkedIn search reveals, psychophysics is very much alive in the most unimagined of places: the labyrinths of behavioral research at Facebook Reality Labs, the game testing cubicles of Electronic Arts, or the perception laboratories of various universities, who are united around a similar aim. They use the sensing machines of our time—networks of sensors, statistical modeling, machine intelligence, and computing infrastructures, human labor and the earth's resources—to capture, calculate, model, and simulate human sense perception beyond the wildest dreams of nineteenth-century scientists and, in the process, create a wholly new relationship between these sensing machines and us. In fact, Fechner's rendering of sensory experience into numbers has won out. His belief in the life of plants, the earth, and the cosmos itself now includes new entities that we interact with and live among: machines that sense, act on, and perceive our world.



Why is a nineteenth-century science that measured how we perceived the world still relevant today? As a natural scientist, Fechner revolutionized different areas of study. With his successful research and experiments in electrophysics and electricity, he founded the first institute and scientific journal dedicated to physics in Germany. Despite his belief in the physical basis of things, however, Fechner was still uncomfortable with the dominant philosophy of the time—what was called materialism, which argued that reality only exists because it is reducible to mechanical laws. What you see is what you get and nothing beyond.

Instead, Fechner sought a unification, a linkage between things that philosophers and scientists had traditionally kept apart: mind and body, material stuff and immaterial consciousness, even life and death. This linkage is what he called the animated substance of the world. Because Fechner did not separate consciousness from physical matter, his view of the world could be described with the philosophical concept of *panpsychism* (literally, *all souls*): that the soul (from the Greek word *psyche*) is rooted in everything, from rocks and minds to plants and stars and finally the earth itself. To panpsychists, the material world is alive and even conscious.<sup>10</sup>

Perhaps the ultimate contradiction (at least for a natural scientist) was Fechner's impassioned belief in immortality. He entertained interests in the afterlife and parapsychology, even attending séances for the dead. Yet even this was not something considered esoteric or strange like it might

be today. Such interests were common, even among scientists, during this period.

It was in Fechner's voluminous and obscure writing that these seemingly outlandish views found their home. In dense books running hundreds of pages long, with enigmatic titles like *Nanna: The Soul Life of Plants* (named after the Norse goddess of flowers Nanna) or the epic *Zend-Avesta: On Matters of Heaven and the World Beyond*, Fechner spun out philosophical beliefs in which spirit, soul, body, and nature were densely connected in an interlocking web.

Fechner laid out two different visions of the world: what he would call the *day view* and the *night view*. The day view was comprised of mind and spirit and encompassed Fechner's anti-materialist beliefs in the aliveness of all things regardless of whether they would be considered biological organisms.

The night view foretold the opposite: the mechanistic and materialist world. These two worldviews were crucial for the *Zend-Avesta* because it was in that book that Fechner also laid the foundations for a new kind of "mathematical psychology," in which a relationship could be drawn between *stimuli*, consisting of material phenomena, and *sensation*, consisting of psychic or mental phenomena. "There is nothing," Fechner wrote, "to stop us from considering the materialist phenomena that underlie a given psychical event as a function of the psychical event and vice versa"<sup>11</sup>

The goal of Fechner's new mathematical psychology was unambiguous. It sought to develop a rigorous, quantifiable science that would replace the fuzzy, speculative understandings of mental phenomena that had already gripped the emerging discipline of psychology. But Fechner's mathematical psychology would do something more radical. It established a quantitative, rigorous relationship between matter and mind, forging a new connection between the accessible material world and the inaccessible spiritual one.



In 1850, Fechner didn't know exactly how the relationship between stimuli and sensation actually worked. But he had a hunch that a measurable connection could be determined between the two.

He proposed a simple question: How could one *measure* sensation and, therefore, perception? Fechner didn't start from scratch in this formulation.



Instead, he drew on an existing theory from one of his contemporaries, German psychologist Ernst Heinrich Weber, who had put forward the idea that there was a relationship between the intensity, *the strength of a stimulus*, and its resulting sensation.

Imagine the following scenario. You have two equally weighted containers. By lifting them, you compare how heavy they are. Then, someone adds a little more weight to both vessels and asks you to verbally state if you feel a difference between the two. The trick is that you will only notice a change if you sense that the *difference* is large enough. Your task is to determine how much the weight changes in order to distinguish one from another.

This scenario is not just dreamed up. Weber, and later Fechner himself, actually tested it. While researching the sense of touch, Weber came up with a concept called the *two-point threshold*. Using a metal compass touching the skin of a test subject, Weber asked what the smallest distance between the two points of stimulation would need to be for the subject to report them as two distinct points.<sup>12</sup> He called this measurement the *difference threshold*—the minimum amount by which the intensity of a stimulus would have to be changed for the subject to perceive a difference in their sensory experience of that stimulus. Revealed in both the weight comparison and the two-point threshold experiments, the difference threshold also went by another, now more famous name: *just noticeable difference*.<sup>13</sup>

Fechner had mathematically restated what he called *Weber's law*. He demonstrated that while sensation was a function of a stimulus, there was not an assumed one-to-one relationship between that stimulus and its perception. In other words, one's sensory response to a stimulus was not proportional to the physical intensity of that stimulus.

Weber's law had shown in an intuitive (but not quantitative) manner the amount that a stimulus would have to change before a subject would recognize an experienced difference in the change of the sensation. Through a series of calculations, Fechner transformed Weber's concept into a mathematical formula, arriving at an equation which expressed the ratio of the JND of a stimulus to the stimulus itself.<sup>14</sup> Fechner then manipulated Weber's law into a formula that would later be called *Fechner's law*, in which he claimed to *precisely show the relationship between the mental and the physical*—the mind and the body:  $S = k \log R$ , where  $S$  = the intensity of the sensation and  $\log R$  represented the intensity of the stimulus, with  $k$  as a constant.<sup>15</sup> To put this in a nonmathematical way, as a stimulus increases in intensity,

the intensity or *magnitude* of the change of sensation also has to continually increase in order for us to perceive a difference.

Although set into mathematical terms by Fechner, his equation of  $S = k \log R$  closely resembled another similar and well-known mathematical formulation: Ohm's law—which also expressed a relationship between two variables (this time, voltage and current) in logarithmic terms.<sup>16</sup> This relationship between concepts in electrical behavior and human perception was not coincidental. Like many nineteenth-century scientists, Fechner was obsessed with the concept of energy and could thereby equate the energy inherent in pure physical phenomena with that of bodily phenomena.<sup>17</sup>

The concept of energy had an almost mystical aura surrounding it. Fechner's formulation of his *fundamental psychophysical law* was focused on the energy inherent in a stimulus and the resulting energy contained in the sensation of that stimulus. In fact, when Fechner had his epiphany about psychophysics, he immediately drew on these energy theories, recognizing that “the relative increase of bodily energy is related to the measure of the increase of the corresponding mental intensity.”<sup>18</sup> At its basis, *psychophysics was about the process of measuring difference in the energy of a stimulus and when that difference would become noticeable in perception*. A law of mathematics was thus translated into human perceptual terms.

While all this might sound needlessly complex, a common example illustrates the basic principle of Fechner's psychophysics. Imagine a standard hearing test in which the volume (magnitude) of a sound is increased or decreased. The person running the experiment asks you to verbally report when you hear something and begins to adjust the volume. In other words, the experiment asks you to identify the exact moment when a tone that at first you cannot hear suddenly becomes audible—perceivable as an auditory sensation. At first, you report that you hear nothing; the volume as a stimulus is too quiet for your ears and auditory nervous system to perceive. Gradually, however, you seem to hear the tone; it can be consciously detected.

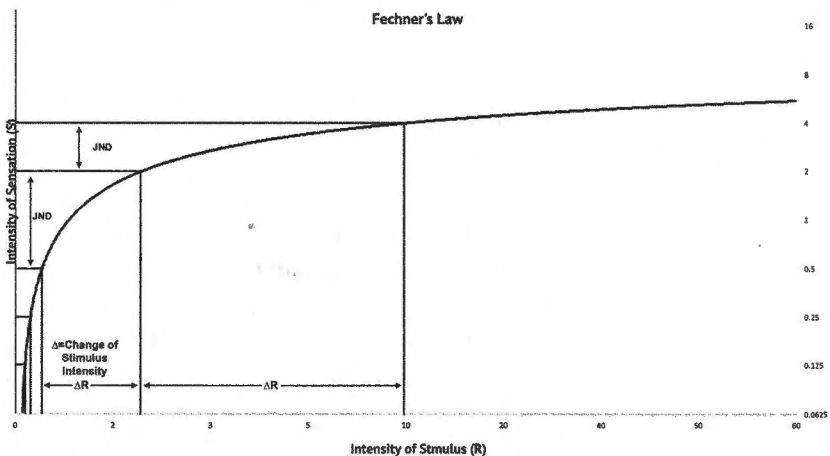
Fechner had a name for this sudden moment at which a stimulus could be detected—he called it the *absolute threshold*. The absolute threshold describes when the intensity of the stimulus “lifts its sensation over the threshold of consciousness.”<sup>19</sup> The absolute threshold could thus measure the smallest amount of stimulation that could be detected by an organism.

But the absolute threshold is only one value on a longer-intensity scale. Fechner therefore had to develop another measurement that would

consider the change of perception as a stimulus would become more or less intense. To put this another way, what would the just perceivable or just noticeable *difference* be as the intensity of the stimulus strengthened or weakened over time (figure 1.2)?

Although detailed over hundreds of pages in more complex numerical analysis, Fechner's psychophysical principles revolved almost entirely on this concept of perceivable difference in the relation between stimulus and sensation/perception. The same could be said for the three core methods that Fechner introduced as core psychophysical principles still in use today—namely, (1) the method of limits or JNDs; (2) the method of adjustment (average error); and (3) the method of constant stimuli (right or wrong cases).<sup>20</sup>

You don the cumbersome virtual reality headset (figure 1.3). Once it sits on your head, the device is turned on. At first, there is a menu that instructs you how to use the handheld controller, which allows you to navigate the visual space soon to be displayed before your eyes. Pressing the left button allows you to move left; the right button, right. If you press the up and down buttons, you travel vertically inside the animated world. After this episode, known as onboarding, the experience begins.



**Figure 1.2**  
Weber's (later called Fechner's) law.



**Figure 1.3**  
VR at Samsung Mobile World Congress 2016.

You are under the sea, accompanied by hundreds of animated swimming creatures in all kinds of fluorescent colors. Turning your head too quickly, you suddenly feel a spell of dizziness. As you navigate this animate and animated undersea world, you run into corals and rocks on the canyon bottom of the ocean floor. Pressing the buttons on the controller doesn't really help, so you just hang out. The undersea world drifts by.

What's more amazing is that this artificial thing, firing complex and detailed 3D images into your retinas, binaural sound into your ears, and vibrations through your hands, follows your movements and actions. As you rotate your head, the sound follows, creating a sphere of audio around your skull. Some of the swimming sea creatures almost bump into you, and sometimes they make contact, bouncing off of you as if you were really there under the sea. Sometimes it seems that the space projected in front of your eyes and into your ears is infinite in dimensions. Other times it feels confined—as if you were restricted to moving only a few steps before reaching the edge of the animated world.

But this is all a ruse. The VR experience you undergo is entirely artificial. None of what is happening seems remotely like how the physical world

that you walk in or move through daily actually functions. In the “real world,” you have to walk toward something to hear it, and, in fact, the sound source that is closest to your ear is the one you hear first. Similarly, if you want to look at something to get a closer sense of its detail, you have to literally move your body toward the object. The object rarely moves toward you (even if it’s alive) in order for you to get a closer look.

How then is this perceptual trickery accomplished? Although the Oculus or HTC Vive *head-mounted display*, as the technical term goes, seems like a glorified but worn projection screen, it is anything but. This roughly 470-gram display is packed with OLED screens and sensors that can measure an inconceivably large range of physiological data: the speed of your eye movements (called *saccades*) or when you blink; where your head is located in space relative to the image you are looking at in the headset; how steady you can hold your hand as you grip a wireless controller or navigation device; or where your ears are in relationship to the visual scene. It’s important to realize how critical these sensors are for guaranteeing the holy grail of a VR experience: creating a sense of presence by being physically immersed in a “nonphysical world.”<sup>21</sup>

Sensing research for VR and for augmented, mixed, and extended reality (AR, MR, and XR) develops in leaps and bounds. As of 2019, so-called six degrees of freedom (6DoF) sensors were the latest technology to be integrated into VR headsets. Based on the engineering concept of *degrees of freedom*—the number of directions a rigid body can move in 3D space—these sensors enable the real-time tracking of full body rotation and position: forward; backward; up and down; left and right; and rotation around the three X, Y, and Z axes, referred to as pitch, yaw, and roll. In essence, any movement you make can be captured and organized by these sensing devices.

While the ability to track such parameters previously relied on external “outside in” sensors, such as cameras or lasers that are placed in a stationary location,<sup>22</sup> the integration of “inside out” sensors, ones placed directly into headsets, enables a new level of simulated experience. The ability to move around in a virtual space will thus soon parallel the way one moves in the real world.

But what does Fechner’s psychophysics have to do with VR? More than we can at first imagine. The detection and discrimination of limits, errors, and thresholds—the basic tools of psychophysics—are one of

the fundamental scientific methods used to test these new reality devices against your own way of perceiving the world. As one group of cognitive and computer science researchers claim, “VR can be seen as a continuation of a long psychophysical tradition that attempts to interfere with our perception in order to clarify its underlying mechanisms.”<sup>23</sup>

Over the more than one hundred years since Fechner’s invention of psychophysics, the discipline has advanced. It is no longer only used to measure the complexities of human perception to gain knowledge about the human senses. Psychophysics has become a *design method* for creating sensing machines and the artificial experiences that such machines make possible. Sensors together with psychophysical methods are not just measuring the world, they are helping create alternative ones. Within Facebook Reality Labs, with its almost military secrecy, scientists with PhDs in neuroscience, applied perception research, robotics, and computer science still draw (albeit with updates) on the quantitative modeling of sensation, stimuli, and perception that Fechner discovered in the late nineteenth century in their twenty-first century aims to create VR, AR, and XR experiences that are both exceedingly real and, at the same time, completely artificial.



In applied perception research, machine sensing, and psychophysics, measuring human sensing and perception go hand in hand. Take one of the major issues in VR: calculating the position and orientation of a user’s head in space to dynamically adjust the image in each eye in order to mimic the stereoscopic way we see. If there is *latency*—a temporal lag between an input action such as a head movement and the resulting image in the visual display—then the sense of virtual presence is disrupted. Worse, this temporal delay can lead to motion sickness or the even more bizarre experience of *oscillopsia*—the perception of a moving image even when the image is stationary.<sup>24</sup>

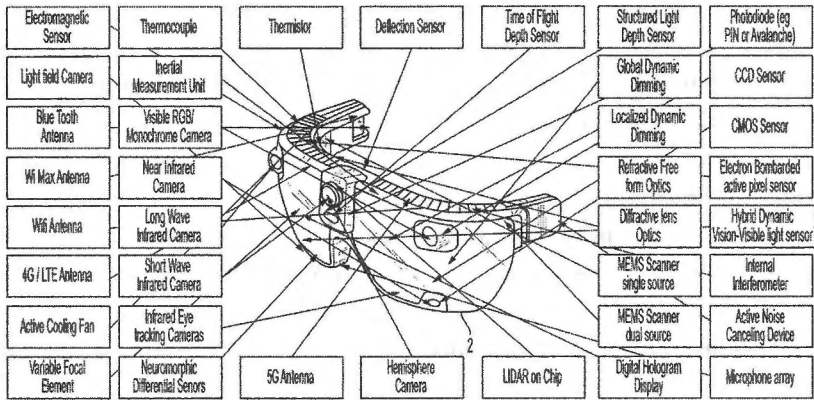
To measure the difference between action and visual response, researchers use modified versions of Fechner’s method of limits, in which a changing stimulus (in this case, a moving object in a virtual environment) is presented at various intensities together with a standard, constant stimulus to determine whether or not the range of intensities is the same as the constant. Calculating these JNDs enables vision scientists to understand whether or not their test subjects could, in fact, perceive just noticeable

differences between their head movements and the speed of movement of a virtual object due to the updating of the 3D image.<sup>25</sup>

Psychophysics is also used as a design method in VR/AR research when determining how fast one's pupils dart about when immersed in a virtual scene—what is called *saccadic eye movement*. One technique called *redirected* or *infinite walking*, freshly emerging from computer science research, utilizes our rapid eye movement (REM) or saccadic suppression that we make when gazing at a scene to actually trick the eyes and brain into thinking we are in a virtual space that is larger than the actual physical space we are in.<sup>26</sup>

Saccades produce a kind of microblindness, a split-second period when the eye actually is closed but we don't perceive it. By measuring the change in rapid eye movement using internal gaze-tracking cameras built into a VR headset and "incorporating guided navigation and planning based on the scenario," researchers take advantage of this momentary gap in seeing that occurs during saccadic movement, "redirecting the user much more aggressively, yet still imperceptibly." This works as follows. Eye trackers calculate the length of the saccades and, within those microintervals, make small, imperceptible adjustments to the rotation or position of a virtual camera in the virtual space so as to "exploit as opportunities for imperceptible transformation of the world."<sup>27</sup> Sensing our eye movements serves to fool the eyes and the brain into believing things have not changed in the virtual scene when they actually have. By then measuring a range of JNDs, the researchers aim to understand how perceptible such changes are to the viewer—or if they are barely noticeable or not noticeable at all.

The complexity of VR and AR headsets and goggles, however, makes them increasingly more like airplane control dashboards than something meant for the living room. The inner guts of the Magic Leap—an MR goggle-based worn device that appeared in late 2018 after many years of stealth development and hype—is covered in so many sensor arrays, from IR-driven eyeball tracking to 6DoF sensors, that its sensing infrastructure has been compared to that of a self-driving car's (figure 1.4). Indeed, in an interview, the former founder of Magic Leap makes clear this strategy of direct perceptual integration: "Your brain is the coprocessor. We spent all of our money and everything we're doing to send a signal for the human brain, not a camera CCD [charge-coupled device]. Not a monitor. Not anything else. I came out of biomedical engineering and the idea was, don't break the brain. Don't break the brain is the number one rule."<sup>28</sup> It seems



**Figure 1.4**  
Magic Leap sensor architecture. Drawing from original patent.

the Magic Leap aims to leave no potential body interaction (with the device) unsensed.<sup>29</sup>

This desire to sense everything is not just technological. It is psychological as well, part of a larger movement to reorganize the human senses as input for designing the simulated immersive worlds that Facebook, Apple, Samsung, Microsoft, and a myriad of Chinese start-ups hope many of us will soon inhabit. Because the key to VR, AR, MR, and XR is achieving a degree of absolute believability, what in the theater has long been called *willing suspension of disbelief*, from a psychophysics perspective it is necessary to numerically judge how much believability of presence an artificial world conveys so that eventually users can no longer tell the difference.

This total synthetic belief is also evidenced by the shift in the rhetoric around VR itself. Long accused by philosophers and cultural critics of denying our bodies, now VR can't seem to get enough of them. In fact, what used to be termed *virtual reality* is increasingly described as *real virtuality*.<sup>30</sup> In a seemingly slightly desperate attempt to integrate its users' bodies into its simulations, VR has been recast to create a believable sense of bodily presence that ironically can only be achieved in the virtual world by artificial perceptual machinery: sensors, high-resolution displays, and computers processing millions of high-polygon graphics.

Contrary to the idea that the senses are simply to be replaced by artificial sensors, a different story is emerging. Perhaps more than ever, our senses



are needed to feed ever newer immersive experiences by increasingly being what researchers call *tightly coupled* to these devices—an inseparable connection that can be achieved by psychophysically measuring the changes in stimuli produced by these systems and incorporating those changes into actual design requirements for the hardware and software itself. Yet, our bodies and senses that carry different histories—cultural, social, economic—are tabula rasa for these systems. Gender, class, race, or ability differences are simply erased in favor of the psychophysical norm.

Modern perception science is fundamentally based on these principles of cultural sameness. But psychophysics is not just erasing cultural and social distinctions between bodies but also creating new loops between design and perception. By providing recommendations for the hardware and software design of new technologies that enact researchers' theories about how our sense perception works, these researchers can then create perceptual experiences that reinforce these models, regardless of the bodies that are part of these new realities.



Today, the relationship between sensing machines and sensation and perception seems a given. But unlike the sensors inside the Oculus Quest or Magic Leap that can instantiate whether a perceivable change happens in the frame rate of an image, Gustav Fechner in 1860 had little access to sensing devices to experimentally prove his theories. His “sensors” were cruder: the perceptual abilities of human beings who, under psychophysical tests, would generate verbal data about what they experienced, which then could be calculated to come up with measurements.

In other words, as mathematically rigorous as they were, Fechner's psychophysical methods still relied on human scientists, physiologists and psychologists who would “subjectively” report what they had perceived from test subjects during an experiment. The experimenter could not control whether the subject's report would be correct or even accurate.

To complement Fechner's psychophysics, nineteenth-century scientists therefore turned to newly emerging technologies to better measure sensorial responses: new sensors to prove their new theories. These researchers invented instruments designed to capture and measure the human (and also animal) senses. From the ophthalmoscope to the acoustic whistle, the olfactometer, chronoscope, aesthesiometer, and photographic gun that

enabled the emerging practice of chronophotography, these instruments became, in effect, *de facto* senses.<sup>31</sup>

Not only were they the earliest versions of the sensing machines on offer today, but these sensing instruments also played a fundamental role in the construction of a vast new domain of knowledge about the human sensorium called *sensory physiology*, which understood the senses as key to the development of psychological and physiological knowledge.

Utilizing scientific observation, experimental procedures, and emerging instruments, sensory physiologists studied a broad range of phenomena, including spatial perception in hearing and seeing and the speed of neuronal firings or sensory *quanta*: tiny measurements in the form of thresholds and differences of stimuli intensities, mainly derived from Fechner's psychophysics.

Sensory physiology took the body and the senses directly into the technological loop; there was not merely a chance or accidental relationship with the technologies of measurement and analysis that would soon proliferate in the first research laboratories dedicated to experimenting upon and analyzing the senses of living bodies.<sup>32</sup> Not only were the senses reconceived as technologies in and of themselves, but also, like our VR and AR headsets, instruments became increasingly integrated into animal and human senses. In other words, the senses became sensors, and sensors assumed the role of sensing.

This "extension" of the senses into instruments seemed par for the course in the early to mid-nineteenth century. Already devices such as the stethoscope and the thermometer were replacing the human senses. The overall effect of these new experimental technologies and the laboratories where they were deployed was that machines not only increasingly regulated the bodies and senses of the subjects being studied but also shaped the senses of researchers themselves. In other words, researchers became data analyzers.

Indeed, for those scientists working in the shared space between physiology, psychology, and medicine, instruments became essential partners in revealing the invisible forces fluxing through bodies, forces that were inaccessible to the human senses. There is no clearer expression of this sentiment than the words of nineteenth-century French physiologist Étienne-Jules Marey, who stated, "How little our senses tell us, so that we are constantly obliged to use apparatuses in order to analyze things."<sup>33</sup>

Three characteristics marked this era of early sensing machines. First, the senses (and sensing itself) became increasingly equated with measurement. For instance, through his experiments with frogs and human muscles on *reaction time*, the temporal difference or lag between a stimulus and its response, German mathematician, philosopher, and sensory physiologist Hermann von Helmholtz introduced new empirical techniques for separating and then studying the individual senses. Helmholtz's reaction-time experiments proved that sensation and quantification were intimately linked with one another. A sensation applied to a muscle in a frog or the skin of a human would naturally result in a reaction, quickly followed by a measurement of that reaction.<sup>34</sup> It's almost as if the experiments were designed to demonstrate the efficacy of the technologies themselves.

Second, such experiments could not have been accomplished without specially designed instruments that enabled the measurements in the first place. As physiologist Marey made clear, such instruments were needed to capture temporal changes that outstripped the human senses' abilities to perceive them. Because sensory experience was simply too slow, the precision of measurement became a core goal.

Third, physiologists, psychologists, and physicians sought to turn the messy, imprecise senses into something externally readable through an early form of data visualization—what Helmholtz and Marey called the *graphic method*.<sup>35</sup> The capturing of sensor data and its writing or *inscription* onto a surface was pioneered by German physiologist Carl Ludwig, who, in 1846, introduced a new machine called the *kymographion* (literally, *wave writer*)—an instrument designed with an explicit graphical purpose: to trace the shape of the heartbeat.

The machine worked through the insertion of a small air-filled bulb into the artery of a live animal. A change of blood pressure would cause the bulb to move up and down, and this motion would subsequently be transferred to a stylus mounted against the head of a rotating drum. As the ink-based stylus contacted the drumhead, visual tracings of the pulse would appear on its surface. \*

The kymographion was an early device to capture physiological data as visual traces in time, and the graphic method took advantage of this by recording time intervals that escaped the human eye's temporal and spatial resolution.<sup>36</sup> For Marey and Helmholtz, who both pioneered the graphic

method around the same period, the possibilities of visualizing hidden forces opened up a new chapter into the analysis of the human body's inner life.

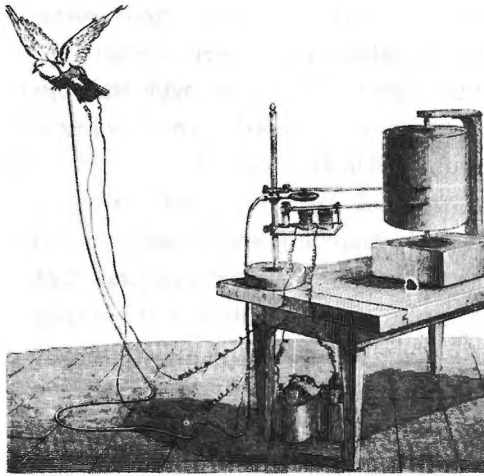
This early method of data visualization also suggested something else: the removal of the human observer from the scientific process of perception. There would no longer be a human intermediary between an action and its visual representation. In the blossoming world of nineteenth-century psychology, sensation could thus only be justified if it could be calculated and visualized. Many years later, American designer Edward Tufte reinforced what many nineteenth-century scientists who justified the graphic method were arguing for when he gave a new name to this interest in the visualization of data: the *visual display of quantitative information*.<sup>37</sup> The pioneering communications designer Muriel Cooper, the first tenured female professor at the MIT Media Lab, went further—she dubbed such quantified visual data “information landscapes.”<sup>38</sup>



This age of quantifying living bodies took off. But it increasingly demanded ever-stranger sensing machines to advance its scientific cause: primitive electrodes; pneumatic tubes and mechanical harnesses that could be attached to the limbs, arms, wings, feet, and legs of unfortunate humans and animals, such as Marey's air pantographe, which was used to study live birds in flight (figure 1.5); recording devices like pneumographs, which graphically represented throat movements produced during vocalization; or tachistoscopic apparatuses that measured how visual sensory impressions could affect consciousness within specified time intervals.

Quantifying the senses also required new kinds of infrastructures in the form of sophisticated spaces, rooms, and human resources (i.e., students) who would operate these new sensing machines so that sensory data could be recorded, studied, and stored. Founded by a Helmholtz protégé named Wilhelm Wundt, one of these new infrastructures opened its doors at the University of Leipzig in 1879.

Wilhelm Wundt has a particularly important position as one of the founders of modern experimental psychology. Influenced by psychophysics, Wundt sought to test Fechner's techniques experimentally, subjecting sensory experience to rigorous methods concurrently being developed in sensory physiology and “physiological psychology.” Here, the inner world of a subject met head on with external instruments that would scientifically



**Figure 1.5**

Étienne-Jules Marey, air pantographe (machine for studying live birds in flight). In *La Méthode graphique dans les sciences expérimentales et principalement en physiologie et en médecine* (Paris: G. Masson, 1878).

validate their deepest psyche—something that psychology had not yet explored in an experimental, technologically instrumented way. Wundt sought to externalize inner perception, thoughts, and even memories by measuring a person's physiological characteristics: breathing, speed of reaction, pulse, and nerve responses.

Like Fechner, who was some thirty years older, Wundt studied sensation and perception in hopes of being able to make a link, a *contact point*, as he called it, between the physical and psychological. He would succeed in doing this by subjecting his laboratory test subjects to artificially generated sensory experiences in experiments designed to observe and analyze their response.<sup>39</sup>

In Wundt's Leipzig-based Psychological Institute, one of the first experimental psychology research laboratories, this goal would be made possible by the newest scientific instruments and environments: a room painted completely black for vision experiments; isolation spaces with padded doors for acoustic experiments;<sup>40</sup> a space housing a gigantic Meidinger battery that could distribute power to a range of testing apparatuses across different spaces; tuning forks; machines to split and measure the color spectrum; chronographs and chronoscopes for reaction time experiments; and

“time sense” apparatuses to calculate the mental representation of time. All of these machines and infrastructures were designed to investigate the key elements of Fechner’s psychophysics: to enable the objective measurement of the intensity of sensation produced by the new instruments themselves.

But Wundt went further. He made physiology itself into a new kind of exploratory playground. Wundt’s experiments usually required three things: a test subject, instruments, and researchers who could administer, gather, read, and analyze the data. Experiments ran the full gamut: psychophysical tests that measured the quality and intensity of sensations; tactile and auditory psychology; experiments on visual sensations, and the sense of taste and smell; visual depth perception; studies of the time sense and attention; and processes of association and memory.<sup>41</sup>

Unlike previous researchers in the senses, Wundt’s laboratory established a collective experimental atmosphere for the training of students in research, one of the reasons that budding psychologists from all over the world came to study with him.<sup>42</sup> Sensory physiology thus not only grew through the development of sensory instruments but also through human experimental teams who would administer and analyze these experiments. The laboratory became a teaching environment in addition to a site of new knowledge about the senses.

The laboratory also helped create a new division of labor between the test subject and the researchers themselves. The effect was that the subject became a data source and the researcher an experimental manipulator.<sup>43</sup> But the results were not entirely in the hands of the experimenters. The test subjects themselves were encouraged to develop an experimental and objective understanding of what was happening to their own selfhood at the time of the experiment—what Wundt called *experimental self-observation* or *introspection*. Observers would be exposed to standard repeatable situations and then requested to respond in a quantifiable manner.

What was critical for Wundt’s method was the scientific governing of his test subjects, enabled by the experimental laboratory environment. Like the verbal reporting of psychophysical limits and thresholds from Fechner’s early test subjects, the controlled conditions of an experiment could allow subjects to immediately report verbally on their perceptions.

Unlike Fechner, however, Wundt verified these reports through measuring instruments. Thus, the subject’s own description of what was happening to them, what Wundt called their *inner perception*, might begin to

approximate the conditions of external observation. Externally produced forms of sensation here served to influence and shape subjects' sense perception; the more the subjects were subjected to such sensation, the more experienced their observations became without regard to any kind of superfluous self-reflection.

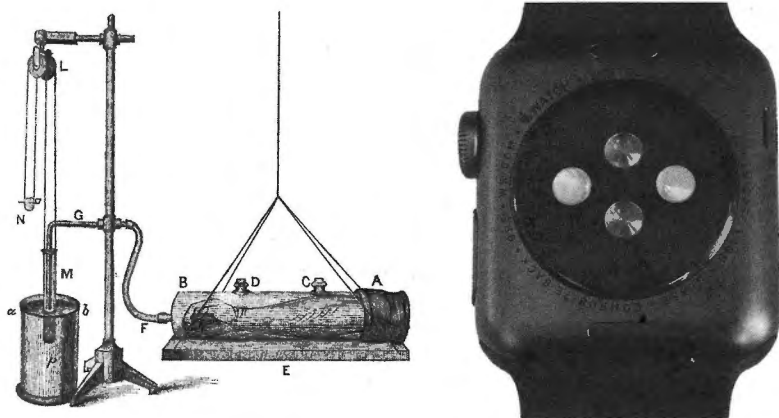
The sophistication of Wundt's laboratory was that in addition to these larger machines, the institute also featured many smaller instruments, some of which could be directly attached to the body in order to gauge the relationship between physiological data (like blood flow, breathing rate, and pulse) and emotion—the subject's response to external stimuli—while the test subject rested in an “indifferent frame of mind.”<sup>44</sup>

These new sensing instruments became so essential for rendering new knowledge about human beings that E. B. Titchener, one of Wundt's students who later set up one of the early psychology laboratories in the United States at Cornell University, put it thus: “The experimenter of the early 1890s trusted, first of all, in his instruments; the chronoscope and the tachistoscope were—it is hardly an exaggeration to say—of more importance than the observer.”<sup>45</sup>

One specific instrument in Wundt's lab bears brief description. The plethysmograph was a new apparatus designed by the Italian physiologist Angelo Mosso in 1874 to measure the change in volume of an organ based on the shifting blood pressure flowing through it (figure 1.6, left). Consisting of an arm-sized glass vessel filled with water, when a subject put their arm into the tube, the change of blood pressure displaced the water level and transferred this to a stylus, which would graphically record the fluctuations on the surface of a turning drum.<sup>46</sup> Presciently, albeit in an updated, electronic version working with light, Mosso's sensor would wind up some 140 years later in a device attached to the body that also attempts to link hidden interior data to our visible actions: the Apple Watch (figure 1.6, right).<sup>47</sup>



Why did these nineteenth-century “engineers of life” believe that their technologies were infallible?<sup>48</sup> That their graphical curves and markings made “without recourse to the human eye or hand” would tell the truth over the fallible human senses?<sup>49</sup> Despite Marey's belief in such instruments rendering visible the hidden language of nature, these instruments were eventually criticized as imprecise.<sup>50</sup>



**Figure 1.6**

*Left:* Mosso plethysmograph (1876). *Right:* Underside of Apple Watch, with PPG (photoplethysmograph) sensor and LEDs. Photo by Fletcher.

In fact, not only was the graphic method imprecise, it was actually considered deceitful. Although there was a fervent belief in the all-powerful ability of these “self-registering” instruments—devices that automatically inscribed or self-recorded their data without human intervention—there was still a need for a human interpreter between the body and the instrument. The human eye had to read and understand the scales of data appearing on the drums of the kymographion or other machines.<sup>51</sup> Wrote one French researcher, “The registering apparatus does nothing but to inscribe undulating lines that fall on our senses; but once it comes to interpreting the traces, the graphic method has no more certitude than direct observation.”<sup>52</sup>

Things now have changed. While the curves of Marey look suspiciously like those Fitbit app or Apple Health app curves on your smartphone, there are major differences. Direct observation replaced by automated algorithms and rows of network servers that store the statistical analysis of the world’s sense data have become our new sensory physiologists. Now sensing machines capture, read, and analyze signals produced by human bodies—blood pressure, glucose, breathing, nerves—with even less recourse to human observers. Precise electronics, digital signal processing, statistical models, and the automation of computation are erroneously believed to have eliminated the imprecision of both the senses and mechanical



instruments. If the data is imprecise, the algorithm can always be tweaked. The same goes for such technologies when they are revealed to actually exhibit cultural, gender, or racial bias. The technological solution is to identify the problem and quickly fix it, rather than recognizing the fundamental flaw in design assumptions in the first place.<sup>53</sup>

The experimental researchers of the end of the nineteenth century who sat with pen, paper, and instrument, ready to measure reaction to stimuli, have instead moved away from the scientific lab where they originally sought new knowledge about the human senses through sensors and into the reality labs of Facebook or Apple's secret "exercise lab."

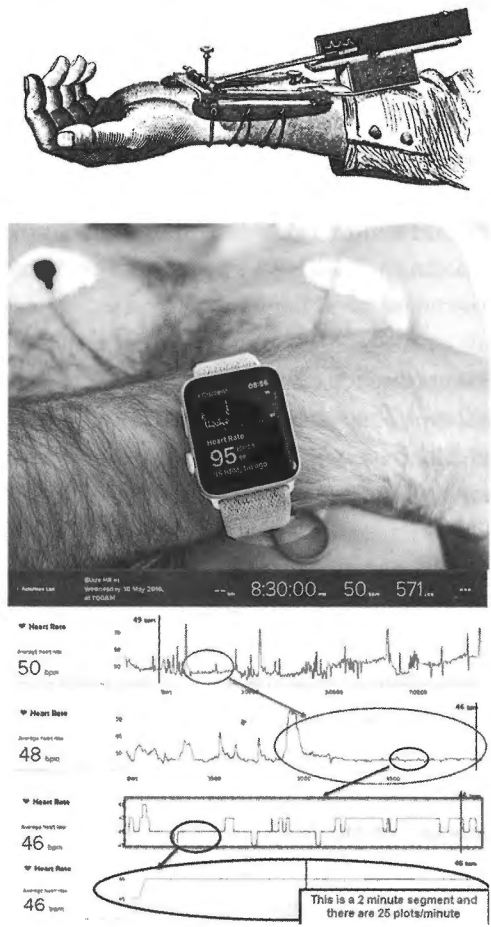
Apple's lab would most likely be the envy of Wundt and his younger disciples. This secret facility in a bland Cupertino, California, building employs not only thirteen exercise physiologists and twenty-nine nurses and medics but also an army of machines to log tens of thousands of hours of subjects' physiological data as benchmarks to test the sensor-embedded products of the world's most valuable corporation. Apple is proud of its instruments. According to the lab's director, it has "collected more data on activity and exercise than any other human performance study in history."<sup>54</sup>

Comparing the emergence of sensing machines in the nineteenth century with today therefore reveals both a historical continuity and a radical break. In the 2020s, every individual who dons a fitness tracker, smart watch, biometric shirt, or wearable sensor engages in a process of transformation: turning oneself into a self-monitoring test subject without the intervention of the human psychologist or physiologist.

The myriad of sensing-measuring gadgets we now take for granted were still laboratory-bound in the nineteenth century. Instruments that logged physiological signals didn't leave the sites of experimental science for the gym or the office as they do now; they were instead parts of larger scientific apparatuses.<sup>55</sup>

Moreover, there is a fundamentally different understanding of the human in relationship to our technologies of digitization. In fact, even if human bodies then were at the whim of instruments that abstracted their senses into graphically plotted signals with nineteenth-century tools, there was still a connection between the person that produced the data and the resulting numbers. One could glance at the squiggly marks on the soot-covered surface of a drum after an experiment and claim, "that is me."

But the computational automation of mathematics and statistics has changed this. The way we understand the temporal role of sensing now is radically different. With the kymographion and sphygmograph (blood pressure) instruments, time was recorded graphically at different scales on the physical surface of a rotating drum or on a paper surface (figure 1.7, top), by manually speeding up or slowing down the mechanical instrument. The visualized curves generated by Fitbits and Apple Watches are different. They are the by-products of statistical processes: the size of a window through



**Figure 1.7**  
*Top:* Marey sphygmograph (circa 1885). *Middle:* Self-monitoring. *Bottom:* Different heart rate signals on a smartphone dashboard.

which you see only part of a longer and continuous signal,<sup>56</sup> or derived from statistical techniques (figure 1.7, bottom). In other words, the curves that are output represent an already computationally processed artificial time.

Like the big data world they are part of, in which meaning is dependent on the right mathematics to find patterns and meaning in a sea of randomness, our new psychophysicians and physiologists also believe that the truth of the senses can be found in the numbers—in statistical techniques that measure and predict the future based on the past.<sup>57</sup>

At first glance, when you click on the Fitbit dashboard, you can believe that world of colorful data represents the whole of you. The glowing curves on the smartphone or computer monitor seem to display *your* benchmarks; they reveal the shape of *your* heartbeat; they visualize *your* overall “performance” doing mundane workaday things like walking to the bus. But what is really output is only a fraction of ourselves. “We” are both before and after what we see in the graph on the screen. We might thus start asking *when are we versus who are we*.

The sophistication of sensing devices to govern our senses has radically shifted as well. As we will see, the instruments of Wundt’s laboratory would undergo their own revolution. Through sophisticated changes in electronics and computation, they eventually would become attached to and interdependent with the bodies they would be measuring and, ironically, at the same time, divorced completely from them (figure 1.7, middle). And yet, this is not all. The technologies of sensing developed in the nineteenth century have a similarity to those sensors we wear on our bodies today: they also ignored the fact that bodies are different. The possibilities of the wearable sensor revolution are endless, but they both recall and radically revise and still render invisible those human subjects who produce new sensory knowledge, whether in the psychology laboratories of the nineteenth century or the cubicles of Facebook research in 2022.

Perhaps most importantly, the context and purpose of sensory measurement itself has radically transformed since Fechner announced his psychophysics. The physiologists and psychophysicists of the past, who turned to instruments to technologize themselves and their test subjects, now go an extra step. They now automate the 172-year-old scientific technique called *psychophysics* to *design* the next generation of perception machines. With today’s sensing machines in our clothing, cars, houses, games, stores,

theaters, and galleries, measurement thus goes hand in hand with design and creation. The need to probe the human senses with instruments and machines is not only about gaining knowledge about how these senses work; it is applying that knowledge to designing and perfecting systems that produce and anticipate new connections between our perception and those instruments and machines, where both expand each other.

In contrast to that which came before, our new sensing machines more accurately capture and analyze the microtime and microspace of our breath, heartbeat, brainwaves, muscle tension, or reaction times. But they do this for another reason. Our sensing machines now conceive and create techniques that aim to fulfill that long sought-after dream of those forgotten nineteenth-century researchers like Fechner and Marey: to become one with what Fechner called the *animated substance* of the technological world itself.