Endure (Hutchinson, Alex)

Joyner emphasized—it was a challenge to his fellow scientists. In some ways, his calculation was the apotheosis of a century's worth of attempts to quantify the outer limits of human endurance. This is how fast a human can run, the equations said. So what explained the chasm between theory and reality? Was it simply a question of waiting for the perfect runner to be born or the perfect race to be run—or was something missing from our understanding of endurance?

You can hit the wall with a heart rate well below max, modest lactate levels, and muscles that still twitch on demand.

Even in repeated all-out weightlifting efforts—brief five-second pulls that you'd think would be a pure measure of muscular force—studies have found that we can't avoid pacing ourselves: your "maximum" force depends on how many reps you think you have left.

Similar larger-than-life (that is, utterly fictitious) claims are a staple in motivational seminars and across the Web: once Bannister showed the way, others suddenly brushed away their mental barriers and unlocked their true potential.

For one thing, Landy was the only other person to join the sub-four club within a year of Bannister's run, and just four others followed the next year. It wasn't until 1979, more than twenty years later, that Spanish star José Luis González became the three hundredth man to break the barrier.11

And the surprising results of their research suggest to me that, when it comes to pushing our limits, we're just getting started.

But this approach still has flaws. Most important, it depends on how motivated you are to push to your limits. It also depends on how well you slept last night, what you ate before the test, how comfortable your shoes are, and any number of other possible distractions and incentives.

It’s a test of your performance on that given day, not of your ultimate capacity to perform.

You can strip away some of this variability by using a time-to-exhaustion test instead: How long can you run with the treadmill set at a certain speed? Or how long can you keep generating a certain power output on a stationary bike? And that is, in fact, how many research studies on endurance are now conducted.

(Modern scientists call it maximal oxygen uptake, since it’s a measure of how much oxygen your muscles actually use rather than how much you breathe in.)

Crucially, they could still accelerate to faster speeds; however, their oxygen intake no longer followed. This plateau is your VO2max, a pure and objective measure of endurance capacity that is, in theory, independent of motivation, weather, phase of the moon, or any other possible excuse. Hill surmised that VO2max reflected the ultimate limits of the heart and circulatory system—a measurable constant that seemed to reveal the size of the “engine” an athlete was blessed with.

With this advance, Hill now had the means to calculate the theoretical maximum performance of any runner at any distance. At low speeds, the effort is primarily aerobic (meaning “with oxygen”), since oxygen is required for the most efficient conversion of stored food energy into a form your muscles can use. Your VO2max reflects your aerobic limits. At higher speeds, your legs demand energy at a rate that aerobic processes can’t match, so you have to draw on fast-burning anaerobic (“without oxygen”) energy sources.

The problem, as Hopkins and Fletcher had shown in 1907, is that muscles contracting without oxygen generate lactic acid. Your muscles’ ability to tolerate high levels of lactic acid—what we would now call anaerobic capacity—is the other key determinant of endurance, Hill concluded, particularly in events lasting less than about ten minutes.

After the race, the student convinced Joyner to volunteer as a guinea pig in one of the lab’s ongoing experiments, a classic study that ended up demonstrating that lactate threshold, the fastest speed you can maintain without triggering a dramatic rise in blood lactate levels, is a remarkably accurate predictor of marathon time.

And every machine, no matter how great, has a maximum capacity.

Worsley, in trying to cross Antarctica on his own, had embarked on a mission that exceeded his body’s capacity, and no amount of mental strength and tenacity could change that calculation. But if that’s true, then why is death by endurance so rare?

That’s the riddle a young South African doctor named Tim Noakes posed to himself as he was preparing to deliver the most important talk of his life, a prestigious honorary lecture at the annual meeting of the American College of Sports Medicine, in 1996: “I said, now hold on. What is really interesting about exercise is not that people die of, say, heatstroke; or when people are climbing Everest, it’s not that one or two die,” he later recalled. “The fact is, the majority don’t die—and that is much more interesting.”43

To understand her extraordinary endurance, in other words, start with her brain.

The brain’s role in endurance is, perhaps, the single most controversial topic in sports science.

In that view, the body sets the limits, and the brain dictates how close you get to those boundaries.

But starting in the late 1990s, a South African physician and scientist named Tim Noakes began to argue that this picture is insufficiently radical—that it’s actually the brain alone that sets and enforces the seemingly physical limits we encounter during prolonged exercise. The claim has profound and surprising implications, and the extent to which it’s true or false remains one of the most volatile flashpoints in exercise physiology, two decades later.

Whatever our limits are, something must prevent us from exceeding them by too much. And that something, he reasoned, must be the brain.

“The one guarantee in an event like this is the pain,” Cox told me, all too prophetically, when we met for coffee the day before the race. “You have to welcome it—say ‘Here you are, my friend.’”

In his keynote lecture at the 1996 ACSM conference, Noakes had argued that A. V. Hill's concept of VO2max was fundamentally flawed: that physical exhaustion isn't a consequence of the heart's inability to pump enough oxygen to the muscles. Otherwise, he reasoned, the heart itself, and perhaps the brain, would also be starved of oxygen, with catastrophic results.

But if Hill's ideas about oxygen were wrong, what was the alternative? Noakes felt the brain had to be involved, and in a 1998 paper he coined the term "central governor," borrowing terminology that A. V. Hill himself had used seventy years earlier.15 But the details remained unclear.

Long before Noakes, researchers had theorized that the brain might sense distress signals from elsewhere in the body and shut things down when the warnings exceeded a critical level. Exercise in the heat is a classic example: if you run to exhaustion on a treadmill in a hot room, your brain will stop driving your muscles when your core temperature hits a critical threshold of about 104 degrees Fahrenheit. But Noakes takes this idea a step further, arguing that in real-world situations like running a 10K on a hot day, the brain gets involved long before you reach that critical temperature.18 You don't hit 104 and keel over; you slow down and run at a pace that keeps you below 104.

In experiments led by Noakes's student Ross Tucker, cyclists started at a slower pace right from the outset when the temperature was high—and crucially, the amount of muscle recruited by the brain was also lower within the first few minutes. At a conscious level, the cyclists were trying just as hard (as their reported level of effort indicated), but fewer muscle fibers in their legs were contracting thanks to their central governor's inbuilt caution.

But when I asked Noakes for the single most convincing piece of evidence in favor of his theory, he said, without hesitation, "the end spurt." How could the runners at Comrades, after pushing themselves through 56 miles of hell, summon a finishing sprint to beat the 12-hour limit?

Conventional physiology suggests that you get progressively more fatigued over the course of a run, as muscle fibers fail and fuel stores are emptied. But then, when the end is in sight, you speed up. Clearly your muscles were capable of going faster in the preceding miles; so why didn’t they? “That shows that our understanding of fatigue is totally wrong,” Noakes said. It must be the brain that holds you back during long efforts, and then releases the final reserves when you’re nearly finished and the danger is past.

The moment of truth: I knuckled down and vowed to run the fourth kilometer as hard as I could—but little by little, I drifted back from the pack I was running with. My next split was a disappointing 2:53. That was as fast as I could move my legs, and my pace slowed even more as I entered the final kilometer. I’d bitten off more than I could chew and was paying the price. At

At most track races, officials mark the start of your final 400-meter lap by ringing a cowbell in your ear. It’s a handy Pavlovian cue that tells you that your suffering is almost over. And on that night on the Stanford track, I once again felt

At most track races, officials mark the start of your final 400-meter lap by ringing a cowbell in your ear. It’s a handy Pavlovian cue that tells you that your suffering is almost over.

As it turns out, it’s not just me. Noakes showed me a study that he, Tucker, and Michael Lambert had published in 2006, analyzing the pacing patterns of almost every world record set in the modern era in the men’s 800 meter, mile, 5,000, and 10,000 meter races.24 For the three longer races, the pattern was startlingly consistent: after a quick start, the record breakers would settle into a steady pace until the final stages of the race. Then, even though they were running faster than they’d ever run before, and their oxygen-starved muscles were presumably awash in a sea of fatigue-inducing metabolites, they accelerated.

Of the 66 world records in the 5,000 and 10,000 meters dating back to the early 1920s, the last kilometer was either the fastest of the race or the second fastest (behind the opening kilometer) in all but one.

Not everyone buys Noakes’s argument that pacing patterns like the end spurt reveal the workings of a central governor. For example, it could be that you speed up at the end of a race because you finally tap into your precious but limited reserves of anaerobic energy, the high-octane fuel source that powers you in short races lasting less than a minute.

But there are other hints that the finishing kick isn't just physiological. In 2014, a group of economists from the University of Southern California; the University of California, Berkeley; and the University of Chicago mined a massive dataset containing the finish times of more than nine million marathoners from races around the world spanning four decades.27 The distribution of finishing times looks a bit like the classic bell-shaped curve, but with a set of spikes superimposed. Around every significant time barrier—three hours, four hours, five hours—there are far more finishers than you'd expect just below the barrier, and fewer than you'd expect just above. Similar but smaller spikes show up at half-hour intervals, and there are barely perceptible ripples even at ten-minute increments.

The cruel metabolic demands of the marathon, which inevitably depletes your stores of readily available fuel, mean that most people are slowing in the final miles. But with the right incentive, some are able to speed up—and it's only the brain that can respond to abstract incentives like breaking four hours for an arbitrary distance like 26.2 miles.

A further curious detail from this dataset: the faster the runners were, the less likely they were able to summon a finishing sprint. Of the runners finishing near the three-hour barrier, about 30 percent were able to speed up in the final 1.4 miles of the race; 35 percent of those trying to break four hours sped up; and more than 40 percent of those trying to break five hours managed it. One possible interpretation is that, over the course of their long hours of training, the more committed runners had gradually readjusted the settings on their central governors, learning to leave as little as possible in reserve.

Over the next few years, he formulated a new "psychobiological" model of endurance, integrating exercise physiology, motivational psychology, and cognitive neuroscience. In his view, the decision to speed up, slow down, or quit is always voluntary, not forced on you by the failure of your muscles. Fatigue, in other words, ultimately resides in the brain—an insight as relevant to motorcyclists as to marathoners.

Marcora had made his first big splash two years earlier, not just among researchers but among the New York Times–reading public, with a provocative study of mental fatigue. He'd asked sixteen volunteers to complete a pair of time-to-exhaustion tests on a stationary bike. Before one of the tests, the subjects spent 90 minutes performing a mentally fatiguing computer task that involved watching a series of letters flash on a screen, and clicking different buttons as quickly as possible depending on which letters appeared. It's not a particularly difficult task, but it requires sustained focus—and doing it for 90 minutes is definitely draining. Before the other cycling test, the subjects spent the same 90 minutes watching a pair of bland documentaries ("World Class Trains—The Venice Simplon Orient Express" and "The History of Ferrari—The Definitive Story"), specifically chosen to be "emotionally neutral."3 Depending on how you look at it, the results were either utterly predictable or, from the perspective of textbook physiology,

Depending on how you look at it, the results were either utterly predictable or, from the perspective of textbook physiology, inexplicable. After the mentally draining computer game, the subjects gave up 15.1 percent sooner in the cycling test, stopping on average at 10 minutes and 40 seconds compared to 12 minutes and 34 seconds. It wasn't because of any detectable physiological fatigue: heart rate, blood pressure, oxygen consumption, lactate levels, and a host of other metabolic measurements were identical during the two trials. Motivation levels, as measured by psychological questionnaires immediately before the cycling tests, were the same—helped along by a £50 prize for top performance. The only difference was that, right from the very first pedal stroke, the mentally fatigued subjects reported higher levels of perceived exertion. When their brains were tired, pedaling a bike simply felt harder.

Though there are many variations, Borg's original scale ran from 6 ("no effort at all") to a maximum of 20 (the penultimate value, 19, was defined as "very, very hard"), with the numbers corresponding very roughly to your expected heart rate divided by ten. A Borg score of 13 to 14, for example, corresponds to an effort you'd call "somewhat hard," which would produce a heart rate of 130 to 140 beats per minute in most people.

"In my opinion," he wrote, "perceived exertion is the single best indicator of the degree of physical strain," since it integrates information from muscles and joints, the cardiovascular and respiratory systems, and the central nervous system.

In his talk at the conference in Bathurst, Marcora took this argument a step further. Perceived exertion—what we'll refer to in this book as your sense of effort—isn't just a proxy for what's going on in the rest of your body, he argued. It's the final arbiter, the only thing that matters. If the effort feels easy, you can go faster; if it feels too hard, you stop.

Cabanac asked volunteers to sit bent-legged against a wall with no chair for as long as they could, offering varying rewards for each 20-second period they stayed in position. When the subjects were offered 0.2 francs per 20 seconds, their quads gave out after just over two minutes, on average; when they were offered 7.8 francs per 20 seconds, their endurance magically doubled.5 If the moment of collapse was dictated by a failure of the muscles, how did the muscles know about the richer payoff?

The simple alternative, Marcora argued, is that anything that moves the "effort dial" in your head up or down affects how far or fast you can run. All the usual physical cues—dehydration, tired muscles, a pounding heart—contribute to how hard an effort feels. Athletes train their bodies to adapt to those cues, and over time the effort of running at a given pace gets lower. But less obvious factors, like mental fatigue, also contribute to how hard your run feels—and trying to hold marathon pace for hours and hours, for example, is pretty taxing on the brain.

This, Marcora told the conference, leads to a radical idea: If you could train the brain to become more accustomed to mental fatigue, then—just like the body—it would adapt and the task of staying on pace would feel easier.

But if something can fatigue you, and you repeat it over time systematically, you'll adapt and get better at the task. That's the basis of physical training. So my reasoning is simple: We should be able to get the same effect by using mental fatigue."

After all, the perception of effort—the master controller of endurance, in Marcora's view—is a fundamentally psychological construct.

University of Mannheim and the University of Illinois asked volunteers to hold a pen either in their teeth, like a dog with a bone, which required activating some of the same muscles involved in smiling; or in their lips, as if they were sucking on a straw, which activated frowning muscles. Then they were asked to rate how funny a series of Far Side cartoons were. Sure enough, the subjects rated the cartoons as funnier, by about one point on a 10-point scale, when they were (sort of) smiling.12 This illustrates what's known as the “facial feedback” hypothesis, an idea that can be traced back to Charles Darwin: just as emotions trigger a physical response, that physical response can amplify or perhaps even create the corresponding emotion. Related experiments have extended this finding to clusters of related mental states: smiling, for instance, makes you happier, but it also enhances feelings of safety and—intriguingly—cognitive ease, a concept intimately tied to effort.

Does that also apply to the effort of exercise? Marcora used EMG electrodes to record the activity of facial muscles while subjects lifted leg weights or cycled, and found a strong link between reported effort and the activation of frowning muscles during heavy exercise.

As the cyclists pedaled, a screen in front of them periodically flashed images of happy or sad faces in imperceptible 16-millisecond bursts, ten to twenty times shorter than a typical blink. The cyclists who were shown sad faces rode, on average, for just over 22 minutes.16 Those who were shown happy faces rode for three minutes longer and reported a lower sense of effort at corresponding time points. Seeing a smiling face, even subliminally, evokes feelings of ease that bleed into your perception of how hard you're working at other tasks, like pedaling a bike.

Just like a smile or frown, the words in your head have the power to influence the very feelings they're supposed to reflect.

To Marcora, the most convincing explanation relates to caffeine's ability to shut down receptors in the brain that detect the presence of adenosine, a “neuromodulator” molecule associated with mental fatigue. Warding off mental fatigue, in turn, keeps your sense of effort lower, allowing you to exert yourself harder and longer.

Such findings reinforce the idea that, all else being equal, the gold medal goes to whoever is willing to suffer a bit more than everyone else. Freund isn't the only one to find that well-trained athletes can tolerate more pain; others have shown that regular physical training, especially if it involves unpleasant high-intensity workouts, increases your pain tolerance. But the link between what's happening in your muscles and what you feel in your head turns out to be much more indirect than you might assume.

While the truth undoubtedly lies somewhere between those two options, a curious footnote in Gijsbers's results points toward the former. He retested the elite swimmers at three different times of year and found that they scored highest on the pain tolerance test in June, during their peak racing season; lowest in October, after their off-season; and somewhere in the middle during their regular training period in March.

These seasonal fluctuations suggest that pain tolerance is linked to the type of training you're doing—and that's exactly what researchers Martyn Morris and Thomas O'Leary, of Oxford Brookes University in Britain, confirmed in a 2017 study. They used the same pain protocol as Gijsbers—fist-clenching with no circulation to the arm—before, during, and after a six-week training period during which volunteers did either medium-intensity continuous cycling or high-intensity interval workouts. The training programs were matched to require roughly the same amount of work, and both groups increased their fitness, as measured by VO2max and lactate threshold, by the same amount.10

This is a profound finding: pain in training leads to greater tourniquet tolerance, and greater tourniquet tolerance predicts better race performance. Many athletes, of course, make this link intuitively.

While there are still plenty of gaps in the research, it does appear that top athletes really push themselves to a darker place, and stay there longer, than most people are willing to tolerate.

The experiments that Alexis Mauger and Samuele Marcora have done trying to untangle the difference between "pain" and "effort" make me think that pain, in most contexts, is a warning light on the dashboard. It instructs you (sometimes very insistently) to slow down, and in most contexts you heed that warning without even realizing you're doing it.

Their conclusion was that “the end point of any performance is never an absolute fixed point but rather is when the sum of all negative factors such as fatigue and muscle pain are felt more strongly than the positive factors of motivation and will power.”

In practice, though, expectations mattered. Within a few reps, those who thought they were only doing 6 were producing slightly more force than the 12-rep control group; and those with no information about how long they would be expected to continue were producing less force than the other groups. Not surprisingly, the average force declined with each succeeding rep—until the last one (and the sixth one, in the deceived group), when they were able to summon a “finishing kick” to exert more force. The pattern, overall, looked a lot like the U-shaped pattern observed in distance-running world records (see Chapter

Even in short, supposedly all-out maximal contractions, when we’re explicitly told to hold nothing in reserve, we pace ourselves—a finding that helps explain why Ikai and Steinhaus were seemingly able to tap into hidden reserves of strength, but doesn’t explain how a human can lift a car.

Zatsiorsky reported that most of us can summon about 65 percent of our theoretical maximum strength. Elite weightlifters can do better, hefting more than 80 percent of their maximum in workouts—and with the psychological boost of a big competition, they can lift, according to one of Zatsiorsky’s studies, an additional 12.5 percent compared to their training best.9 Plug these numbers in and you find that Magee, with the fear of God buzzing in his circuits, might have been able to hoist another one or two hundred pounds of cheese—but still less than half a Camaro.

Guillaume Millet, a French researcher who heads the University of Calgary’s Neuromuscular Fatigue Lab, says Zatsiorsky’s numbers are “absolutely crazy.” When I contacted Zatsiorsky in 2016, he was eighty-three years old, long retired from Penn State, but still very active as a researcher—he was listed as coauthor of no less than seven academic journal articles dealing with the subtleties of motor control that were published between January and September of that year. But he couldn’t fill in any details about his much-quoted maximum strength numbers.

The supposed reserve of muscular strength, in other words, was an illusion—a result, Merton concluded, that flew in the face of the then-widespread belief that “lunatics, persons suffering from tetanus or convulsions or under hypnosis, and those drowning are exceptionally powerful.”

In Mark Burnley’s lab, at the University of Kent, typical scores for all-out quadriceps contractions are 92 to 97 percent, and anything less than 90 percent suggests something has gone wrong with the test. Under normal conditions, in other words, we’re utilizing pretty much all the strength our muscles have to offer.

The basic measure of fatigue Guillaume Millet uses in his studies is simple: how much does the biggest force you can produce with a given muscle decline? Not surprisingly, he has found that the force produced by two key muscle groups in the legs, the quadriceps and the calves, gets progressively weaker as the distance of a running race increases—up to a point. By the time you’ve been out there for about 24 hours, your leg muscles will be 35 to 40 percent weaker, and they won’t lose much more. In fact, his Tor des Géants subjects, who took more than 100 hours, on average, to complete the race, ended up losing just 25 percent of their pre-race leg strength—a result that, on the surface, makes little sense. “Okay,” Millet jokes, “so if I run 200 miles, I’m less fatigued than if I run 100 miles!”

For ultra-endurance runs, it turns out, the muscles themselves typically only lose about 10 percent of their force-producing capacity; the rest is central, reflecting a progressive decline in the brain’s voluntary activation of muscle. “The brain is able to do more, but it doesn’t,” Millet says. But, he adds,

For ultra-endurance runs, it turns out, the muscles themselves typically only lose about 10 percent of their force-producing capacity; the rest is central, reflecting a progressive decline in the brain’s voluntary activation of muscle.

Even though voluntary activation is, by definition, a reduction in the command signal from your brain, it appears to respond to what’s happening in your muscles. We have special nerve fibers that send information from the muscles to the brain about pressure, heat, damage, metabolic disturbances, and any number of other data points, and we integrate this information in our actions without even realizing it. Trying to make a clean divide between “brain fatigue” and “muscle fatigue,” in other words, is inevitably an oversimplification, because they’re inseparably linked.

So where is the crossover between short, muscle-limited acts of strength and prolonged tests of will?

Brooks and others have shown that lactate plays a complex role in muscles, serving as a crucial source of emergency fuel during intense exercise. Top athletes, far from being immune to lactate, are actually able to recycle it into fuel more efficiently than lesser athletes. Moreover, if lactate was really the problem, you’d be able to reproduce the sensation of rigging by injecting lactate into your muscles—but, as it turns out, it’s not that simple.

The reason we have such elaborate defense mechanisms against running out of oxygen is that the consequences are so dire.

One intriguing explanation for the limiting role of oxygen comes from research on “cerebral oxygenation”—the life-sustaining flow of blood to the brain.41 When you start exercising, the brain’s oxygen levels initially rise, feeding the increased neuronal activity involved in sending instructions to muscles and monitoring effort. Then levels settle into a steady plateau—until you approach your limits. As you breathe more and more heavily, the carbon dioxide levels in your blood fall, which in turn makes the blood vessels leading to your brain constrict. (The same thing happens when you deliberately hyperventilate, causing you to get dizzy and eventually black out.) The resulting shortage of oxygen in the brain might directly interfere with muscle recruitment, or it might contribute to the sensation of fatigue signaling you to slow down or stop.

These subjects were truly world-class, with half-marathon bests of 62 minutes on average—and during their 5K trial, levels of oxygen in their brains stayed roughly constant right to the end. While it’s hard to draw definitive conclusions from two small studies, the researchers suggested that being born at altitude and having very active childhoods ensured that the Kenyans were better equipped to maintain the brain’s oxygen supply: they had more blood vessels to the brain, with thicker walls that were harder to squeeze shut.

You also begin to sweat: the transformation of liquid water to vapor as sweat evaporates consumes energy, creating a powerful cooling effect on the skin. In very hot conditions, when the air temperature is comparable to or higher than your skin temperature, evaporation is the only effective cooling method you've got. And if it's so humid that sweat starts dripping off you instead of evaporating, the clock is ticking as your core temperature starts to inch upward.

When you exercise repeatedly in hot conditions, your body's protective responses get progressively better: you sweat more heavily, starting at a lower temperature; your vessels dilate even wider to deliver heat-laden blood to the skin; and the total volume of blood in your body increases, allowing your heart rate to stay lower during exercise.

This acclimatization process takes about two weeks, which is why organizations like the National Athletic Trainers' Association recommend limiting intensity and the use of full equipment during the first fourteen days of football practice each summer.

Simply living through a hot summer isn't enough; you have to stress your system with exercise.

As expected, the riders lasted longest when they were precooled, more than doubling their performance compared to the preheated condition. But despite the large differences between trials, the cyclists' core temperatures at exhaustion were strikingly consistent. In nearly every ride by every rider, the thermometer read between 104.0 and 104.5 degrees at the moment of failure.16 It was as if, in crossing that critical threshold, a temperature-sensitive circuit-breaker had been tripped.

By drinking the slushies, researchers speculated, the athletes might have also cooled their brains as the ice passed through their mouth and throat.

Jay, who has since moved to the University of Sydney, notes that this may help explain the long-standing tradition in some cultures of drinking a hot drink like tea during scorching summer afternoons. By triggering the temperature receptors in your stomach, the hot drink ramps up your sweating response without heating the rest of your body, which has the net effect of cooling you down.

So is it brain temperature or stomach temperature that matters most? It's probably a bit of both—along with temperature signals from other parts of the body, like the skin. There's a reason athletes don ice-filled vests and cooling sleeves and drape ice towels over their necks: these interventions don't alter your core temperature, but they do influence how hot you feel—and that, in turn, dictates how hard you're able to push. Further evidence that perception is reality:

a British study in 2012 showed that cyclists in a heat chamber went 4 percent faster when the thermometer was rigged to display a falsely low temperature (79 instead of 89 degrees Fahrenheit).

In a military-funded experiment, he showed that fit, well-trained athletes could push to a higher core temperature during a treadmill test than less fit subjects—evidence that the brain's temperature settings can indeed be altered.

Cheung's most recent work provides even more remarkable evidence of the brain's power. He and his colleagues put a group of eighteen trained cyclists through a battery of physical and cognitive tests at 95 degrees Fahrenheit. Then half the cyclists received two weeks of training in "motivational self-talk" specifically tailored to exercising in heat, which basically involved suppressing negative thoughts like "It's so hot in here" or "I'm boiling," and replacing them with motivational statements like "Keep pushing, you're doing well." The self-talk group improved their performance on one of the endurance tests from 8 minutes to 11 minutes—and in doing so, pushed their core temperatures at exhaustion more than half a degree higher. "We're now pretty sure it's not just a physical thing," Cheung says of the critical temperature concept. "There seems to be a strong mental-psychological component to it."

The right frame of mind, in other words, allows you to push beyond your usual temperature limits: "Even if you're already fit, you can still improve your perception of heat and how you perform in it."

When you fail to replace lost fluids, you start craving a drink, and your kidneys begin reabsorbing fluid that would otherwise become urine. If that's not enough to restore your internal balance, fluid will start draining out of your cells and into your veins and arteries to maintain the necessary volume of blood pumping through your body.

These adjustments will buy you some time, but eventually your blood will get so concentrated that your brain will start shrinking as fluid is sucked out by osmosis, tearing delicate cerebral veins and ultimately killing you.

At any rate, Valencia clearly stretched the limits of human dehydration well beyond their usual breaking point. And his case offers one additional twist. After a week with no water in furnace-like heat, covering more than a hundred miles on foot, he was very, very thirsty—but he didn’t get heatstroke.

No topic of advice in modern sports science has provoked more whiplash than hydration.

In Falmouth, where he undoubtedly ran himself into heatstroke, the race was only 7 miles long—barely more than half an hour—and he was already in trouble shortly after the halfway mark. Salazar was a prodigious sweater (later lab tests showed he could squeeze out an unusually high three liters of sweat per hour), but it’s still impossible to get dangerously dehydrated in twenty minutes.17 Even if he’d been careless about drinking and started the race mildly dehydrated, the math of how much fluid he would have to lose in such a short time simply doesn’t add up.

In contrast, he was clearly dehydrated after the Duel in the Sun, and for good reason: he had been pushing himself for more than two hours. The six liters of IV fluid he received suggests he might have lost more than thirteen pounds of sweat during the race. And yet, despite the sun and the excessive dehydration, he didn’t suffer from heatstroke. Quite the opposite, in fact: in the medical tent immediately after the race, his body temperature was measured as 88 degrees, 10 degrees below normal.18 This measurement, which was recorded with an oral thermometer, stirred up a tempest among sports medicine doctors after the race.

Since it wasn’t a core temperature measured in the rectum or ear, skeptics maintained that Salazar wasn’t really hypothermic. Instead, they argued, severe dehydration and the associated reduction in blood volume had compromised his body’s ability to regulate temperature.

19 Without a time machine (and a rectal probe), it’s impossible to settle the debate one way or the other—but we can rule out heatstroke. This

19 Without a time machine (and a rectal probe), it’s impossible to settle the debate one way or the other—but we can rule out heatstroke. This seemingly contradictory pattern—heatstroke without dehydration, dehydration without heatstroke—is no fluke, it turns out. Dehydration is a greater concern in longer races, because you have more time to sweat; heatstroke, in contrast, is most common in shorter races. That’s because your body temperature is primarily determined by your “metabolic rate”—that is, how hot your engine is running. In a thirty-minute race, you can sustain a fast enough pace to drive your core temperature way up, even though you don’t have time to get seriously dehydrated.

In a three-hour race, in most circumstances, you simply can’t sustain a hard enough effort to push your temperature into heatstroke territory, even though you might get seriously dehydrated.

But the biggest factor dictating core temperature (aside from the weather conditions) is metabolic rate.

At marathons, triathlons, and cycling races around the world, researchers have tried a simple test: weigh athletes before and after the race, and look for a relationship between race finish and degree of dehydration. The results are consistently the opposite of what you would expect: the fastest finishers tend to be the most dehydrated. For example, among 643 finishers in the 2009 Mont Saint-Michel Marathon in France, sub-three-hour finishers averaged a loss of 3.1 percent of their starting weight; finishers between three and four hours averaged 2.5 percent; and those clocking more than four hours were the only ones to obey the 2 percent rule, losing on average 1.8 percent.22 The results don’t prove that drinking makes you slower, but they certainly raise further questions about the claim that any loss greater than 2 percent slows you down. As for the relatively common sight of athletes needing assistance or even collapsing after the finish of a long race, there are several reasons to be suspicious of the idea that these athletes are paying the price for insufficient hydration.23 One is that studies have found no difference between the typical dehydration levels of collapsed athletes and those who walk away from the finish line untroubled. Another is that an estimated 85 percent of collapses take place shortly after crossing the finish line.

But physiologists have shown that this isn't how thirst works. Instead of monitoring fluid levels, your body monitors "plasma osmolality," which is the concentration of small particles like sodium and other electrolytes in your blood.25 As you get dehydrated, your blood gets more concentrated, and your body responds by secreting an antidiuretic hormone that causes your kidneys to start reabsorbing water, and by making you thirsty. Unlike your body's fluid levels, plasma osmolality is very tightly regulated: when you're looking at the right variable, your thirst sensation (along with other homeostatic mechanisms like antidiuretic hormone) doesn't make mistakes.

This means that what looks like a potential problem—voluntary dehydration—may actually be completely normal from the body's perspective.

In a 2011 study, eighteen South African Special Forces soldiers undertook a sixteen-mile march carrying 57-pound packs, including rifles and water supplies, in temperatures that peaked at 112 degrees Fahrenheit.26 The soldiers were permitted to drink as much water as they wanted, but—as expected—they nonetheless lost an average of six pounds, corresponding to 3.8 percent of their starting weight. Their plasma osmolality, in contrast, was essentially unchanged. From the perspective of the body's primary hydration sensor, they were just fine.

By adjusting the amount of salt in our sweat, we're able to keep plasma osmolality stable even as we lose water—for a while, at least.

There's another twist that helps explain how we're able to tolerate seemingly extreme losses of water. In this discussion, we've been assuming that if you lose a pound of weight during exercise, that means you've lost a pound of water. But that's not necessarily the case.

The results showed that for every pound of weight lost, the amount of water circulating in the body dropped by only 0.2 pounds—a dramatic difference

The results showed that for every pound of weight lost, the amount of water circulating in the body dropped by only 0.2 pounds—a dramatic difference that helps explain why the soldiers didn't feel the need to drink more.

Part of the explanation, according to University of Cape Town researcher Nicholas Tam, is that not all the weight you lose is water. During prolonged exercise, "you will use fat, and you will use carbohydrate," he explains, "and once you've burned it up, it's not there anymore."

British scientists at the University of Loughborough estimated that a marathoner could conceivably lose 1 to 3 percent of his or her body mass without any net loss of water.28 The study with South African soldiers seemed to confirm these estimates, as did a 2011 study by Tam that found no change in total body water content in runners at a half-marathon despite an average weight loss of more than three pounds.

Avoiding thirst, rather than avoiding dehydration, seems to be the most important key to performance.

A 2013 meta-analysis in the British Journal of Sports Medicine concluded than any losses of less than 4 percent are "very unlikely to impair [endurance performance] under real-world exercise conditions," and concluded that athletes should be encouraged to drink according to thirst.31

If you're stuck in an uncomfortable heat chamber and told you'll only be allowed to drink a few thimblefuls of water, your performance will likely suffer whether you're dehydrated or not.

This, in turn, helps to explain why a later study found that swallowing small mouthfuls of water—too small to make any difference to overall hydration levels—boosted exercise performance by 17 percent compared to rinsing the same amount of water in the mouth and then spitting it out.34 When it comes to quenching your thirst, perception—not just in your mouth, but in the cool flow of liquid down a parched throat—is, at least in part, reality.

One final caveat is that our ability to tolerate temporary bouts of dehydration is, well, temporary. Marathoners can handle 10 percent dehydration for a few hours.

But that assumes you're properly hydrated when you arrive at the start line—a factor that is, if anything, even more important than what you drink during exercise, according to Stephen Cheung's research.

To me, the primary message is that, like oxygen and heat and (as we'll discover) fuel, the loss of fluids first makes itself felt via the brain. Thirst, not dehydration, increases your sense of perceived effort and in turn causes you to slow down. Eventually, the physiological consequences of dehydration assert themselves, increasing the strain on your cardiovascular system and pushing your core temperature up as the volume of blood in your arteries decreases.

Empirically speaking, this advice seems to work pretty well. One study found that Kenyan runners, who currently hold 60 of the top 100 men's marathon times in history, typically get 76.5 percent of their calories from carbohydrate, including 23 percent from ugali, a sticky and stomach-filling cornmeal mash, and 20 percent from the copious spoonfuls of sugar they heap into their tea and porridge.13 Another 35 times on the top-100 list are held by Ethiopians; a similar study found that they get 64.3 percent of their calories from carbohydrate, with the biggest contribution from injera, a sourdough flatbread made from a local grain called teff.14 If there's an alternative diet plan that's better for endurance performance, no one has told the best endurance athletes in the world.

In reality, as Volek's data shows, we all use both. And given the complementary strengths and weaknesses of the two options—carbohydrate as a fast fuel with limited storage capability, fat as an inexhaustible but rate-limited alternative, it makes sense to aim for what Louise Burke, of the Australian Institute of Sport, calls "metabolic flexibility," by maximizing both fuel pathways.

Think back to Tim Noakes's observation about the second-place Olympic marathoner jogging around the track waving his country's flag. "Do you notice he's not dead?" he asked. "It means he could have run faster."

Pacing, in Tucker's formulation, is the process of comparing the effort you feel at any given point in a race to the effort you expect at that stage—an internal template that you develop and fine-tune from experience. If the start of a race feels like a 10 out of 20 effort on the Borg scale, and you expect to hit 20 by the end, then halfway through the race the effort should feel like a 15. If, instead, you're at 16 halfway through the race, you'll feel a powerful urge to slow down—even though you're still far from the max of 20.

In this picture, my struggles when I moved up from 1,500-meter to 5,000-meter races (as described in Chapter 3) were the result of an ill-formed pacing template. In the fourth kilometer of each race, when I felt unable to maintain my pace, it was because of a mismatch between anticipated and actual effort, not because I was hitting a physical limit. That's why, in the final laps where I expected effort to be near-maximal, I was suddenly able to speed up again.

There are, to be sure, many questions that remain to be answered about the brain's role in endurance. But on the central question, in my view, Marcora, Tucker, and Noakes are now saying essentially the same thing. Effort is what matters.

The process of training expands the capabilities of the muscles and heart, sure, but it also recalibrates the brain's horizons. As we saw in Chapter 5, trained ultra-runners have a higher pain tolerance than nonathletes, and even over the course of a single year the pain tolerance of athletes waxes and wanes with training cycles. In this sense, all training is brain training, even if it doesn't specifically target the brain.

The result was mPEAK—Mindful Performance Enhancement, Awareness & Knowledge—another eight-week program modeled on Kabat-Zinn's stress-reduction course. This version of mindfulness training puts more emphasis on sport-specific skills like concentration and embracing rather than avoiding pain, and addresses common athlete pitfalls like perfectionism by teaching self-compassion.

Even in training sessions, with nothing but pride on the line, he noticed that Kenyan and Western runners had markedly different mentalities. The Kenyan up-and-comers would simply run with the leaders—often international champions—for as long as possible, then drop out or start jogging when they could no longer keep up. Coolsaet and other foreigners, meanwhile, would maintain a steady but sustainable pace. At one point, he took some friends to watch the famous weekly fartlek workout in the hills around the town of Iten. More than two hundred runners streamed past them, raising a cloud of red dust from the dirt roads; about a third of them had dropped out of the workout before the halfway mark.3 After hearing enough of these stories, I finally started to consider the obvious question. Given how good the Kenyans are, should I be emulating their racing style rather than laughing at

Even in training sessions, with nothing but pride on the line, he noticed that Kenyan and Western runners had markedly different mentalities. The Kenyan up-and-comers would simply run with the leaders—often international champions—for as long as possible, then drop out or start jogging when they could no longer keep up. Coolsaet and other foreigners, meanwhile, would maintain a steady but sustainable pace. At one point, he took some friends to watch the famous weekly fartlek workout in the hills around the town of Iten. More than two hundred runners streamed past them, raising a cloud of red dust from the dirt roads; about a third of them had dropped out of the workout before the halfway mark.3 After hearing enough of these stories, I finally started to consider the obvious question. Given how good the Kenyans are, should I be emulating their racing style rather than laughing at it?

If you execute a perfectly paced race, that means you effectively decided within the first few strides how fast you would complete the full distance. There is no opportunity to surprise yourself with an unexpectedly good day: you've put a ceiling on your potential achievement from the moment the starting gun fires. As a result, this approach may produce better results on average, but it is less likely to produce dramatic outliers: jaw-droppingly fast (or slow) times.

I also lost to some considerably less credentialed runners—another Kenyan named Francis Komu, for example—whose typical performances were pretty similar to my own. The difference in Komu's racing history is that, by racing aggressively, he now and then hit one out of the park, like he did that day in Washington when he beat me by a minute and a half. Instead of a consistent string of pretty good performance, he opted for a few great ones mixed in with some undeniable stinkers—which, when I thought about it, was a pretty good trade.

Even the humblest Kenyan runner, he noticed, wakes up every morning with the firm conviction that today, finally, will be his or her day. They run with the leaders because they think they can beat them, and if harsh reality proves that they can't, they regroup and try again the next day. And that belief, fostered by the longstanding international dominance of generations of Kenyan runners, becomes a self-fulfilling prophecy.

At a conference in 2013, Stellingwerff noted the wide variety of supplements and training methods that have been shown to produce a 1–3 percent boost in performance, from caffeine to beet juice to altitude training. In theory, combining all these approaches should create a superathlete; in practice, studies that combine multiple interventions in elite athletes tend to see overall improvements of . . . 1 to 3 percent. If 1 + 1 + 1 = 1, the implication is that many different "proven" training aids act, at least in part, on the same target: the brain.

Harnessing a belief effect, on the other hand, doesn't involve any trickery; rather, it's "very strategically and slowly developing maximal trust, belief, and evidence with your athletes and coaches over time." In the ideal scenario, he says, you're offering advice with real, evidence-backed physiological benefits, while bearing in mind that "the words you choose, how much info you provide, and how you describe it can all dictate the eventual performance impact of that intervention."

If you ask athletes how sore they feel the day after a workout, ice baths seem to help; if you take blood tests to look for objective signs of reduced muscle damage, not so much.

Consider the purported benefits of a post-workout ice bath, which is supposed to ward off inflammation and hasten muscle recovery.5 Athletes at every level swear by them; researchers, meanwhile, have published hundreds of studies investigating their effects, with results that are ambiguous at best.

This, you might think, debunks the value of ice baths once and for all—except for the fact that the athletes who had either ice or oil really did seem stronger in the two days following the workout.

Chris Beedie, a researcher at Canterbury Christ Church University in Britain who studies placebos in sport, once had a group of cyclists complete a series of ten-kilometer time trials. The subjects were told they would receive various doses of caffeine before each trial, but they wouldn't be told which dose they had received. As expected, the cyclists rode 1.3 percent faster when they thought they had received a moderate dose, 3.1 percent faster after a high dose, and 1.4 percent slower when they thought they got the placebo.10 In reality, all the pills were placebos. The performance boost, and associated changes in how much pain or effort they perceived during the rides, were entirely fueled by their own expectations.

The brain rules the body, Burfoot concluded, which is why his super-workout consisted of five times a mile as hard as possible, followed by your coach telling you to do anot <You have reached the clipping limit for this item>