A Racing Mind

How Time Perception Impacts Athletic Endurance

By Sierra Smith

Take out a stopwatch, hit "start", and immediately close your eyes. Without counting, open your eyes once exactly 20 seconds have passed. What does the watch say? How accurate was your timing? Try this again, this time, for 60 seconds. Were you closer or further away from being correct? How accurate do you think you'd be if you tried this for an hour — 24 hours, even? While this exercise may feel bizarre, there are many ways we replicate this process of internally measuring time throughout the day. From determining exactly how much time is necessary to wash our hands, to anticipating when the red light our car is stopped at will turn green, our ability to conceptualize time guides many of our actions. Can you also think of instances when losing track of time isn't necessarily a bad thing? Watching the clock during a 3 hour college lecture, or even a 30 minute jog, has a unique capacity for wearing someone out. While it is easy enough to train yourself to ignore the clock on the wall during a lengthy activity, what would happen if you were also able to ignore your internal clock? There is one woman who potentially holds the answer to this question: Diane Van Deren.

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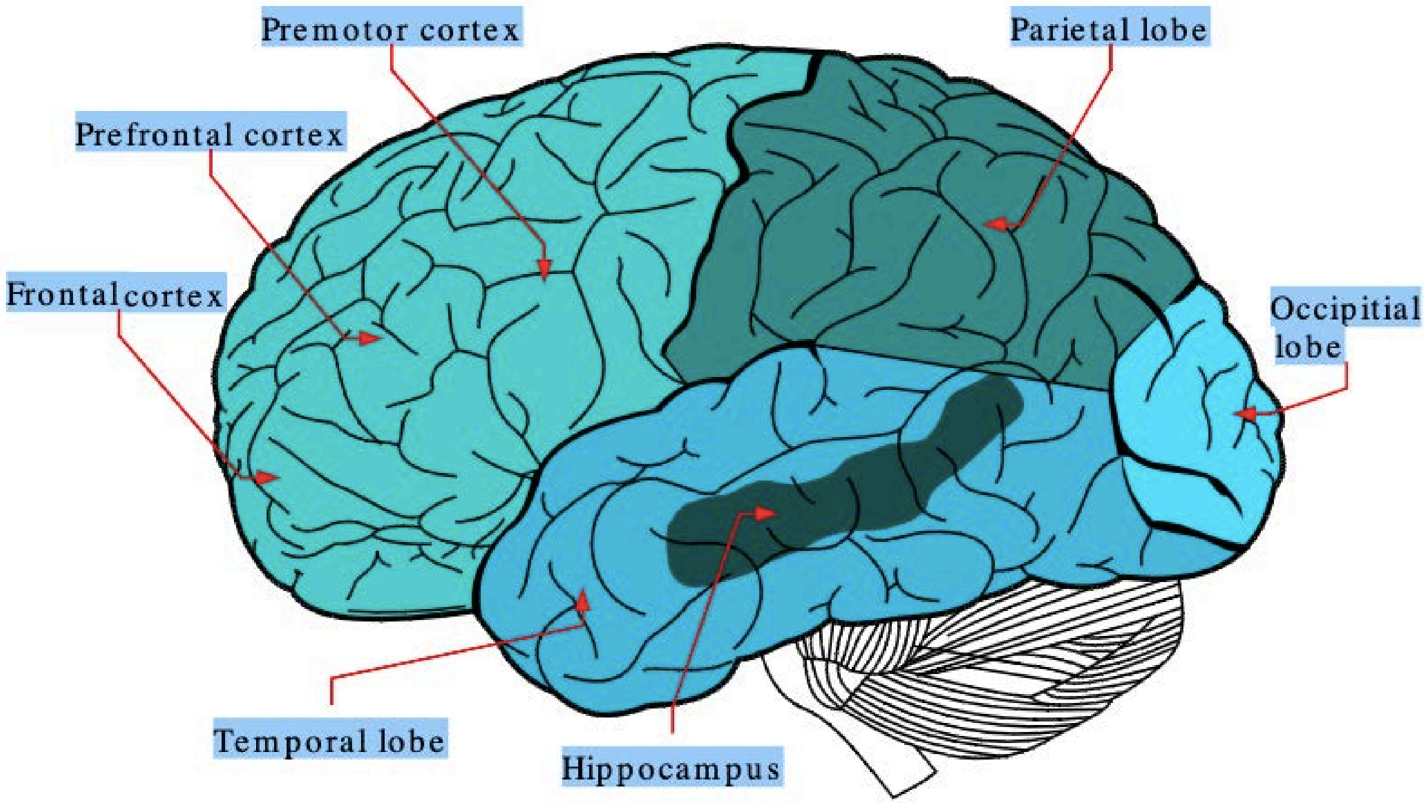
The Ultrarunner

Diane Van Deren, a 61 year-old from Omaha, Nebraska, began her professional athletic career as a tennis player. However, in 2006 at 46 years-old, Diane was the runner-up to Lance Armstrong for outdoor person of the year for ultramarathon running (a race exceeding 26 miles and 385 yards). WNYC studios reporter Mark Phillips highlighted how Diane did not compete in her first ultramarathon until the age of 42, when she entered a 50-mile ultramarathon on a whim, and subsequently won (1). Testing her luck, she entered a second ultramarathon (a 100-mile race through the Bighorn Mountains in Wyoming), and managed to place. Diane was just getting started. A non-exhaustive list of her running victories includes: the Alfred Packer 50 mile race, second place. The Bear 100-miler, first place. The Tahoe Rim 100-mile race, first place. First in "Dances with the Dirt," a 50-mile race in Hell, Michigan. First place in the "24 hours in Frisco" trial run. Upping the ante by adding the challenge of extreme cold to these races, she won first place in the Canadian Death Race, a 78-miler in Edmonton, Canada (1). One of her craziest accomplishments, however, was when she became the first woman to complete the Yukon Arctic Ultra 300 race — a race where she ran 430 miles in -48 degree weather in the Yukon territory while dragging a 50-pound sled behind her. The race lasted about 10 days, with Diane averaging 1 hour of sleep per night, and trekking onward with frozen shoes. What makes someone wake up one day at 42 years old and become an elite endurance athlete? In Diane's case, it involved literally losing her mind — to be precise, the removal of a kiwi-sized portion of her brain (1).

While Diane had always been an athlete, (playing professional tennis, winning a marathon, and competing in other athletic competitions) it was not until she had a brain surgery to remove a portion of her temporal lobe as a treatment for epilepsy that she became an ultra-runner. To first provide some background on Diane's condition: at 28-years old she experienced her first seizure. In an interview with WNYC studios, Diane describes feeling a peculiar sensation, blacking out while in the car with her mother, and waking up in the hospital (1). This "peculiar sensation", which many epileptics describe feeling before a seizure,



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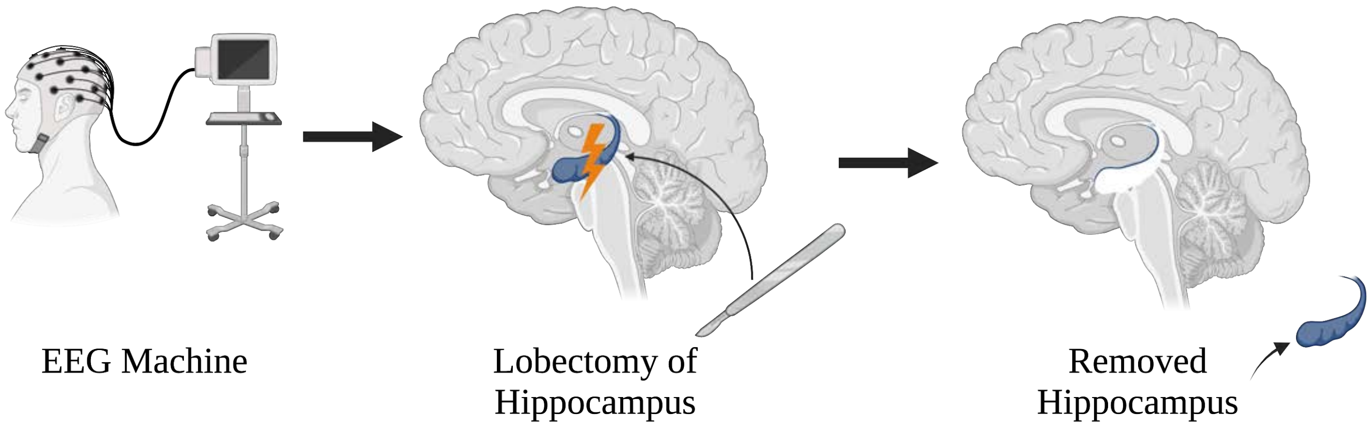
is known as a "premonition" or "aura", and can serve as a warning sign for the onset of a seizure. The sensation can differ from person to person, but has been described by some as a rising feeling in the stomach — similar to that experienced when riding a roller coaster. For Diane (who began to regularly experience seizures after this initial incident), the seizure premonition was also accompanied by the urge to run. Every time Diane would experience a seizure premonition, she would throw on running shoes, and dash onto the trails in the woods behind her home in Colorado (1). Though this habit frightened her family, it was surprisingly successful at preventing seizure onset. Running potentially "reset" her brain activity to normal levels, and prevented the electrical activity from becoming erratic (which occurs during a seizure) (1, 2).

Diane continued this seizure-preventing strategy, but eventually the time from seizure premonition to the occurrence of the seizure became too short for her to take off running. The seizures became increasingly disruptive to her life at this point, and Diane worried about her ability to care for her 3 children, and perform simple tasks such as safely bathing and driving. After exhausting other potential treatment methods such as special diets and medication, Diane's doctors proposed a more aggressive procedure: lobectomy.

How to Lose Your Mind

A lobectomy is a procedure involving the targeted removal of a small portion of the brain. To conduct a lobectomy procedure (1, 2) in epileptic patients, doctors use an EEG determine if there is a discrete region of the brain where a patient's epileptic seizures are originating (1, 2). This device measures the electrical activity of different brain regions by pasting dozens of electrodes to the head of the patient. While the patient is hooked up to an EEG, doctors measure the activity in different regions of their brain when they experience a seizure. If there is erratic electrical activity in a specific brain region during the patient's seizure, this portion of their brain can potentially be removed to prevent further seizing. While removing a segment of the brain comes with its own risk, for people like Diane with persistent seizures disrupting their daily activities, a lobectomy has the potential to restore some normalcy to their lives. At 37-years old, Diane entered the

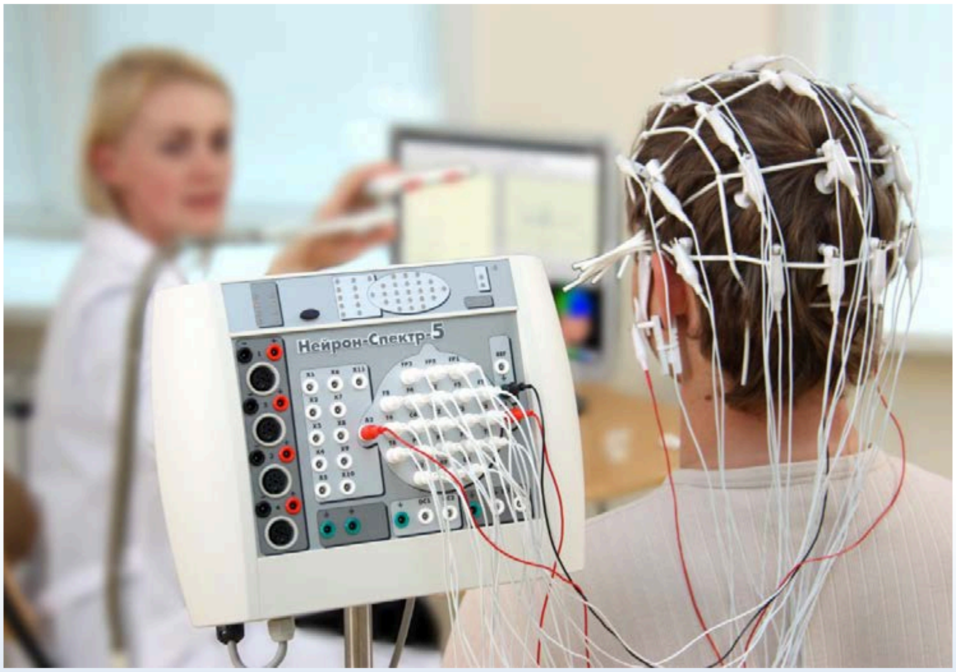


Schematic of process of localizing brain region of seizure origin with EEG device, and undergoing brain surgery to this region. Hippocampal region of the brain removed from Diane Van Deren highlighted in blue. Original image by Sierra Smith. Created in BioRender

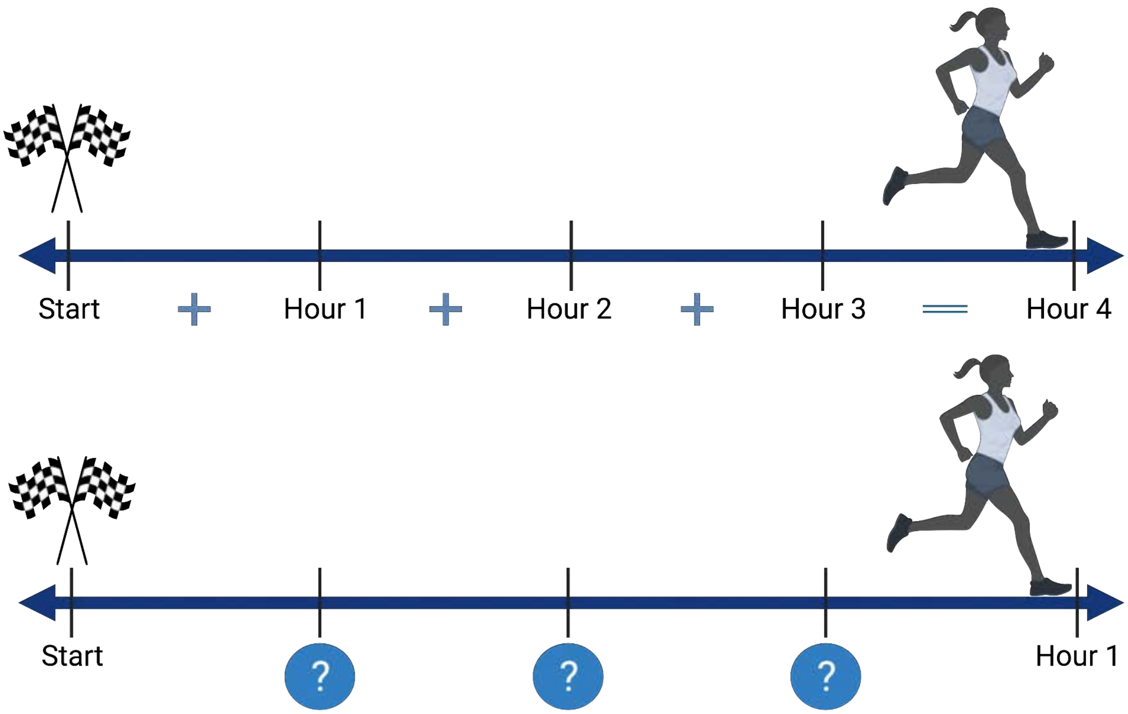
hospital to have dozens of EEG electrodes glued to her head, and await the arrival of a seizure for the EEG to record. Doctors cheered at the success of the procedure: a discrete seizure-initiating region of her brain was found. Diane underwent surgery to remove this section of her brain, and never experienced a seizure again (1, 2).

The chunk of brain removed from Diane was pretty significant; a human brain is roughly the size of two clenched fists, and the piece of brain removed from Diane was about the size of a kiwi (3). The damaged brain segment was on the right side of her head in a region known as the temporal lobe, and included a portion of a sea-horse shaped structure known as the hippocampus. The hippocampus is a structure with a variety of functions, including imagining the past and future, learning, memory, spatial navigation, and the temporal organization of memories (which may allow us to register the passing of time) (4, 5, 6). What about the removal of this brain region caused Diane's seizure to stop, and her ultra-running career to begin? Some theorize that by removing part of Diane's hippocampus, doctors disrupted her "internal clock" and inadvertently enhanced her endurance (1).

During an interview with WNYC radio reporter Mark Phillips, when asked to describe how she conceptualizes time while she runs by, Diane simply replied, "I stay in the moment." Diane described her thought processes during a grueling endurance race, emphasizing her focus on the rhythm of her strides rather than the passage of time (1). This ability to "stay in the moment" is potentially a result of her brain processing individual moments of the race, but due to the missing portion of her hippocampus, being unable to stitch these moments into a coherent timeline. If this is the phenomenon Diane is experiencing, it would prevent her from recognizing how much time has elapsed. A lack of time recognition could be the



EEG device attached to human subject "Eeg registration" by Baburov, https://commons.wikimedia.org/wiki/File:Eeg_registration.jpg Available under CC BY 4.0



Temporal organization of memories. If events can be remembered in the order in which they occurred over time, it could be easier to distinguish how much time has passed (as the sum of the time it's taken to experience each event). Original image by Sierra Smith. Created in BioRender.

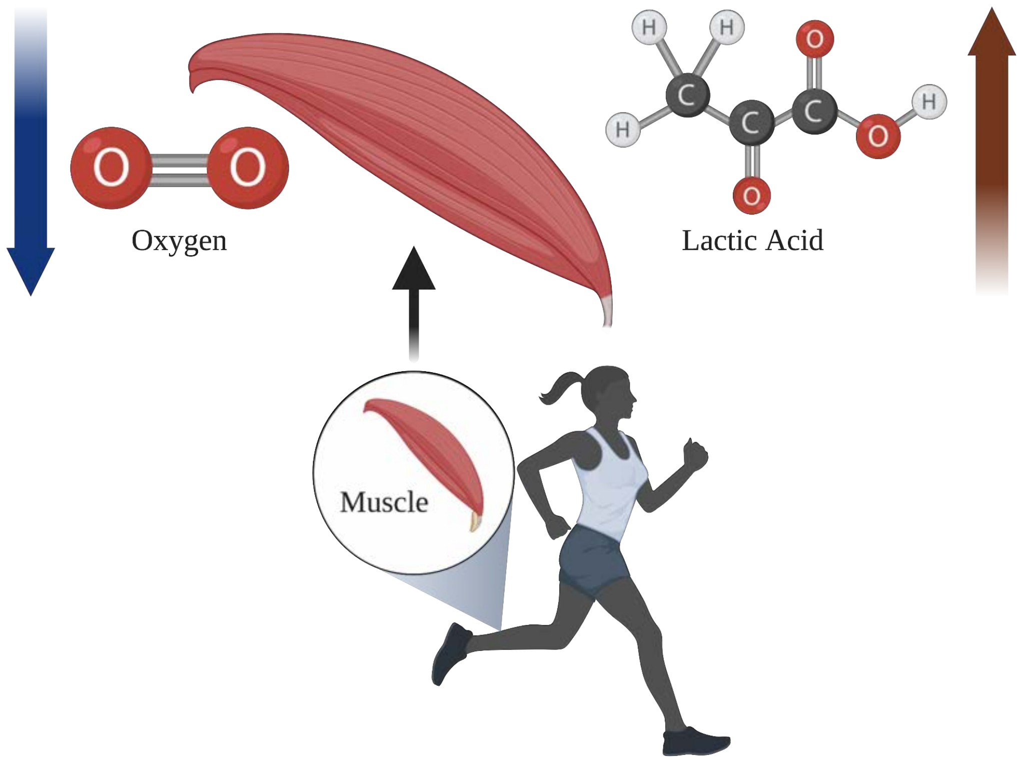
key to understanding the mental processes behind endurance — if you do not know how long you have been running, and therefore cannot determine how tired you think you should be, this could delay feelings of exhaustion. In a much simpler example, think of the exercise from the beginning of this paper. If every second you had your eyes closed felt like the first second, do you think it would be easier to keep your eyes closed for longer?

Feeding Fatigue

When you consider the feeling of exhaustion, there are two distinct forms that come to mind: physical exhaustion, and mental exhaustion. While physical exhaustion can be easier to identify through sore muscles and achy joints, mental exhaustion can be slightly harder to define. However, it's likely we've all experienced mental exhaustion in some form or another; picture how you feel taking your last exam during finals week, or how ready you are to leave a very long, boring meeting. If mental exhaustion has a profound ability to affect our motivation to continue a task, for someone on the 30th mile of an ultramarathon race, a combination of their level of physical exhaustion (how willing/able their body is to continue), and mental exhaustion (how willing/able their mind is to continue) could shape their ability to run onward. If we consider the development of mental exhaustion in a similar vein to the development of physical exhaustion, we can think of it as operating in a "feedback loop" system.

Many systems in our body operate in a "feedback loop", where the output of the system has the ability to alter future outputs from this same system. Feedback loops have the potential to be either positive or negative (which does not refer to the connotation of the effects of these loops). Outputs from a positive feedback loop induce the system to produce even more outputs, while outputs from a negative feedback loop inhibit the production of future outputs. While this concept may seem abstract, it is how our body automatically regulates many functions; feedback loops are why we naturally feel more awake during the day than at night, why our heart rate doesn't forever remain elevated after exercise, and why we can maintain a steady body temperature (7). Let's focus now on how physical exhaustion operates in a feedback loop.

Picture this: you wake up early, and decide to start your day with a long run. Your plan is to run for about an hour. The weather is nice, and you're feeling well-rested, so you start at a fast pace. The first 10 minutes of your run feel great — your legs feel strong, your breathing is even — and you feel like you could run forever. You begin to slow your pace around 20 minutes into the run, and each



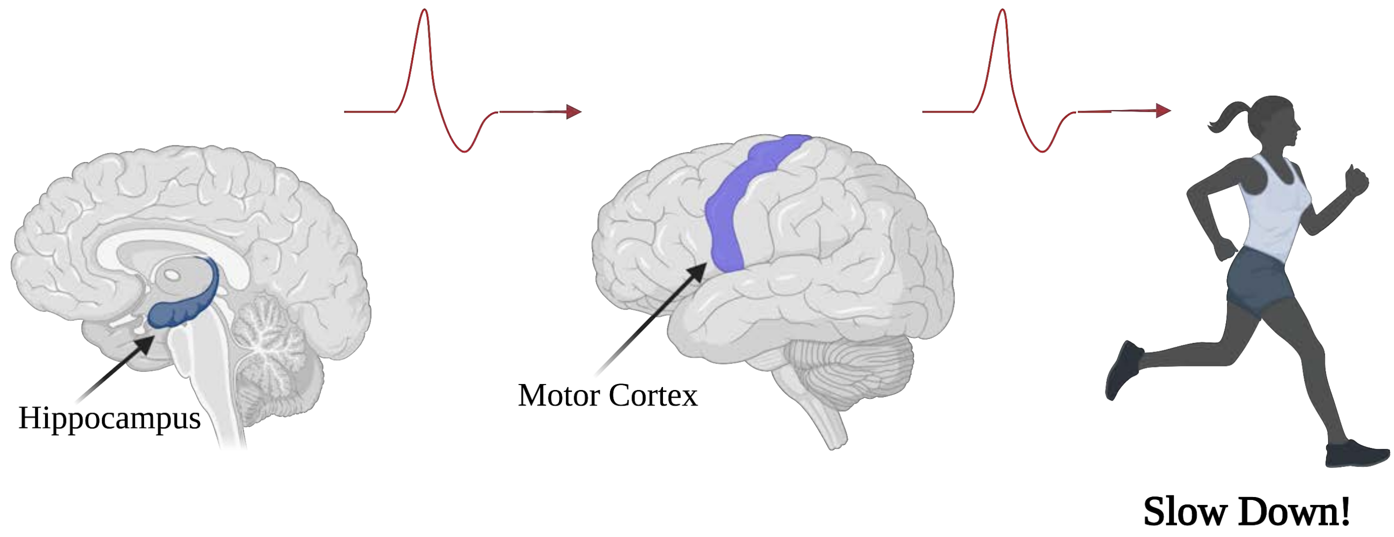
As oxygen levels in muscles decrease during exercise, a new method of energy production is used that increases lactic acid levels. Rising lactic acid levels eventually cause muscle fatigue and physical exhaustion. Original image by Sierra Smith. Created in BioRender.

footfall on the running path feels a little harder. By 30 minutes the muscles in your thighs and calves are beginning to feel sore. Over the course of the rest of your run, your muscles grow increasingly sore, and when you finally stop running after an hour, you're ready to sit and rest. How can you start the run feeling so energetic and strong, but feel so sore and tired by the end? Throughout exercising, your muscles need a source of energy, which is supplied to them in the form of the molecule "ATP". During the early stages of exercise, your body easily supplies your muscles with ATP; there are high levels of oxygen in your muscles, which react with glucose stores to create ATP. However, as exercise continues, your body needs to produce more ATP, but oxygen levels in your body have dropped (8). Your body can no longer directly react glucose with oxygen to create ATP, so glucose is converted to a molecule called "lactic acid", and the process of this conversion sets off a chain of events that eventually results in the production of more ATP. However, there's a catch. When lactic acid is formed during energy generation in prolonged exercise, this molecule accumulates in your muscles and causes them to feel pain and fatigue. This is where physical exhaustion becomes a feedback loop; as ATP (energy) input into your muscles increases, lactic acid will eventually increase, inhibiting your muscles from continuing to work and stopping the production of more lactic acid (8). To decrease the rate at which this physical fatigue advances, athletic training over time can increase oxygen availability in muscles to reduce the type of ATP generation that produces lactic acid as a byproduct (9).

If we now turn our attention back to the development of mental exhaustion, how could this too operate in the feedback loop? When you think of instances in which you feel mentally exhausted, you'll usually notice a common denominator: time. A boring five minute meeting is more tolerable than a boring five hour meeting.

When the Clock Stops

Considering mental exhaustion as a feedback loop of its own, it's important now to consider, like any feedback loop, what the inputs and outputs are. If we consider time as an input in this system, mental exhaustion (involving decreased motivation, and decreased motor output from the body) could be the output. Even something as intangible as



In a normal brain, the hippocampus sends signals to the motor cortex with increased duration of an activity (such as running). These signals tell the motor cortex to signal the body to stop performing the activity. Original image by Sierra Smith. Created in BioRender

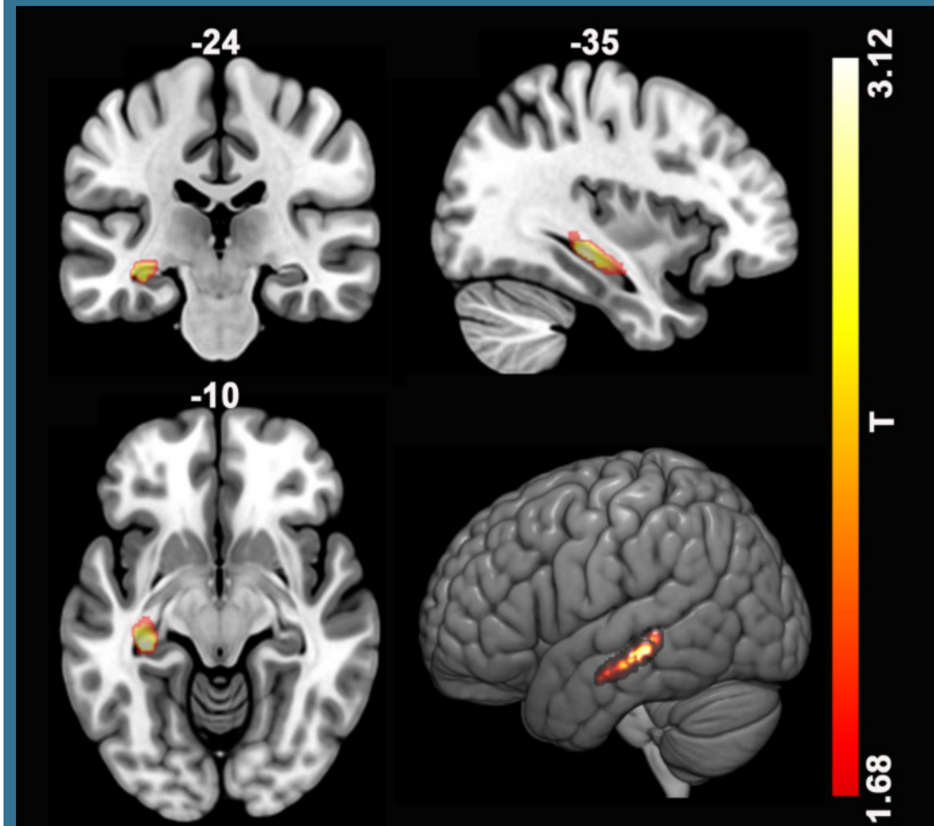
time can reasonably be an input into a functional system due to the hippocampus (the structure that Diane lost), which allows us to register and remember time passage. If we think of the hippocampus as "consuming," or "taking in" time as an input, how does mental exhaustion manifest as an output? A recent study performed functional brain imaging on people given tasks that induce mental exhaustion, which allowed them to examine the participants' brain activity during these tasks (10). The authors found that with increasing duration of mentally exhausting tasks, there was a decrease in the activation of the motor cortex of the brain (among many other structures) (10). The motor cortex allows us to execute movements, and forms connections with the hippocampus (11). This suggests that as time is "input" into the hippocampus, the hippocampus could be sending signals to decrease the activity of the motor cortex and cause the feelings and impulses we associate with mental exhaustion. This correlates mental exhaustion with decreased physical ability, and could explain the feeling of "I've been doing homework for 4 hours, and I now feel physically incapable of writing the answer to another question."

What happens then, if your body cannot intake time into this feedback loop — if your internal clock essentially "stops?" A method through which the perception of time could be disrupted is through changes to the hippocampus. The hippocampus helps us determine the amount of time that has elapsed while performing a task. It is often credited with (at least in part) regulating our perception of time due to its ability to store memories in sequential order. This is where we turn our attention back to Diane Van Deren.

Time Warp

Time loosely exists in Diane's universe ever since she lost a portion of her hippocampus. To Diane, hour 8 of a run feels like minute 8, and in interviews, she describes never knowing how long she's been running during an ultramarathon (1). If Diane is unable to receive the input of time into her hippocampus, this could reduce, or even eliminate her ability to feel mental exhaustion. In an endurance event like an ultramarathon, this is wildly beneficial. Given that Diane has always been a high-level athlete (even prior to her brain surgery), she likely has so much physical training that she experiences less physical exhaustion during a long run than the average person. Similar to other ultramarathon runners, Diane's endurance training limits the amount of lactic acid that accumulates in her muscles and slows her down. On top of this, if she does not have the barrier of mental exhaustion to deter her from completing a time-intensive activity, she now has the ultimate combination of features to elevate her ability to run long distances. This could uncover the mystery of Diane's superhuman running ability.

While Diane's running ability seems to be enhanced by her lack of hippocampus, this severely contradicts findings from studies of other ultramarathoners. There are challenges in studying what exactly makes an elite athlete an elite athlete (it is hard to discern what is



Highlighted regions of brain images show areas of increased gray matter volume (neuron volume) in endurance runners compared to healthy control subjects. The left hippocampus in endurance runners was found to have greater gray matter volume, which is correlated with greater use of this brain region. Figure adapted from 'Structural and functional brain signatures of endurance runners,' from Cao, L. et al. (2021). Brain Struct and Funct, licensed under CC BY 4.0

an innate ability vs what has been acquired through years of training). However, numerous studies have attempted to find neurological commonalities between elite athletes that could potentially explain their distinction. Over the past several years, research groups have examined brain morphology differences (differences in the sizes of certain brain regions) between marathon runners and healthy, non-runners (12). These studies have found that the hippocampi of the ultramarathon runners have a greater volume — which can indicate an increase in neurons (and potentially use) of this portion of the brain (12). Additionally, in a study of a type of mouse bred to have higher running capacity than a standard mouse, scientists also found greater activation of the hippocampus of the high running capacity mice while they were running compared to normal mice (13). Numerous other studies demonstrate a correlation between endurance aerobic exercise and an increase in neuron growth in the hippocampus, positively associating the hippocampus with endurance activities (14). However, this makes Diane Van Deren's case even more puzzling — how can the hippocampus be a prominent feature in the brains of endurance athletes if one of the most competitive endurance athletes is missing it?

Your Brain on Running

This link between increased hippocampal size, increased hippocampal activation, and increased hippocampal neurogenesis from endurance athletic activities may say more about what running is doing to the brains of endurance athletes, rather than what their brains are doing for their running. For endurance events — especially those like outdoor running and cycling that involve navigation — it is logical that the hippocampus would be highly activated throughout the competition. Since the hippocampus plays a large role in spatial memory and navigation, activation of this brain region to have a strong grasp of the course of the race would likely occur. If you're running up the side of a mountain, it's helpful to know what direction you should be heading in. In short, the hippocampus plays an important role in the brain, and thus its presence has persisted in the brains of athletes and non-athletes alike over the course of evolution. This being said, while the hippocampus is intensely utilized by people performing tasks where it could be of aid, this does not mean that the hippocampus causes someone to become a better runner. Becoming a better endurance athlete can increase the size and activation level of the hippocampus, but this doesn't mean that this state of the hippocampus greatly influences their athletic performance(12).

Lost

When asked in an interview if she believed her hippocampal loss gives her a leg up in ultra-running, Diane replied that she doesn't believe having a brain

"Trail Running Forest" by natachagagnekinesiolog, https://pixabay.com/photos/trail-running-forest-woods-6497875/ Available under CC0

injury gives her an edge on her competitors(1). While it is easy to hear about all of her athletic accomplishments and focus on how hippocampal loss could increase Diane's running capacity, Diane is forced to confront the other consequences of missing a region of her brain. Given how intricately involved the hippocampus is with memory, Diane reports struggling with remembering the names of people she has met, or remembering to pick her children up from school. Maps appear like gibberish to her, as her brain can no longer interpret spatial directions and information correctly. Looking even at how her brain surgery has negatively impacted her running, Diane talks in interviews about getting horribly lost during dangerous ultra-marathons (1). She laughs, saying that her competitors know better than to follow her on trails now (1). In the Yukon 300 race (the 430-mile race she finished in the Yukon territory), Diane describes getting lost for over an hour in the frozen tundra. She found strategies to combat this issue, such as bringing pink ribbons to drop along her path during a race so she can retrace her steps in case she gets lost, but this impedes her running, and daily life (1). While hippocampal removal could have greatly increased Diane's mental endurance, the effects are not purely beneficial. Diane has simply learned to work around her injury.

What's on your mind?

Stories like Diane van Deren's offer a better understanding of the intricacies of the brain, and cause us to reflect on how we view extreme endurance or athletic ability. It raises the question of whether we are emphasizing the correct strategies when training endurance athletes. You can easily call to mind what is associated with athletic training — fast-paced running workouts, weight lifting, etc., all of which have an emphasis on increasing physical fitness, and ultimately physical endurance. Less emphasis is explicitly placed, however, on how to increase mental endurance. If Diane van Deren's incredible athletic ability is the result of a combination of superior physical AND mental endurance, this makes the argument that increasing mental endurance should be focused on just as much as physical endurance when training for competition. Disclaimer: this is not advocating in any way for anyone to have their hippocampus carved out of their brain to improve their athletic performance. However, if people could learn strategies that disrupt their ability to perceive time during long activities, this could be beneficial for athletes and non-athletes alike! Whether you're running 50 miles, or simply trying to remain attentive throughout a long conference call, developing strategies to make yourself neglect the passage of time could improve your ability to persist through monotonous daily activities.

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