Leverage Biology to Learn Rapidly from Mistakes without Feeling like a Failure

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Abstract

Our biology affects how we interact with the world, including how we learn new knowledge and respond to challenges. This article explores the impact of neurochemicals in our brain on learning and explains how to leverage our biology to improve education and problem-solving, focusing on computing education. Within this context, the article particularly examines the role of failure while learning. Learning, especially in technical fields, includes making errors on the path to success. While these errors trigger the necessary neurochemical conditions for rapid learning, these failures can also be demotivating. To gain the benefits of failure while mitigating its negative consequences, this article recommends evidence-based behavioral strategies for making the best out of failing while learning and designing for failure in learning environments.

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Abstract—Our biology affects how we interact with the world, including how we learn new knowledge and respond to challenges. This article explores the impact of neurochemicals in our brain on learning and explains how to leverage our biology to improve education and problem-solving, focusing on computing education. Within this context, the article particularly examines the role of failure while learning. Learning, especially in technical fields, includes making errors on the path to success. While these errors trigger the necessary neurochemical conditions for rapid learning, these failures can also be demotivating. To gain the benefits of failure while mitigating its negative consequences, this article recommends evidence-based behavioral strategies for making the best out of failing while learning and designing for failure in learning environments.

This article explores the profound impact of neurochemicals on learning and how to leverage biology to support education and training. Hormones like cortisol, dopamine, and serotonin play a pivotal role in shaping behavior and cognitive processes, making them crucial factors in optimizing learning. In particular, this article examines the role of making errors and failing as a catalyst for learning. Failure triggers the neurochemical conditions necessary for neuroplasticity, enabling the brain to adapt and grow after making mistakes [1]. Despite this benefit for learning, failure is also an unpleasant experience that people typically avoid. Understanding the neurochemicals at play allows learners and educators to use strategies that mitigate the demotivational consequences of failure.

The primary audience for this article is those learning or teaching computing, especially for students who do not wish to become computer scientists. Computing is a design-focused field that requires a lot of failure on the path to success. These failures can be particularly demotivating when a learner is not inherently interested in computing. To support students, this article will discuss evidence-based behavioral tools that learners can use to benefit from failure while minimizing negative consequences. The causal connections between neurochemicals and human behaviors are well-studied in neuroscience, and this article will cite the most robust findings from this research related to learning (additional references can be found in the supplemental material). Though these connections are causal, they are not deterministic. Thus, this article does not support biological determinism and, instead, advocates for integrating biological tools with other tools. By embracing this holistic approach, we pave the way for advancements in education that harness the power of our biology.

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HOW FAILURE IMPROVES NEUROPLASTICITY

Neuroplasticity, the brain's ability to learn and adapt, plays a crucial role in our ability to acquire new knowledge and skills. While children effortlessly engage in passive neuroplasticity, this natural learning process diminishes over time and ceases completely around age 25. However, adults can still achieve comparable learning outcomes to adolescents through active neuroplasticity, which requires concentrated effort and incremental learning [2]. Activating neuroplasticity is possible by increasing the presence of epinephrine, a neurochemical in the brain that is released in response to facing challenges or stress, like failure. Research shows that epinephrine enhances memory by triggering a cascade of events. Epinephrine increases amygdala activation, which, in turn, triggers activation of cholinergic neurons that improve memory formation [3]. Therefore, experiencing failure during the learning process can effectively trigger this cascade of events and enhance neuroplasticity [3].

Repetitions and failures are often part of the learning process, including in computing education. Various instructional paradigms, such as productive failure, investigate the role of failure in learning [4]. Productive failure involves asking students to attempt a task before providing instruction on how to achieve it. After spending at least 30 minutes failing to accomplish the task, students are then given instruction on the correct solution [4]. Meta-analyses of instructional design studies have shown that productive failure before instruction has a significant, strong effect on learning outcomes [5]. In fact, the larger quantity of incorrect solutions learners create, the better they perform on later tasks [4]. Additionally, personal failure is found to be more impactful than vicarious failure [4], likely because it elicits the affective component that triggers neuroplasticity-promoting neurochemicals.

Productive failure and other instructional paradigms based on failure have improved learning in various domains, including creative and applied fields such as design, business, and computing. While failure is often embraced in these professions, formal education rarely teaches the skills of dealing with uncertainty while problem-solving and learning from and coping with failure [6]. However, intentional applications of failure in computing education have shown positive results, particularly in tasks like program debugging, where novices frequently make errors [7].

Balance Alertness and Calmness with Epinepherine

The neurochemical epinephrine is produced in response to high-stress situations that trigger a spike in epinephrine and to situations that require sustained attention or cognitive strain, which produce lower, consistent levels. Lower levels of epinephrine are better for learning as they create a feeling of calm alertness rather than agitation. However, our capacity to produce these molecules diminishes after 90 minutes of sustained attention, leading to a decline in learning efficiency. Moreover, high levels of epinephrine trigger a quitting mechanism that compels us to stop, impairing attentional control.

Learners' experience of different epinephrine levels and the likelihood of triggering the quitting mechanism depend on individual tolerance. Tolerance for epinephrine can be increased through training, where individuals expose themselves to safe but challenging stressors and dissociate stress from feelings of danger, such as tackling a difficult programming problem [8]. Developing a high tolerance for epinephrine will benefit learners who frequently face situations involving uncertainty or frequent errors, such as solving computing problems.

To maintain optimal levels of epinephrine, learners should limit learning bouts to 90 minutes with at least 20 minutes of rest between bouts. Because epinephrine is a short-lived molecule with a half-life of only a couple of minutes, learners can also use behavioral tools to change their current level of epinephrine. While there are many possible behavioral tools, some of the most effective are breathing techniques. To decrease epinephrine, learners can use exhale-dominant breathing, where individuals take deep breaths through the nose and exhale slowly over several seconds. Exhale-dominant breathing artificially lowers the heart rate, producing a state of relaxation and decreasing alertness. Conversely, to increase alertness, such as for an early class or during a late-night work session, learners can use the opposite technique. Inhale-dominant breathing involves deep inhalation through the nose followed by quick exhalation through the mouth, stimulating the production of epinephrine and enhancing alertness. These breathing techniques and other behavioral tools can be employed to modulate alertness levels by changing epinephrine levels in different learning contexts.

Improve Focus with Acetylcholine

Neuroplasticity is triggered by epinephrine and ends with the activation of cholinergic neurons, which release acetylcholine. Acetylcholine is crucial for learning, memory formation, and strengthening memories, and blocking its receptors inhibits memory formation. Alzheimer's patients, who have cholinergic neuron loss, experience memory difficulties, while cholinergic stimulation improves memory in older adults. Attention (i.e., epinephrine) and focus (i.e., acetylcholine) are distinct biological processes, with attention being generated first before focus can be directed [9]. Initially, there can be a brief period at the start of a task when focusing attention is challenging due to the influence of epinephrine, which promotes attention but also induces movement and undifferentiated awareness [10]. When transitioning through failure or uncertainty, conscious effort may be required to maintain focus during the increase in epinephrine levels before acetylcholine sharpens focus. While there are limited behavioral recommendations for optimizing acetylcholine levels, maintaining visual focus on a single point, such as the tip of a pen, for 30-60 seconds can help generate sufficient acetylcholine to direct attention toward the learning task [10].

MAINTAIN MOTIVATION THROUGH FAILURE

While failure can enhance learning by activating neuroplasticity, it is important to avoid excessive failure that can be unproductive. The same neurochemicals that promote neuroplasticity also cause frustration and demotivation when making errors. If learners fail so much that these emotions lead to giving up, learners experience the negative aspects of failure without reaping its benefits.

The effect of failure on motivation is influenced by how we frame it psychologically. When we view failures as being on the right track, we are more likely to persist, whereas perceiving them as setbacks often leads to quitting. This framing process occurs in the prefrontal cortex, which is larger in humans compared to other animals. Framing allows humans to pursue long-term goals by leveraging a hormone that normally rewards short-term goals–dopamine [11].

Though pop culture treats dopamine as a molecule of reward for achievement, this is only half the story. The dopamine system consists of two parts: one related to the expectation of a reward, driving us to overcome challenges and pursue goals we value, and the other associated with the reward for achieving those goals [11]. The first part is what we should harness to drive motivation because it rewards the pursuit and anticipation of valuable things [11]. These things include food when we are hungry, water when we are thirsty, or other things we enjoy, like coffee, chocolate, or novel information. While the dopamine system naturally motivates us subconsciously, humans can exert conscious control over it through the prefrontal cortex, allowing us to frame and redirect it towards abstract pursuits [12], such as learning computing.

Manage Dopamine to Manage Motivation

The prefrontal cortex allows us to perceive challenging pursuits as pleasurable by framing them as valuable [12]. This framing enables us to receive dopamine from difficult tasks, but it takes time to establish these connections, which is why habits take at least 18 days to form. The dopamine system is also influenced by reward prediction error, where the release of dopamine is based on the disparity between expected and actual rewards. This system helps calibrate our behavior and encourages us to pursue achievable goals while discouraging pursuits that are less likely to succeed. To maintain motivation in the face of failure, reframing large projects as achievable short-term goals and focusing on actions rather than outcomes can help mitigate the negative impact of reward prediction error and sustain long-term motivation [12], [11]. For example, setting a goal to study or practice problem-solving each day for an hour will result in better motivation than setting a goal to attain a certification by a particular date or to complete weekly assignments.

In addition to framing and focusing on achievable short-term goals, other features of the dopamine system can help maximize our benefit from it.

- Dopamine tends to be higher in the morning. In addition, dopamine is the precursor to epinephrine, which improves neuroplasticity. Thus, many people find doing concentrated work easier in the morning.
- Avoid other activities that require little effort to activate the second part of the dopamine system, especially in the morning. These activities, such as using social media or eating high-fat and high-sugar treats, can offset the dopamine system and decrease motivation all day.
- Caffeine increases dopamine, producing feelings of motivation. In addition, it can increase the number of dopamine receptors and might have a protective effect on dopaminergic neurons for long-term health.
- Exposure to bright light, such as screens, in the middle of the night (a few hours after sunset to a couple of hours before sunrise) blunts dopamine release long-term, reducing motivation during the day.

IMPROVE TOLERANCE FOR FAILURE

Learning computing, or applying computing for that matter, involves enduring failure on the path to success, making a high tolerance for failure crucial for learners of computing. Of course, tolerance for failure is also valuable in other technical fields, like engineering and science. Tolerance for failure varies among individuals and can be increased through training or decreased through negative experiences. Understanding tolerance for failure can shed light on how students experience failure, why some students thrive or wither in different environments, and how to support learners' success while learning computing.

This tolerance is associated with the activity level in the amygdala, the same brain region responsible for activating cholinergic neurons to enable neuroplasticity [3]. The amygdala's level of activation affects the balance between positive learning benefits and negative emotions, with experiences that cause high amygdala activation leading to increased risk aversion and fear of failure [13]. Hormones like serotonin buffer these effects by inhibiting amygdala activity, thereby increasing risk tolerance and reducing fear of failure, while other hormones like cortisol increase activation of the amygdala and decrease tolerance for failure.

Increase Tolerance for Failure with Serotonin

Serotonin, often known for its dysregulation in depression, is associated with feelings of reward and satisfaction, fostering gratitude and contentment [14]. Serotonin levels naturally rise throughout the day, peaking in the afternoon and declining after sunset when it is converted into melatonin to help us sleep. The production of serotonin is influenced by sunlight, which explains the link between seasonal depression and reduced sunlight exposure in winter [14].

In terms of tolerance for failure, higher serotonin levels are linked to persistence in challenging situations and a willingness to embrace new experiences. Behavioral interventions that boost serotonin, such as exercise, promote less defensive behaviors and a preference for larger delayed rewards. Serotonin's effects are mediated through the prefrontal cortex and amygdala, reducing the perception of threats and decreasing negative emotions associated with novel or challenging experiences.

To maintain a healthy level of serotonin and support tolerance for failure, learners can use several free behavioral tools. Sunlight exposure is a significant factor, and modern individuals who spend most of their time indoors typically experience lower levels of sunlight than is optimal [14]. Increasing exposure to bright light, especially in the morning, can help raise serotonin levels [14]. Early exposure to bright light is beneficial even for people who prefer to work later in the day. Diet also plays a role, as serotonin is produced from tryptophan. Consuming tryptophan-rich foods, particularly earlier in the day, supports serotonin synthesis. Exercise is another effective way to boost serotonin production by increasing the amount of tryptophan that reaches the brain and, thus, is used for mood regulation [14]. Lastly, while gratitude practices are commonly associated with serotonin increase, it is now believed that they primarily influence our perception of events rather than directly impacting serotonin levels. Framing events through appreciation rather than evaluation or comparison can lead to more positive experiences, and expressing gratitude can also influence how others interact with us [15]. Any of these four tools can be used to increase serotonin, which is likely to benefit more than just learning of computing.

Maintain Optimal Levels of Cortisol

Though we commonly think of stress as unilaterally harmful, stress also helps us maintain alertness and achieve goals. For example, our body naturally produces a cyclical level of cortisol throughout the day to help us wake up in the morning, be alert throughout the day, and then relax at night. However, many people face constant exposure to stress, which disrupts this cycle and has long-term negative consequences. Part of this dysregulation is that cortisol increases activity in the amygdala, increasing our perception of how stressful events are. As a result, chronic stress can create a self-sustaining feedback loop in which the amygdala is always active at a high level.

Reducing unhealthy cortisol levels can be achieved through various behavioral approaches, with exercise and meditation being particularly effective. While exercise may temporarily increase cortisol during activity, low- and moderate-intensity exercise has a long-term cortisol-reducing effect [16]. Bursts of exercise immediately after a stressful event can also help clear cortisol from the bloodstream [16]. Further, exercise offers additional long-term benefits, including enhanced prefrontal activity, which is relevant to framing, motivation, and tolerance for failure. Research supports the positive impact of exercise interventions on education, including studies involving computing students. Fitbreaks, short periods of physical activity inserted into lecture times, have been found to improve student well-being, stress levels, retention, and academic performance [17].

Meditation, on the other hand, provides a different approach to cortisol management. By altering how stressful events are perceived and helping individuals separate stressors from their reactions, meditation interrupts the fight-or-flight response and regulates the intensity of stress responses. Several reviews highlight the benefits of meditation in education, demonstrating improvements in student well-being and academic achievement. In one randomized experiment involving college students, just 13 minutes of daily meditation resulted in decreased cortisol levels and feelings of stress, alongside increased attention and memory [18]. Both exercise and meditation present valuable strategies for cortisol management and have demonstrated positive effects on various aspects of education.

CONCLUSION

Learners' experience of failure involves an interconnected set of neurochemical systems that affect neuroplasticity, motivation, and tolerance for failure. While failure activates neuroplasticity to facilitate learning, it can also lead to task avoidance if used inappropriately. The authors aim to provide a new perspective for understanding and designing factors in computing education related to failure, emphasizing the importance of framing of failure and fear of failure and their biological consequences.

Educators can use these behavioral tools to support their students through failure. Much like with metacognitive strategies, learners often benefit from being reminded of strategies they can use to improve their learning. For example, educators can guide students to set small, achievable goals throughout the semester (e.g., study class notes for 1 hour after class) or towards large projects to improve their motivation through dopamine. Further, offering fit breaks during class or encouraging students to get some sunlight or exercise for the sake of their studies might improve their tolerance for failure. The authors suggest using these factors alongside other instructional tools in computing education, such as peer interactions.

The authors acknowledge that learners' relationship with failure cannot be expected to change instantly, as these biological systems served life-saving functions throughout our evolution. However, through training and reframing, individuals can become better at failing over time, reaping the rewards of neuroplasticity while experiencing fewer negative consequences. The hope is that these tools will be utilized in conjunction with other approaches to enhance computing education and support students in their learning journey.

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