Background. How does motivation drive learning? Evidence abounds that reward, motivation, and curiosity can all enhance learning and memory[1]; these findings have far-reaching implications for education. However, a fundamental problem undermines our ability to apply this research in classrooms: extrinsic reinforcement can actually *decrease* intrinsic motivation[2]. In other words, although rewards like candy, stickers, and money are often used as incentives for students, these secondary reinforcers may decrease internal motivation, curiosity, and fulfillment.

In the brain, dopamine pathways are strongly implicated in reward and motivation[1]. Dopaminergic cells in the ventral tegmental area (VTA) project to the hippocampus and surrounding medial temporal lobes[3], influencing memory by enabling the brain to prioritize and remember important information[4]. Moreover, high-reward contexts increase sustained VTA activation and memory encoding[5]. Past studies of intentional encoding strategies have shown the importance of elaborative and self-referential processing[6], but have yet to link these methods to dopaminergic modulation. Importantly, it remains an open question whether cognitive strategies can act upon dopaminergic pathways to enhance memory, either immediately or over time.

Cognitive neurostimulation, the volitional modulation of one's own brain activity through mental imagery and thoughts, offers a promising method of enhancing motivation. However, past research has found that without guidance, individuals struggle to self-motivate and modulate VTA activity[7]. *Neurofeedback* provides individuals with real-time information about their own brain activity. Past studies in the Adcock lab have successfully used neurofeedback to train participants to self-activate the VTA; this activation is associated with self-reported motivation[7]. A day later, trained participants retained the ability to self-activate, even without neurofeedback.

Intellectual Merit. Thus far, no study has shown that self-activation of the VTA can influence memory encoding or consolidation. **This missing link is essential for elucidating neural mechanisms of motivation and memory, as well as extending cognitive research to education.** The proposed research will take a novel approach to address this gap in the literature by embedding neurofeedback training within a memory task. The present study seeks to: **(1)** Train participants to drive intrinsic motivation and self-activate the VTA, **(2)** Test whether self-activation enhances memory encoding and consolidation, and **(3)** Identify effective motivational strategies with a data-driven approach. **I hypothesize that with neurofeedback, participants will learn to self-motivate and drive VTA activation, thus enhancing subsequent memory.**

Methodology. Fifty healthy participants will be recruited to participate in a study at the Duke University Brain Imaging and Analysis Center, which houses a GE Premier 3T MRI scanner. First, participants will complete two trait motivation surveys, the Motivational Trait Questionnaire[8] and the Behavioral Inhibition-Approach System[9] (BIS/BAS). In the scanner, I will collect fieldmap, T1-weighted structural, and functional scans (TR=1s, voxels=2x2x2 mm^3).

Participants will complete three kinds of tasks: ***Activate task.*** Participants will be instructed to self-motivate by using personally-relevant thoughts and mental imagery (e.g., one past participant reported success with visualizing a cheering crowd[7]). Using PYNEAL software, previously developed in the Adcock lab, I will calculate real-time VTA activation and inform participants with a dynamic thermometer display. ***Watch task.*** Participants will passively view the thermometer display, but will be informed that fluctuations are random, *not* neurofeedback. On these trials, the thermometer display serves as the *control task*, equating visual input with the Activate task. ***Encode task.*** On each trial, participants will try to memorize a series of 7 object images (2 sec. each), sampled randomly without replacement from a set of 336 images.

In total, participants will complete 8 runs of 6 trials each. A random half of the trials will begin with the Activate task (20 sec), and the other half will begin with the Watch task (20 sec).

The Encode task (20 sec) will conclude every trial. **Between runs, participants will verbally describe the motivational strategies employed on preceding trials.** After the MRI scan, participants will be randomly assigned to either the *Same-Day group* (memory test immediately after the scan, *n*=25) or the *Next-Day group* (memory test 24-hours later, *n*=25). In a behavioral testing room, participants will complete a recognition memory test of the images from the Encode task (336 old images, 168 novel images), and rate confidence on a 5-point Likert scale.

Analyses. In summary, I will employ a 2x2 design (**Task**: *Watch, Activate* X **Time**: *Same-day, Next-day*) to address the following questions: ***1. Does VTA self-activation enhance memory?*** I expect that within-subjects, average memory accuracy (*d'*, signal detection theory) and event-related VTA activation will be greater on Activate than Watch trials. Moreover, trial-wise VTA activation will be parametrically related to memory for the stimuli encoded on a given trial. Previous work in the lab has detected similar neuromodulatory effects on single trials[10].

2. Does self-activation of the VTA influence memory encoding and/or consolidation? If VTA-activation enhances consolidation, then the Next-Day group will exhibit greater disparity in memory accuracy between Activate and Watch trials (relative to the Same-Day group), because consolidation is time- and sleep-dependent. Within the Next-Day group, I will compare memory accuracy for Activate and Watch trials to control for sleep-consolidation effects that are independent of VTA-effects. An alternative hypothesis is that VTA-activation will improve memory equally in both groups, reflecting selective effects at encoding.

3. What cognitive factors drive motivation and enhance memory? Using the trait motivation survey data, I will test whether individual differences in personality (e.g., higher scores on trait motivation and the BIS/BAS Reward Responsiveness subscale) predict success on the Activate task and subsequent memory accuracy. Moreover, I will employ a data-driven approach to identify the self-reported motivational strategies that most effectively increased VTA activation (e.g., verbalizations, various types of mental imagery). Importantly, the existing literature on motivation and reward is constrained by a limited set of strategies that are imposed by experimenters. Informed by my fMRI findings, I will develop future behavioral studies that test the efficacy of the diverse motivational strategies that participants intuitively employ.

Broader Impacts. Motivation is a core component of learning. **Critically, low-income and disadvantaged students exhibit low intrinsic motivation, which predicts poor academic outcomes**[11]. In 2016, a staggering *29.7 million* American children (41%) lived in low-income families[12]. In classrooms, fostering intrinsic motivation can improve learning outcomes and student retention[9]. Extrinsic reinforcers, such as monetary rewards, can have restricted and short-lived effects; in contrast, intrinsic motivation predicts long-term student success[10]. The proposed research seeks to empower individuals to drive intrinsic motivation and self-activate motivational brain systems, thus engaging the brain to improve learning. With a novel neurofeedback approach, I will identify cognitive strategies that effectively act upon dopamine systems to enhance memory. In future behavioral studies, I will directly test whether these strategies can successfully bolster motivation and memory without neurofeedback. The present program of research seeks to uncover accessible and non-invasive methods of fostering intrinsic motivation and improving memory, thus broadly benefiting learning and education.

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