The Neurophysiological Correlates of Choice on Engagement, Motivation, and Motor Skill Learning

by

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Abstract

Autonomous practice conditions have time and again shown to be advantageous for motor skill learning, but the reason for this benefit is still unclear. Some studies suggest this benefit arises from increased motivation during practice; others suggest the benefit arises from better information processing. The purpose of Experiment 1 was to investigate the relationship between autonomy over difficulty level, engagement, and motivation during a motion-controlled video game task. Participants were randomly assigned to a self-controlled group, who chose the progression of difficulty during practice, or to a yoked group, who experienced the same difficulty progression but did not have a choice. Controlling for pre-test, participants in the self-controlled group showed greater retention on the moderate level post-test given one week after practice, and reported greater levels of intrinsic motivation during practice. However, the latter effect was found only at the group-level, as we found no individual differences in engagement or motivation that were associated with learning. Thus, the results from Experiment 1 were inconsistent with strictly motivational accounts of how autonomy benefits learning, instead suggesting the benefits of autonomy may be mediated through other mechanisms (i.e., greater information processing).

To further investigate the relationship between autonomy and learning, as well as address limitations of exhaustive and subjective survey measures in Experiment 1, we designed Experiment 2 to include shorter, single-item engagement and motivation questions and objective neurophysiological measures (frontal asymmetry and spontaneous eye-blink rate). As in

Experiment 1, participants were randomly assigned to a self-controlled group or a yoked group. Unlike Experiment 1, however, we did not see significant differences between groups on the retention post-tests. However, the combined data from Experiment 1 and 2 did show greater learning effects for the self-controlled participants compared to yoked participants. Furthermore, there was not a significant Group by Experiment interaction, suggesting this result falls within what we may expect with our given effect size and sampling variability. We found no relationships between learning and engagement, motivation, frontal asymmetry, or spontaneous eye-blink rate. However, practice frontal asymmetry was positively related to average difficulty level and changes in difficulty level during practice (i.e., participants who played at a higher difficulty level and switched difficulty levels more often had greater left frontal cortical activity). The new single-item engagement and motivation questions significantly correlated with the previously used long-form engagement and motivation surveys, which can be utilized in future studies to dynamically measure these constructs throughout practice. Survey results from Experiment 2 also question motivation's role in autonomy and motor learning. Although self-controlled groups showed superior learning to yoked groups, individual differences in motivation were not related to individual differences in learning across the two experiments. Our chosen neurophysiological measures also did not show support for the idea that these benefits arise from enhanced motivation (specifically dopaminergic processes). More investigation into the underlying neural mechanisms of autonomy must be completed in order to better understand this construct.

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List of Abbreviations

EEG	Electroencephalography
ENG	Engagement
IMI	Intrinsic Motivation Inventory
LTP	Long-Term Potentiation
MOT	Intrinsic Motivation
RM	Repeated Measures
SC	Self-Controlled Group
sEBR	Spontaneous Eye-Blink Rate
YK	Yoked Group

Chapter 1

General Introduction and Applied Impacts

Traditional forms of rehabilitation for neurological injuries (e.g., stroke) may not provide the necessary amount of task-specific movements, or “dosage”, required to induce neuroplastic changes and regain optimal function of an affected limb (Lang et al., 2009), based on both human and animal studies of recovery (Hsieh, Wu, Lin, Yao, Wu, & Chang, 2012; Nudo, 2011; Nudo, Milliken, Jenkins & Merzenich, 1996). These traditional therapies, often housed in hospitals or specialized facilities, are time, resource, and cost intensive (Saposnik et al., 2010). Gamifying rehabilitation using motion-controlled video game systems could help remedy these issues, as they may provide cheaper, more accessible, and more motivating sources of physical therapies compared to regular in- and out-patient therapies. Particular game mechanics, such as clear and compelling goals (Garris, Ahlers, & Driskell, 2002; Maclean, Pound, Wolfe, & Rudd, 2000), reward (Adcock, Thangavel, Whitfield-Gabrieli, Knutson, & Gabrieli, 2006; Wise, 2004; Wittmann et al., 2005; Wolosin, Zeithamova, & Preston, 2012), feedback (McGonigal, 2011), interactivity and choice (Andrieux, Danna, & Thon, 2012; Schultz, 1998), and appropriate and progressive challenge (Lazzaro, 2004), have been shown to enhance learning.

When comparing the efficacy of motion-controlled video game play to regular therapy sessions in patients diagnosed with stroke, there seem to be no differences (Laver et al., 2012), and even some improvements (Saposnik et al., 2010), in physical performance measures of the gaming groups. A possible cause for this augmentation of learning is that gameplay increases a person’s motivation. This is a hypothesis that has been debated in the motor learning literature, as the relationship between motivation and learning has been explored, but the underlying neurophysiological mechanisms are still unclear. Motivation may increase coincidently with learning, as suggested by recent studies (Leiker, Bruzi, et al., 2016; Leiker, Miller, et al., 2016; Ste-Marie, Carter, Law, Vertes, & Smith, 2015), but the enhanced learning effect may be due to greater information processing during the activity.

This dissertation is meant to delve deeper into the relationship between motivation, engagement, the game mechanic of choice, and motor learning. I will first introduce each of these constructs—motivation, engagement, and autonomy—and discuss how they relate to learning and to each other. Building off that background information, I will explain what we did, why we did it, and what we found for Experiment 1, then Experiment 2 of this dissertation. Finally, I will address some of the limitations of this dissertation, and how future research may be influenced by the subsequent findings.

Motivation

Motivation is the psychological attribute that produces goal driven behaviors (Wise, 2004). Motivation as a whole is an important concept to study, but for our experiments, it is important to delineate two key forms of motivation: extrinsic motivation and intrinsic motivation. Extrinsic motivators are the rewards associated with the action that comes from outside of ourselves (e.g., money, status, or praise), while intrinsic motivators are the rewards that come from inside ourselves (e.g., positive emotions or social connections) (McGonigal, 2011). Positive psychologists have found that the happiness that comes from extrinsic rewards habituates quickly and that more and more extrinsic rewards are needed to produce the same reward "high" (Bottan & Truglia, 2011). Whereas intrinsic rewards precipitate more durable motivation—their effects are robust and renewable (Lyubomirsky, 2008). We are most interested in studying intrinsic motivation, as there have been studies that suggest this construct affects learning and performance (even in non-movement fields) (Hagger, Sultan, Hardcastle, & Chatzisarantis, 2015; Taylor, et al., 2014).

Intrinsic motivation and learning. Perhaps the strongest supported relationship between motivation and learning comes from dopamine activity to reward and reward anticipation. The dopamine hypothesis of reward, as described by Wise (2004), suggests that rewarding and reward predicting stimuli cause motivational arousal and increase the likelihood of response initiation. Rats that received rewarding brain stimulation through a lever-bar press before and after running had increases in response rates to the lever-bar, as well as increases in speed through the runway (Wetzel, 1963). This effect was found in subsequent trials as well—rats were excited, eager, and motivated to move through the runway when they knew a reward was coming (as measured by increased running speed). Additionally, Bao, Chan, and Merzenich (2001) found that stimulating dopamine neurons from the ventral tegmental area together with an auditory stimulus increased reorganization of the primary auditory cortex in rats. Neural responses to the tone became more selective, and responses were also seen in a multimodal association area. This effect was not present in naïve rats, however, suggesting that dopamine is responsible for the learning-related neuronal changes that occurred.

There has been a considerable amount of support in human research for the relationship between motivation and learning. The medial temporal lobes (hippocampus and surrounding cortex) are believed to sustain memory formation, and are anatomically and functionally related to the midbrain dopamine systems (Adcock et al., 2006). Because of these connections, it has been hypothesized that long-term potentiation can be enhanced and prolonged by dopaminergic inputs. Studies have found that increased activation in and connectivity between the ventral tegmental area, nucleus accumbens, and hippocampus are associated with improved long-term memory (Adcock et al., 2006; Wittman et al., 2005). Similarly, researchers have studied the effect of curiosity (as an intrinsic motivator) on memory formation, and higher levels of curiosity led to greater memory retention and more activity in the midbrain and hippocampus (Gruber, Gelman, & Ranganath, 2014; Kang et al., 2009).

Autonomy and motor learning. Choice may be key for augmenting the motor learning process. Autonomy over feedback, amount of practice, and task difficulty have all been shown to be advantageous in retention of motor skills compared to conditions in which participants have no control (Andrieux, Danna, & Thon, 2012; Chiviacowsky & Wulf, 2002, 2005; Fairbrother, Laughlin, & Nguyen, 2012; Post, Fairbrother, Barros, & Kulpa, 2014).

Although the underlying mechanisms are unknown, there are two major hypotheses for why autonomous conditions may improve learning and performance—the information processing hypothesis and the motivation hypothesis. The information processing hypothesis suggests that by having control over some aspect of practice, participants are able to obtain the information they need at the most appropriate time, which may increase the amount (or quality) of information processing that occurs (Grand et al., 2015; Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997). The second hypothesis suggests that self-control increases motivation and engagement during practice, which subsequently increases learning (McNevin, Wulf, & Carlson, 2000; Wulf & Lewthwaite, 2016). There is psychological evidence that shows the magnitude of rewards (either intrinsic or extrinsic) moderates reinforcement learning (Spence, 1956) and that this process depends, in part, on dopaminergic signaling in the brain (Wise, 2004). A number of studies have shown that engagement and motivation are associated with superior learning at the group level (Chiviacowsky, Wulf, Lewthwaite, & Campos, 2012; Lohse et al., 2015), however, recent evidence suggests there is no direct influence of these two constructs on learning (Ste-Marie, et al., 2015).

Engagement

Engagement is an emotional and cognitive multidimensional experience that can be operationalized by a key set of attributes: perceived usability, aesthetics, focused attention, felt involvement, novelty, and endurability (Leiker, Miller, et al., 2016; O'Brien & Toms, 2008, 2010). In games, engagement is associated with states of enjoyment, immersion, flow, and presence (Boyle, Connolly, Hainey, & Boyle, 2012). Flow theory, proposed by Csikszentmihalyi and Csikszentmihalyi (1992), suggests that "flow" occurs when players are in a state of optimal experience to perform the task at hand. While experiencing flow, there is a complete absorption in the activity, a sense of control, concentration on the task, reduction in self-consciousness, and distorted perception of time. For an activity to produce flow, it must have a challenge with an attainable goal and known rules, clear goals, and immediate feedback. This makes flow conceptually similar to the construct of engagement, which is thought to be elicited by interactivity, choice, exploration, and reward (Hunicke, LeBlanc, & Zubek, 2004; O'Brien & Toms, 2008).

Engagement and learning. Experimental studies in mice have shown that being exposed to an enriched environment (i.e., a specially designed cage to allow for complex stimulation through the addition of plastic tubes, a running wheel, nesting material, etc. and the opportunity for social interaction versus a standard cage with limited cohabitants) causes an increase in hippocampal volume and retention of new neurons (Kempermann, Kuhn, & Gage, 1997). The opportunity for greater interactivity, exploration, choice, and reward (enriched environment mice received extra treats) may have increased engagement for mice in the enriched environment, and led to an increase in neurons, synapses, and dendrites. Similarly, exposure to novel stimuli in freely moving rats incites exploratory behavior and increases the release of dopamine in the midbrain, which targets the hippocampus (Legault & Wise, 2001; Schultz, 1998). Greater exploratory behavior may increase the likelihood of an encounter with even more novel stimuli, consequently perpetuating the effect of novelty on areas of the brain responsible for memory. Kilgard and Merzenich (1998) have also suggested that engagement in a task leads to more movement and greater physiological arousal, and this arousal may improve learning by increasing neural plasticity through cholinergic processing.

However, there is limited empirical evidence in humans thus far that supports the idea that engagement directly augments learning. Increased engagement during practice may indirectly augment learning by increasing practice time (for a theoretical perspective see Hunicke et al., 2004; O'Brien & Toms, 2008), and there is evidence that the amount of time spent on the task increases learning (Kuh, Kinzie, Schuh, & Whitt, 2011). Additionally, there is limited evidence to suggest that creating engaging practice environments can directly augment learning (i.e., by increasing the quality of practice rather than the quantity of practice). Results from Lohse et al. (2015) suggest increasing engagement during practice can directly augment learning, but more research is needed for the robustness of this effect to be determined.

Furthermore, the mechanisms underlying this effect are still unknown. Engaging environments may lead to greater dopaminergic activity, which increases neuroplasticity (Bao, et al., 2001). As seen in Zimmerli et al. (2013), engaging environments can also lead to greater energy expenditure during practice and increased physiological arousal is associated with increased neuroplasticity (Kilgard & Merzenich, 1998). Increased engagement has also been associated with increased information processing (Leiker, Miller, et al., 2016), and more elaborative rehearsal/deeper information processing has been associated with superior learning in other domains (Dunlosky, Rawson, Marsh, Nathan, & Willingham, 2013; Ericsson, 2008). Any one of these mechanisms, or some combination of all of these mechanisms, may explain why engagement during practice can augment the learning of motor skills.

The Relationship Between Intrinsic Motivation and Engagement

It is important to understand the difference between intrinsic motivation and engagement, as they are often used interchangeably, but incorrectly so. As previously discussed, motivation is the psychological property that produces goal driven behaviors (Wise, 2004), while engagement is a psychological state one experiences during a behavior that has both affective and cognitive components (Leiker, Miller, et al., 2016; O'Brien & Toms, 2008). Someone may be motivated to run a race, but that doesn't necessarily mean that they are fully emotionally and cognitively immersed during the race if it becomes either too boring or too challenging. In the gaming literature, Salen and Zimmerman (2004) suggest that motivation is what initiates the playing of a game, while engagement, or what they refer to as "sustained motivation", is what keeps players participating throughout the gaming experience.

Perhaps the most defining difference between intrinsic motivation and engagement is the amount of information processing that occurs during the task. In defining user engagement with technology, O'Brien and Toms (2008) hypothesized that focused attention, which requires greater amount of neural processing than just attending during an activity, is an integral part of engagement. Their definition of engagement does not rely on intrinsic motivation, as engaging experiences can occur even during non-voluntary participation. Additionally, using electroencephalography as a neurophysiological measurement, Leiker, Miller, et al. (2016) found that as self-reported ratings of engagement during a motion-controlled video game task increased, the amount of cognitive resources allocated to the task increased as well (i.e., participants were processing information to a greater extent). Engagement is more than performing an action to achieve a goal; it requires more cognitive effort to reach a state of full immersion.

Summary of Experiments

This dissertation contains two experiments designed to explain the benefits of self-controlled practice on learning. As shown in Figure 1, previous research has established that self-control over task relevant choices (e.g., difficulty or when to receive feedback) have positive effects on learning and have been shown increase self-reported motivation and engagement.

Both experiments used a motion-controlled video game task (described in greater detail in subsequent sections) and each consisted of two groups: a self-controlled group (SC), in which participants chose what level of difficulty they played during each block, and a yoked group (YK), in which participants were matched to a self-controlled counterpart's difficulty scheduling. Experiment 1 was a behavioral experiment in which we were interested in effect of group (SC versus YK) on learning outcomes and the potential moderating effects of self-reported motivation and engagement (which were collected through paper and pencil surveys). Experiment 2 was a neurophysiological experiment in which we wanted to replicate the learning effects found in Experiment 1 and gain deeper insight into why these effects arise through neural correlates of motivation and engagement using electroencephalography (EEG) and eye-blink recording.

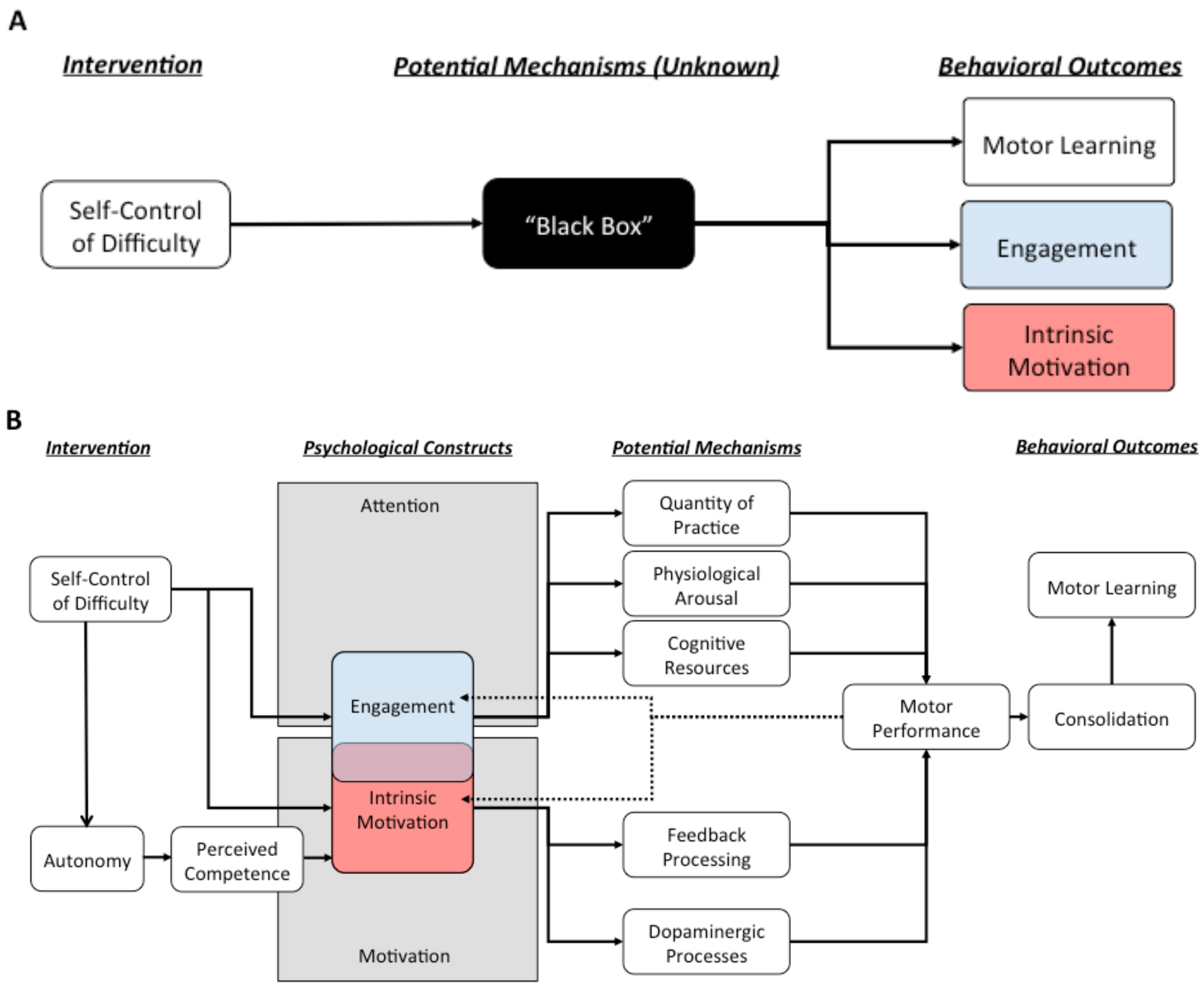

Figure 1. (**A**) Schematic showing current knowledge from previous experiments. Self-control appears to have reliable effects of motor learning, engagement, and motivation. (**B**) A new potential model showing some of the potential mechanisms that might explain why self-control of difficulty improves motor learning.

Chapter 2

Experiment 1

From very fundamental skills in the laboratory to complex skills in applied settings (e.g., rehabilitation), motion-controlled video games have the potential to improve motor learning (Laver et al., 2012; Lohse, Boyd, & Hodges, 2015; Saposnik et al., 2010). These games may enhance learning, not because of something inherent to video games, but because well-designed games utilize mechanics that increase engagement and motivation in their players (Hunicke, LeBlanc, & Zubek, 2004).

Engagement is a psychological state experienced during activity that has both affective and cognitive components (Leiker et al., 2016; O'Brien & Toms, 2008). In games, engagement comprises concepts of enjoyment, immersion, flow, and presence (Boyle, Connolly, Hainey, & Boyle, 2012). Game mechanics that are thought to contribute to engagement include viscerally pleasing stimuli, interactivity/choice, clear goals/mechanics, feedback, novelty/exploration, and adaptive difficulty (Lohse, Shirzad, Verster, Hodges, & Van der Loos, 2013; Zimmerli, Jacky, Lunenburger, Riener, & Bolliger, 2013). It is important to distinguish between engagement and motivation, although they are similar constructs, as a participant could be motivated to play a game, but if the game no longer offers adequate challenge, they may not be engaged by the game, potentially reducing future motivation. Also, in our previous work, we have found separable effects of engagement and motivation (Leiker et al., 2016; Lohse, Boyd, & Hodges, 2015). Furthermore, in the present study, we are specifically interested in intrinsic motivation, motivation that is driven by interest/enjoyment in an activity itself, not external rewards or pressures (Ryan & Deci, 2000).

In order to explore how engagement and motivation change as a function of the practice environment, the game mechanic we chose to manipulate was interactivity/choice. Interactivity is what allows the player to communicate with the gaming system through various actions (Ritterfeld, Shen, Wang, Nocera, & Wong, 2009), while choice is the freedom to make decisions during the game. These two mechanics are intertwined, as interactivity involves choosing an option, and making a choice that affects the game is an interaction. Thus, we collectively refer to this mechanic simply as choice. More specifically, we gave participants choice over how difficulty progressed during practice, by allowing some participants to choose when and how to adjust the difficulty of practice. Progressive and appropriate challenge is regarded as a key component of "flow", which is a state of full immersion and enjoyment in an activity, such as a game (Csikszentmihalyi & Csikszentmihalyi, 1992). If a game is too easy or too hard in the beginning, then players will become either bored or frustrated, respectively, and lose motivation to play the game. However, gamers seem to enjoy what is known as "positive failure", or falling just short of success (Ravaja et al., 2005). Some studies indicate that players can be nominally failing approximately 80% of the time during game play, yet they are still engaged and optimistic to try again (Lazzaro, 2004).

The concept of using choice to potentiate learning has also been examined in the motor learning literature. Autonomy over when to receive feedback (Chiviacowsky & Wulf, 2002, 2005; Fairbrother, Laughlin, & Nguyen, 2012; Grand et al., 2015), when to view a video demonstration (Wulf, Raupach, & Pfeiffer, 2005), and the number of trials (Post, Fairbrother, Barros, & Kulpa, 2014) during practice has been shown to enhance motor skill learning compared to yoked conditions. When given control over difficulty levels throughout a motor task that required intercepting falling targets by displacing a stylus on a pen tablet, participants performed better and with more accuracy during immediate and delayed retention tasks than their yoked counterparts (Andrieux, Danna, & Thon, 2012). Thus, self-control over different aspects of practice seems to be advantageous for motor learning (compared to control conditions), but the underlying mechanism/s for this advantage are still unknown.

There are two major hypotheses for why autonomous conditions may improve learning and performance. The first hypothesis is that having control over aspects of practice may allow participants to receive information that is better suited for their preferences and needs (Chiviacowsky & Wulf, 2002). Participants are able to ask for what they need when they need it, which in turn may increase the amount of information processing that occurs (Grand et al., 2015; Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997). The second hypothesis is that self-control increases motivation and engagement during practice, subsequently increasing learning (McNevin, Wulf, & Carlson, 2000). Behaviorally, a number of studies have shown that engagement and motivation during practice are associated with superior learning at the group level (Chiviacowsky, Wulf, Lewthwaite, & Campos, 2012; Lohse et al., 2015). To the contrary, there has also been evidence that suggests there is not a direct, causal effect of motivation and engagement on learning (Ste-Marie, Carter, Law, Vertes, & Smith, 2015).

The goal of the present study was to explore the relationship between autonomy, motivation, and engagement, but primarily to see if increased engagement during practice was associated with better learning of the skill, similar to Lohse et al. (2015). In that study, Lohse et al. (2015) manipulated the aesthetics of a gaming environment while keeping the amount of practice and the mechanics of the game constant. Participants who trained in the “game” group (complex, space-themed graphics with ambient and task-related sound) showed statistically superior retention and transfer compared to participants in the “sterile” group (simple, geometric graphics with no sounds). Additionally, the game group self-reported statistically higher levels of engagement than the sterile group, however, the individual engagement scores were not correlated with participants' post-test performances.

In Experiment 1, we manipulated a different game mechanic, choice, during a motion-controlled video game using only the "game" aesthetic condition adapted from Lohse et al. (2015). Participants were assigned to either a self-controlled or a yoked group, completed one day of practice, and then returned one week later for delayed retention tests. We hypothesized that participants in the self-controlled group would show superior learning (i.e., better performance on retention and transfer tests) compared to the yoked group. We also hypothesized that if autonomy were related to motivation and engagement, then participants in the self-controlled group would learn more and have higher self-reported levels of motivation and engagement than the yoked group.

Methods

Participants. Sixty participants were recruited through classes, flyers, and an online advertisement at Auburn University (22 male, 38 female). The average age of the participants was 21.1 (1.96) years, shown as Mean(SD). Five participants indicated that they had used the Kinect system at some point in the past. Four of the participants had played the Kinect system in the last three months or regularly played before that, self-reported frequency 0.06 (0.23) days/week. Forty-seven participants indicated that they played some other form of motion-controlled game (mostly Nintendo Wii ®), with an average frequency of 0.26 (0.41) days/week. Fifty-four participants indicated that they played games in some other medium (most commonly a mobile phone) with an average frequency of 1.41 (1.51) days/week. Participants were pseudo-randomly assigned to either a self-controlled group, in which participants chose the difficulty level of each practice block, or a yoked group, in which practice block difficulty was matched to a self-controlled counterpart. Assignment was pseudo-random because yoked participants were matched to a self-controlled participant by handedness and gender. Participants also self-reported no musculoskeletal or neurological impairments that would affect their performance and all had normal or corrected-to-normal vision.

Game apparatus. Participants played a custom-built computer game using the Microsoft Kinect ® (Microsoft, Redmond, WA) which was written in Visual Studio 2013 using XNA Game Studio 4.0 and the Kinect SDK 1.8 (Microsoft, Redmond, WA). The game was displayed on a 152cm Samsung ® HDTV that was 193cm above the ground. The Kinect camera was placed 106cm above the ground and approximately 145cm away from the participant (who could move forward or back to improve tracking).

Procedures. All procedures were approved by Internal Review Board of Auburn University (15-229 EP 1506). On Day 1, participants provided written informed consent and the initial survey measuring handedness and past experience with video games. The Kinect system was then calibrated to track the participant's non-dominant hand. Participants controlled the motion of a spaceship on the screen in order to catch asteroids and throw them into a yellow target that would appear at the top, bottom, or sides of the screen. All participants were given standardized instructions on how to play the game. Participants in both groups were instructed to catch the objects as quickly as possible and hit as many targets as they could. This combined speed-accuracy constraint was reinforced by the participants' in-game score. Participants lost a single point for every ten frames (~167 ms) that they had not yet hit the target and scored 100 points for every target hit.

Following the standardized instructions, all participants completed a 20-trial pre-test at the lowest difficulty level (Novice I). After the pre-test, participants in the self-controlled group were told they were allowed to choose whether they wanted to increase, decrease, or remain at the same difficulty level before each block began for the remaining 19 practice blocks (380 trials total). There were nine difficulty levels participants could choose from (listed as easiest to hardest): Novice I, Novice II, Novice III, Professional I, Professional II, Professional III, Expert I, Expert II, and Expert III. The names of these difficulty levels were displayed for each participant between each practice block.

Participants in the yoked group were told that the difficulty level would increase, decrease, or remain the same for the remaining 19 practice blocks (unknown to participants, the exact schedule of this depended on their self-controlled counterpart). Yoked participants also saw the names of each difficulty level between blocks, so they were aware of what difficulty they had just completed and which difficulty they would complete next (identical to the self-controlled participants).

Approximately one week later (5-9 days with a median of 7 days), participants returned for three post-test conditions—each participant completed a 20-trial block at the easy (Novice II), the intermediate (Professional II), and the intense (Expert II) difficulty levels (60 trials total). The order of the post-tests was counterbalanced across participants.

Survey measures. Following the end of practice on Day 1, participants completed a post-training survey that included a language-adapted version of a user-engagement scale that was developed in the human-computer interaction literature (O'Brien & Toms, 2010), and language-adapted version of the intrinsic motivation inventory, IMI (McAuley, Duncan, & Tammen, 1989), which was edited to include only the interest/enjoyment, perceived competence, effort, and pressure/tension subscales. Participants were allowed to complete these surveys at their own pace. Participants were instructed to provide what they thought was the "best" answer for a given question. (The full-text of these surveys is presented in the Appendix A.)

Statistical power and analyses. *A priori*, this study was designed to detect two effects: 1) the effect of choice on learning, defined as the main-effect of group controlling for pre-test score in a regression model predicting post-test scores and 2) the effect of engagement on learning, defined as the main-effect of engagement controlling for group and pre-test score in a regression model predicting post-test scores. Based on G*Power 3.1.9.2 (Faul, Erdfelder, Lang, & Buchner, 2007), the sample-size required to achieve 80% power for the effect of choice on learning was $N = 55$ (assuming $f^2 = 0.15$, $\alpha = 0.05$, tested predictors = 1, total predictors = 2), and the same sample size was determined to be the same for the effect of engagement on learning (assuming $f^2 = 0.15$, $\alpha = 0.05$, tested predictors = 1, total predictors = 3). To allow for attrition/missing data, the decision was made to recruit $N = 60$ participants.

The primary outcome in our experiment was the participants' in-game score. In-game score combines the requirements of accuracy and speed and has been found to be representative of these variables in previous work (Lohse et al., 2015). In order to conduct the *a priori* regression analysis, we needed to justify the assumption that post-test scores can be averaged into a single score, thus we started with repeated measures (RM) ANCOVA, controlling for pre-test, with a between-subjects factor of group (self-controlled versus yoked) and a within-subject factor of test difficulty (easy, moderate, or intense). Provided that group differences were in the same direction across all tests, we reasoned it was valid to average across tests into a single post-game score for our regression models. In secondary analyses, we also decomposed in-game score into the proportion of asteroids caught, the time to catch (for successful catches), and the number of targets hit (for successful catches) and conducted identical analyses (see Appendix A).

For the survey measures, we first conducted reliability analyses for all items of the User Engagement Scale to make sure these items could be collapsed into subscales, and then we calculated the reliability among the subscales (Cronbach's $\alpha = 0.82$) before collapsing into a single Engagement score. For the IMI, the key subscale is the Interest/Enjoyment subscale (which represents intrinsic motivation), whereas Perceived Competence, Effort, and Pressure/Tension subscales measure related but distinct constructs. As such, we were primarily interested in group differences in the composite Engagement score and the Interest/Enjoyment subscale score. However, we tested group differences across all subscales using independent samples t-tests (following tests of normality and homogeneity of variance).

A priori, we were interested in the potential effect that engagement during practice would have on learning. Thus, following our regression analysis predicting post-test performance as a function of group controlling for the pre-test performance, we added the composite Engagement score to this model. Other exploratory analyses were conducted with the other survey measures and are detailed below.

Finally, we also assessed participants' in-game scores during practice and how participants in the self-controlled group chose to switch. As exploratory analyses, we looked at potential relationships between performance/switching behavior during practice and the composite Engagement and Interest/Enjoyment scales that were assessed at the end of practice.

Results

The effect of choice on learning. There was no difference between groups on the pre-test, $t(58) = -0.21$, $p = 0.84$, but prior to our primary regression analysis, we conducted a RM ANCOVA to validate the assumption of collapsing across the different post-tests to create a single post-test score. Controlling for pre-test, there was a significant main effect of group,

$F(1,57) = 4.51$, $p = 0.04$, $\eta_p^2 = 0.07$, such that participants in the self-controlled group performed better on the post-test than participants in the yoked group, see Figure 1. There was also a main effect of difficulty, $F(2,114) = 61.55$, $p < 0.001$, $\eta_p^2 = 0.52$, such that participants performed worse on the moderate difficulty test than the easy test, and worse on the intense difficulty test than either of the other two. Complicating these effects was an interaction of group with difficulty, $F(2,114) = 3.21$, $p = 0.04$, $\eta_p^2 = 0.53$, such that the effect of group was not statistically significant on the easy test ($p = 0.24$) or the intense test ($p = 0.88$), but was statistically significant on the moderate difficulty test ($p = 0.004$). The reason group differences may have only manifested on moderate difficulty is because of ceiling and floor effects, for the easy and intense conditions, respectively. Although the significance of the group effect was only present on moderate difficulty, the group effect was consistently in the same direction (self-controlled > yoked), so we reasoned that averaging across post-tests was justified to reduce the total number of regression models and thus the false positive rate.

Consistent with the RM ANCOVA, the regression model revealed the self-controlled group performed significantly better on average across the post-tests ($p = 0.04$, see Table 1) when controlling for pre-test performance. This multivariable relationship is shown in Figure 1B. The same analyses were also conducted for the proportion of asteroids caught, the time to catch (for successful catches), and the proportion of targets hit (for successful catches). The results of these analyses generally accord with the analysis of in-game scores and are presented in Appendix A.

Survey measures. Descriptive statistics for the survey measures are provided in Table 2. Contrary to predictions, there was no difference between groups on the engagement scale overall ($p = 0.99$). However, there was a difference on the interest/enjoyment subscale of the IMI ($p =$

0.01), such that the self-controlled group reported greater interest/enjoyment than the yoked group. There were no other statistically significant differences between groups.

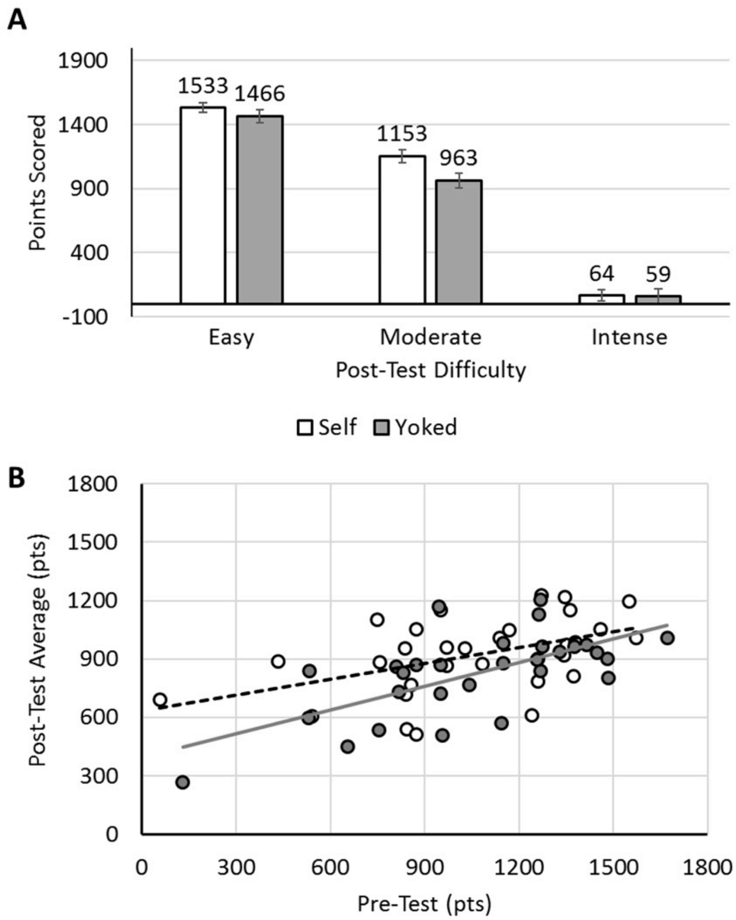

Figure 2. (**A**) Adjusted means for each post-test as a function of group and difficulty (evaluated at the pre-test average of 1058 points). Error-bars show the standard-error of the mean. (**B**) Averaging across test difficulty, the post-test average for each participant is shown as a function of group and pre-test score.

Table 1. Parameters for the Regression Model Testing the Effect of Choice on Learning.

	Coefficient	**95% CI**	***p*-value**	**Model *F(2,57)***	**Model R^2**
Model:	--	--	--	15.37	0.35
Intercept	873.24	829.16, 917.32	<0.001		
Pre-Test Score	0.34	0.21, 0.47	<0.001		
Group	46.78	2.68, 90.87	0.038		

Note. For the group variable, self-control was coded as +1 and yoked was coded a -1 and pre-test score was centered around the average of 1,058 points.

Table 2. Group differences on the User Engagement Scale and the Intrinsic Motivation Inventory.

Scale	**Self-Control – M(SD)**	**Yoked – M(SD)**	***p*-value**
*Engagement (Total)	4.55 (0.82)	4.54 (0.87)	0.99
Focused Attention	4.05 (1.26)	4.33 (1.17)	0.39
Usability	4.70 (0.97)	4.22 (1.04)	0.07
Aesthetics	4.57 (1.07)	4.72 (1.10)	0.59
Endurability	4.27 (1.21)	4.37 (1.18)	0.75
Novelty	4.38 (1.41)	4.49 (1.24)	0.75
Involvement	5.31 (1.08)	4.49 (1.15)	0.57
*Interest/Enjoyment	4.85 (1.31)	4.12 (0.79)	0.01
Competence	4.35 (1.31)	4.04 (1.21)	0.35
Effort	5.33 (1.34)	5.20 (1.24)	0.69
Pressure/Tension	5.05 (1.21)	4.57 (1.49)	0.18

Note. The interest/enjoyment scale is the subscale of the IMI thought to most closely represent intrinsic motivation. P-values are for independent samples t-tests with $df = 58$. * denotes the subscales of *a priori* interest.

Testing effects of engagement and motivation on learning. Although there was no difference in engagement between groups, that does not preclude the possibility of a relationship between individual differences in engagement and individual differences in learning. Thus, we continued with our *a priori* hypothesis that, controlling for group and pre-test, there might be a relationship between engagement during practice and post-test performance. Additionally, because the participants' interest/enjoyment rating was sensitive to the experimental manipulation, we conducted an exploratory regression testing the hypothesis that, controlling for group and pre-test, there might be a relationship between interest/enjoyment during practice and post-test performance.

As shown in Table 3, there was no statistically significant relationship between post-test performance and engagement during practice (p = 0.20) or interest/enjoyment during practice (p = 0.87), controlling for group and pre-test performance. Thus, consistent with our previous work, these data show an improvement in learning (self-controlled > yoked) coincident to increased motivation (self-controlled > yoked), but there was no evidence that individual differences in motivation or engagement were related to individual differences in learning (see also Figure 2A).

Table 3. Parameters for the Regression Models Testing the Effects of Engagement and Intrinsic Motivation on Learning.

	Coefficient	**95% CI**	***p*-value**	**Model *F(3,56)***	**Model R^2**
Model 1:	--	--	--	10.93	0.37
Intercept	873.14	829.30, 916.97	<0.001		
Pre-Test Score	0.33	0.21, 0.46	<0.001		
Group	46.67	2.82, 90.52	0.038		
Engagement	34.06	-18.55, 86.69	0.200		
Model 2:	--	--	--	10.08	0.35
Intercept	873.24	828.76, 917.72	<0.001		
Pre-Test Score	0.34	0.21, 0.47	<0.001		
Group	45.49	-1.53, 92.50	0.058		
I/E	3.56	-38.47, 45.59	0.87		

Note. For the group variable, self-control was coded as +1 and yoked was coded a -1, pre-test score was centered around the mean of 1,058 points, engagement was centered around the mean of 4.55, and interest/enjoyment (I/E) was centered around the mean of 4.49.

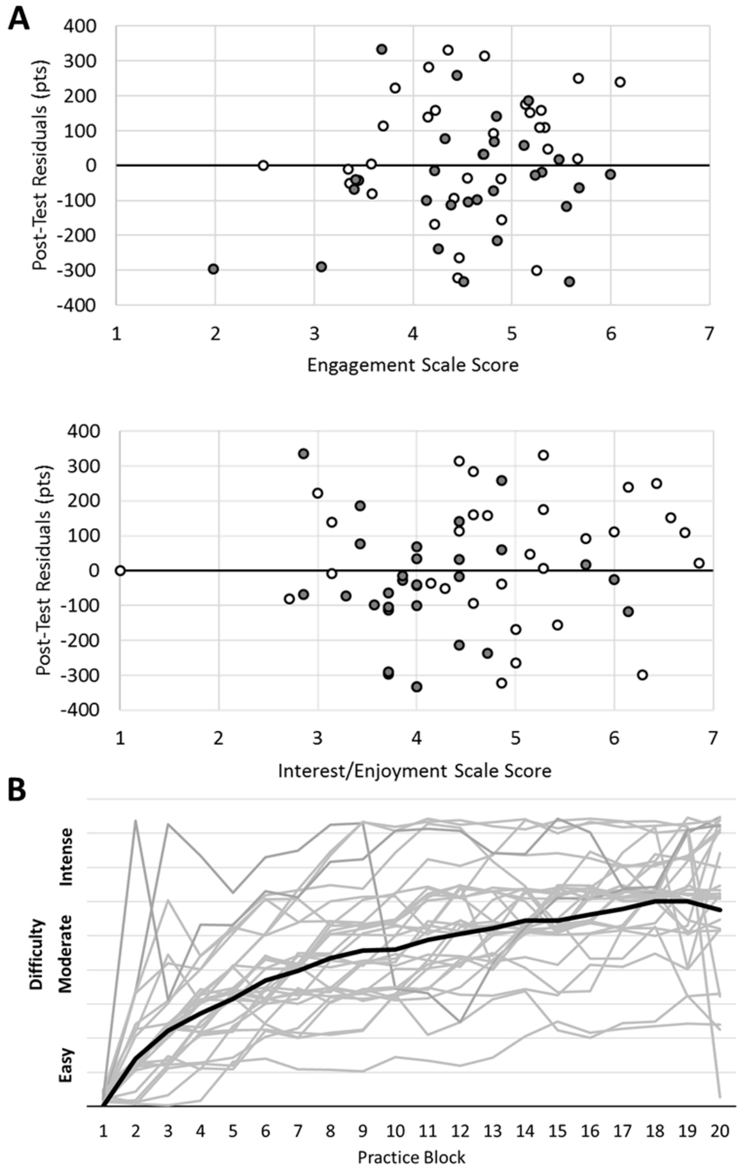

Figure 3. (***A***) Post-test residuals controlling for pre-test (i.e., positive numbers mean performance was better than predicted from pre-test) as a function of group, engagement scale score, and the enjoyment subscale of the IMI. White dots represent the self-control group and grey dots represent the yoked group. (***B***) Choices of difficulty during practice as a function of block for the self-controlled participants. Individual trajectories are shown in grey; the group mean trajectory is shown in black.

Performance during practice and relationships to engagement and motivation. As shown in Figure 2B, participants in the self-controlled group generally chose to increase the difficulty of practice over time. A RM-ANCOVA controlling for pre-test was used to test for potential differences between groups during practice. There was a main effect of practice block, $F(8.69,495.5) = 2.03$, $p = 0.007$, $\eta_p^2 = 0.03$, $\varepsilon_{gg} = 0.48$ (following a Green-Geisser correction for the violation of sphericity), such that participants' scores generally decreased from the first block of practice, 1128.85 points (495.49), to the last block of practice, 539.70 (600.24). (This decrease over time makes sense, because participants were continuously increasing the difficulty of practice.) There were, however, no differences between the self-controlled and yoked groups during practice as the main effect of group was not significant, $F(1,57) < 1$, nor was there a Group by Block interaction, $F(8.69,495.5) < 1$.

To look for possible relationships between participants' performance during practice, engagement, and motivation, we restricted our analyses to the self-controlled group. We conducted a series of exploratory bivariate correlations between the overall Engagement scale and the Interest/Enjoyment scale and three features of participants' performance: average number of points scored during practice, the average level of difficulty during practice (on a 9-point scale), the number of changes in difficulty during practice. The details of these correlations are shown in Table 4. None of these relationships were statistically significant.

Table 4. Correlations between Engagement, Interest/Enjoyment, and performance during practice.

Practice Variable Name M(SD)	**Engagement (Overall)** 4.55 (0.82)	**Interest/Enjoyment** 4.85 (1.31)
Average Points Scored 764.52 (234.69)	r = -0.06, p = 0.74	r = 0.03, p = 0.86
Average Level of Difficulty 5.28 (1.20)	r = 0.08, p = 0.68	r = -0.02, p = 0.91
Number of Changes in Difficulty 8.13 (2.40)	r = 0.35, p = 0.06	r = 0.32, p = 0.09

Note. Only data from the self-controlled participants were used in these analyses.

Discussion

Consistent with previous motor learning research, our data provide further evidence that autonomy during practice improves learning. When allowed to choose what difficulty level at which to play, the self-control group had superior learning effects compared to the yoked group, as measured by post-test performance. This effect was complicated by a Group by Test Difficulty interaction, such that the difference between groups was only statistically significant on the moderate difficulty post-test. This interaction is likely attributable to ceiling and floor effects on the easy and intense difficulty tests, respectively. It is also important to note, that even though the difference between groups was only significant on the moderate difficulty test, the direction of the effect was the same for the easy and intense tests. Thus, on average, the self-controlled group who was given more autonomy during practice showed improved retention compared to the yoked controlled group. Furthermore, in our investigation into the underlying mechanisms for why autonomy seems to be advantageous for learning, we found a significant increase in intrinsic motivation for the self-control group during practice, however, no significant differences were found for any of the other IMI subscales or for any measure on the User Engagement Scale.

At first glance, the relationship between intrinsic motivation and learning appears to support the motivation hypothesis for explaining the autonomy effects (McNevin, Wulf, & Carlson, 2000). An argument could be made to counter this, however, as the relationship only exists at the group level. If motivation and learning were as robustly related as postulated (Wulf & Lewthwaite, 2016), then individual differences in motivation should reflect individual differences in learning. However, in the current study, neither individual differences in motivation nor individual differences in engagement were associated with individual differences in learning. Thus, although there have been multiple studies that observed an increase in motivation or engagement coincident to improved learning at the group-level, individual differences in motivation/engagement do not appear to explain individual differences in learning (Leiker, Miller, et al., 2016; Lohse et al., 2015; Ste-Marie et al., 2015).

It is important to clarify that the results of the current study are not evidence against the importance of motivation in learning, but evidence against a strict interpretation of the motivation hypothesis. These data leave open the possibility that relationships between intrinsic motivation and learning might be mediated by other variables. Participants clearly enjoy autonomy, as measured by the intrinsic motivation subscale of the IMI, but the benefits that come from choice may actually stem from getting critical information when it is needed. Having control over the level of difficulty allows participants to choose what is most appropriate for them when they need it, which may increase the amount of information processing that occurs as a player navigates through the game (Janelle et al., 1997). Using a similar motion-controlled video game task while simultaneously recording EEG, Leiker, Miller, et al. (2016) found that as individual self-reported engagement scores increased, the amount of cognitive resources devoted to performing the task increased as well (measured by EEG), suggesting that changes in affective variables (like motivation and engagement) might have ancillary effects on information processing. These findings, along with a recent study by Ste-Marie and colleagues (2015), argue that there is not a direct correspondence to motivation during practice and learning, and that the effects of motivation may be mediated by other mechanisms.

As such, we interpret the present data as evidence against a strictly motivational account of learning effects. However, we cannot rule out the possibility that there may be mediating variables that complicate the learning-motivation relationship. Nor can we ignore the clear role that motivation has been shown to play in learning in other contexts (e.g., fMRI studies and animal studies). Similarly, there are also some concerns for the sensitivity of the engagement and motivation survey measures used in our analysis. Although these are reliable and valid survey tools (McAuley, Duncan, & Tammen, 1989; O'Brien & Toms, 2010), future investigations may benefit from more neurophysiological methods. For instance, current hypotheses have proposed that dopminergic projections from the midbrain into the cortex may explain motor learning benefits (Lohse et al., 2013; Wulf & Lewthwaite, 2016). Electrophysiological correlates of dopaminergic activity (e.g., readiness potentials or reward positivity) or pharmaceutical agents to perturb normal dopaminergic processing (e.g., Santesso et al., 2009) would be very effective methods for better understanding the relationship between motivational processes, consolidation, and the long-term retention of motor skills.

Further, the surveys used to measure motivation and engagement (IMI and User Engagement Scale, respectively) were lengthy and only given at the end of practice. Because of this, the self-reported scores may not be truly reflective of the levels of motivation and engagement that were occurring throughout practice. Participants' motivation and engagement are dynamic variables that change over the course of practice, likely being influenced by performance on previous trials and perhaps affecting performance on subsequent trials. As such, measuring these variables at only one time-point (the end of practice) is a limitation of the current study and it may be better to measure these variables at multiple time points to better understand the dynamic nature of performance, affect, and the decision to change practice difficulty.

Dynamically measuring motivation and engagement poses a problem, however, because as mentioned above, the survey measures are quite long. Shorter measures need to be developed to investigate the relationship between autonomy, motivation/engagement, and learning over time, while also preventing participant boredom or exhaustion. Further, survey measures administered in this way are retrospective and subjective so again, complimenting survey data with more objective and immediate physiological measures of motivation and engagement may give us a clearer understanding of how autonomy during practice facilitates learning.

In conclusion, the present study suggests that autonomy over the difficulty of practice enhances motor learning, but it is still unclear as to why this occurs. Our results are inconsistent with strictly motivational explanations for these effects and thus leave open the possibility that autonomy over the practice environment benefits learning by augmenting information processing in some way. Further research is needed to delve deeper into the reasoning behind the advantages of giving participants self-control. The results of this study help to advance our theoretical understanding of the mechanisms that underlie motor learning, but the results also provide an easily translatable mechanism by which practitioners, coaches, patients, and therapists can facilitate learning: increasing self-control of practice difficulty. Autonomy in motor skill learning is clearly advantageous, but its true relationship with motivation and engagement is currently uncertain.

Chapter 3

Proposing Experiment 2—Replication and Extension

In both applied contexts and the basic science of learning, there is increasing interest in whether engagement during practice augments the learning process. This is important in many situations where learning takes place, such as in physical therapy, sports practice, and even school settings, in order to maximize learning under time constraints. For instance, punctuating study sessions with testing sessions (to increase engagement) improves students' recollection of facts, even for the untested items (Healy et al., 2017). This result suggests that testing might convey direct benefit (i.e, practice on the tested items makes them more memorable), but also an indirect benefit (i.e., generally increased engagement during practice makes all items more memorable). Similarly, it has been posited that engagement during physical/occupational therapy can have indirect benefits (i.e., engaged clients practice *more*, Lohse et al., 2015) and direct benefits (i.e., engaged clients invest more effort, practicing in a *qualitatively different* way, Zimmerli et al., 2013).

One mechanism for increasing engagement during practice is to offer participants more autonomy and interactivity within the practice environment (Lohse et al., 2015). Although there is some debate about whether or not these choices need to be task relevant or if *incidental/irrelevant* choices are sufficient (see Carter & Ste-Maire, 2017; Grand et al., in press; Lewthwaite et al., 2015), the benefit of *task-relevant* choices has been well replicated (for review see Wulf & Lewthwaite, 2016). Specifically, separate laboratories (Andreiux et al., 2012; Andreiux et al., 2015; Leiker, Bruzi, et al., HMS, 2016) have shown that having choice over difficulty level during motor skill practice (self-control group, SC) enhances learning compared to the same difficulty progression without choice (yoked control group, YK).

Although these effects have been well documented, the neural mechanisms underlying the benefits of task-relevant choices are not clear. Some researchers have hypothesized that these benefits may be attributable to changes in dopaminergic processing resulting from increased motivation (Wulf & Lewthwaite, 2016). Other research has called this hypothesis into question by showing (1) that increased motivation is coincident to increased learning at the group level, but individual differences in learning are not explained by individual differences in motivation (Leiker, Bruzi, et al., 2016). Furthermore, other researchers have shown that (2) the benefits only emerge for task-relevant choices and not irrelevant choices (suggesting that the benefits arise from task-specific information processing, not general motivation (Carter & Ste-Marie, 2017)). Finally, although the data are limited, (3) EEG data show that SC over feedback leads to greater information processing than yoked feedback schedules (Grand et al., 2015), suggesting a cognitive explanation of group differences rather than a motivational explanation.

Therefore, to address the limitations in Experiment 1 and attempt to explain possible neural mechanisms underlying choice in motor learning, I proposed a second experiment designed to include a shorter survey (to prevent participant boredom/exhaustion) at multiple time points and two neurophysiological measures: (1) spontaneous eye-blink rate and (2) frontal EEG asymmetry, which were chosen for their established relationships to dopaminergic processing and motivation (detailed below).

Spontaneous eye-blink rate. As a marker of striatal dopaminergic activity (Karson, 1983), spontaneous eye-blink rate (sEBR) can be measured easily in laboratory settings using a camera or electrophysiological tools. Evidence from animal studies suggest that the frequency of eye-blinks per minute is reflective of striatal dopamine levels, as sEBR was reduced in monkeys treated with a dopamine antagonist but increased again when given a dopamine agonist (Taylor et al., 1999). In humans, similar results have been found in patients with Parkinson's disease (which depletes striatal dopamine), as they have lowered sEBR that can be reversed by the administration of L-DOPA, a dopamine agonist that can cross the blood-brain barrier (Karson et al., 1982). By collecting sEBR, we can measure a correlate of participants' striatal dopaminergic activity and potentially gain insight into how individual dopamine levels might relate to intrinsic motivation and learning.

Being able to measure dopaminergic activity is important, as dopamine is involved in learning and consolidation processes. Dopamine is vital for reinforcement learning; during reward-seeking behavior, for instance, dopamine antagonists disrupt the ability to learn associations between new unrelated stimuli and appropriate responses (Wise, 2004). Further, long-term potentiation (LTP), or the strengthening of synapses during consolidation, is positively affected by dopaminergic neurons in the substantial nigra (Overton, Richards, Berry & Clark, 1999) and ventral tegmental areas (Bonci & Malenka, 1999). In animals, LTP can also be blocked by dopamine antagonists (Frey, Matthies, Reymann, & Matthies, 1991; Frey, & Schroeder, 1990).

Previous research has suggested that people with high dopamine levels (elicited by a dose of L-DOPA) learn better from positive outcomes (Pessiglione et al., 2006), while people with low dopamine levels (as measured by sEBR) learn better from negative outcomes (Slagter, Georgopoulou & Frank, 2015). Collecting sEBR yields a proxy of dopaminergic activity, allowing us to test the mediating influence of this factor on learning (as predicted by Wulf & Lewthwaite, 2016).

Frontal asymmetry. Emotion and motivational state have been shown to correlate with frontal EEG alpha power during rest and information processing (Coan & Allen, 2004). EEG alpha power is inversely related to cortical activation, so less alpha power (i.e., more cortical activation) in the left frontal region relative to the right frontal region is indicative of approach motivation (Coan & Allen, 2004). In previous research, greater left frontal activity (i.e., reduced left alpha power) has been associated with approach motivation and positive affect, whereas greater right frontal activity (i.e., reduced right alpha power) has been associated with avoidance/withdrawal motivation and negative affect (Harmon-Jones, 2004; Harmon-Jones & Winkielman, 2007).

Based off of Davidson's (1993) approach/withdrawal motivation model of emotion, approach motivation refers to wanting to engage with a stimulus, while withdrawal motivation refers to wanting to disengage from a stimulus. For instance, Sobotka, Davidson and Senulis (1992) found that rewards provoked greater left frontal activation during a cognitive task, but punishments provoked greater right frontal activation. This effect of greater left anterior activation is even seen in newborn infants and 10-month-olds when presented with sucrose (compared to water) and their approaching mothers, respectively (Fox & Davidson, 1986; Fox & Davidson, 1988). Based on these and other similar results, it has been postulated that there may be specific neural substrates for approach (and withdrawal motivation) in anterior parts of the left hemisphere.

Evidence has also suggested that the desire to engage with a stimulus, as defined in approach motivation, can be due to enjoyment during the activity, or can be due to dispositional or situational anger that arises while completing the activity (Harmon-Jones & Allen, 1998). Participants are approaching the stimulus in either circumstance, but it is important to note that engaging with a stimulus does not always correlate with positive affect. Multiple studies have found that EEG activity recorded immediately after being insulted led to greater left frontal activity compared to those who were not insulted, which also correlated with reported anger (Harmon-Jones & Sigelman, 2001; Jensen-Campbell et al., 2007). Further, participant state anger elicited in a study by Harmon-Jones et al. (2004) increased left frontal activity, as well as decreased right frontal activity. Approach motivation, regardless of underlying affect, can be measured by EEG alpha power in the left front cortical region.

Collecting EEG data about frontal alpha asymmetry to both establish a resting baseline and to see how it varies throughout practice will provide us with an objective and physiological index of motivation and engagement. We may be able to use this measure to show support for the motivational hypothesis as well, if we are able to predict learning from left frontal asymmetry.

Neurophysiological measures. Frontal asymmetry and sEBR are important measures that may uncover evidence to support our primary learning hypothesis: that participants in the self-controlled group will show superior learning compared to the yoked group. Both of these variables will give us a better understanding of what may improve learning—whether autonomy augments learning based on motivational components (frontal asymmetry), or dopaminergic processing components (sEBR).

Methods

Participants. Sixty participants were recruited through classes, flyers, and an online advertisement at Auburn University. Participants were pseudo-randomly assigned to either a self-controlled group, in which participants chose the difficulty level of each practice block, or a yoked group, in which practice block difficulty was matched to a self-controlled counterpart. Assignment was pseudo-random because yoked participants were matched to a self-controlled participant by sex. The participants were right-handed, had no musculoskeletal or neurological impairments that affected their performance, and had little-to-no experience playing Microsoft Kinect®. Additionally, during recruitment, participants were asked to avoid alcohol and nicotine consumption and get a sufficient amount of sleep prior to coming in for Day 1 of the experiment (Slagter, Davidson, & Tomer, 2010; Slagter et al., 2015). All experimental sessions were held before 5 PM, as sEBR increases in the evening (Barboto et al., 2000).

Game apparatus. Participants played a custom-built computer game using the Microsoft Kinect® (Microsoft, Redmond, WA) which was written in Visual Studio 2013 using XNA Game Studio 4.0 and the Kinect SDK 1.8 (Microsoft, Redmond, WA). The game was displayed on a 152cm Samsung® HDTV that was 193cm above the ground. The Kinect camera was placed 106cm above the ground and approximately 145cm away from the participant (who could move forward or back to improve tracking).

Procedures. All procedures were approved by Internal Review Board of Auburn University (16-402 EP 1610). On Day 1, participants provided written informed consent and completed the initial survey measuring handedness and past experience with video games. Participants were then be prepared for EEG recording. Resting sEBR and frontal asymmetry were recorded while the participant was sitting for 2 minutes. Next, the Kinect system was calibrated to track the participant's non-dominant (left) hand, as determined by the Edinburgh Handedness Inventory (Oldfield, 1971). Participants controlled the motion of a spaceship on the screen in order to catch asteroids and throw them into a yellow target that appeared at the top, bottom, or sides of the screen. All participants were given standardized instructions on how to play the game (see Appendix B). Participants in both groups were instructed to catch the objects as quickly as possible and hit as many targets as they can. This combined speed-accuracy constraint was reinforced by the participants' in-game score. Participants lost a single point for every ten frames (~167 ms) that they had not yet hit the target and scored 100 points for every target hit.

Following the standardized instructions, all participants completed a 20-trial pre-test at the lowest difficulty level (Novice I). After the pre-test, participants in the self-controlled group were told they are allowed to choose whether they want to increase, decrease, or remain at the same difficulty level before each block begins for the remaining 19 practice blocks (380 trials total). There were nine difficulty levels that participants could choose from (listed as easiest to hardest): Novice I, Novice II, Novice III, Professional I, Professional II, Professional III, Expert I, Expert II, and Expert III. The names of these difficulty levels were displayed for each participant between each practice block. As difficulty increased, the asteroids and targets became smaller, the asteroids moved faster, and the asteroids disappeared if not caught in time (the time to catch decreases as difficulty increases). Thus, as difficulty increased, both the speed and accuracy requirements of the game increased.

Participants in the yoked group were told that the difficulty level would increase, decrease, or remain the same for the remaining 19 practice blocks (unknown to participants, the exact schedule of this depended on their self-controlled counterpart). Yoked participants also saw the names of each difficulty level between blocks, so they were aware of what difficulty they completed and which difficulty they would complete next (identical to the self-controlled participants).

Between 5 to 9 days later, participants returned for three post-test conditions—a 20-trial block at the easy (Novice II), the moderate (Professional II), and the intense (Expert II) difficulty levels (60 trials total). Because we wanted to directly replicate the learning effects of our previous study, we used the same post-test difficulty levels, even though there were only significant differences between the self-controlled and yoked groups at the moderate difficulty (Professional II). The order of the post-tests was counterbalanced across participants.

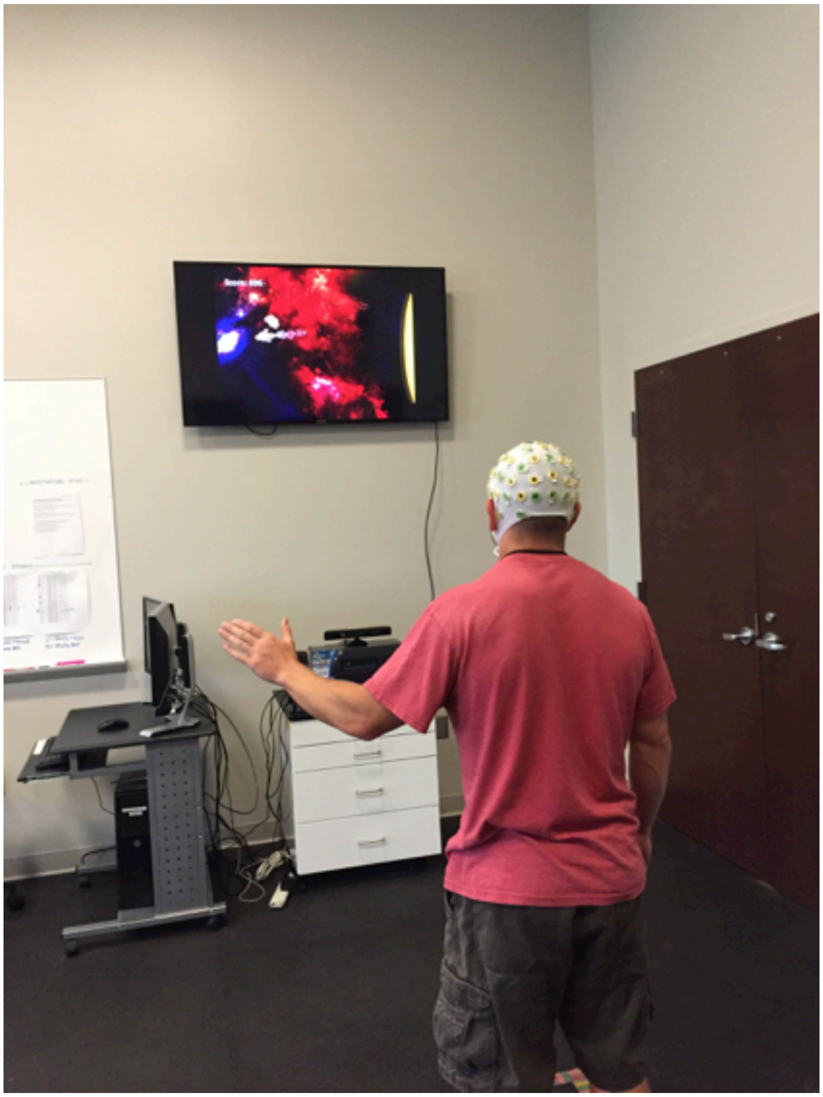

Figure 4. Experiment 2 participant set-up.

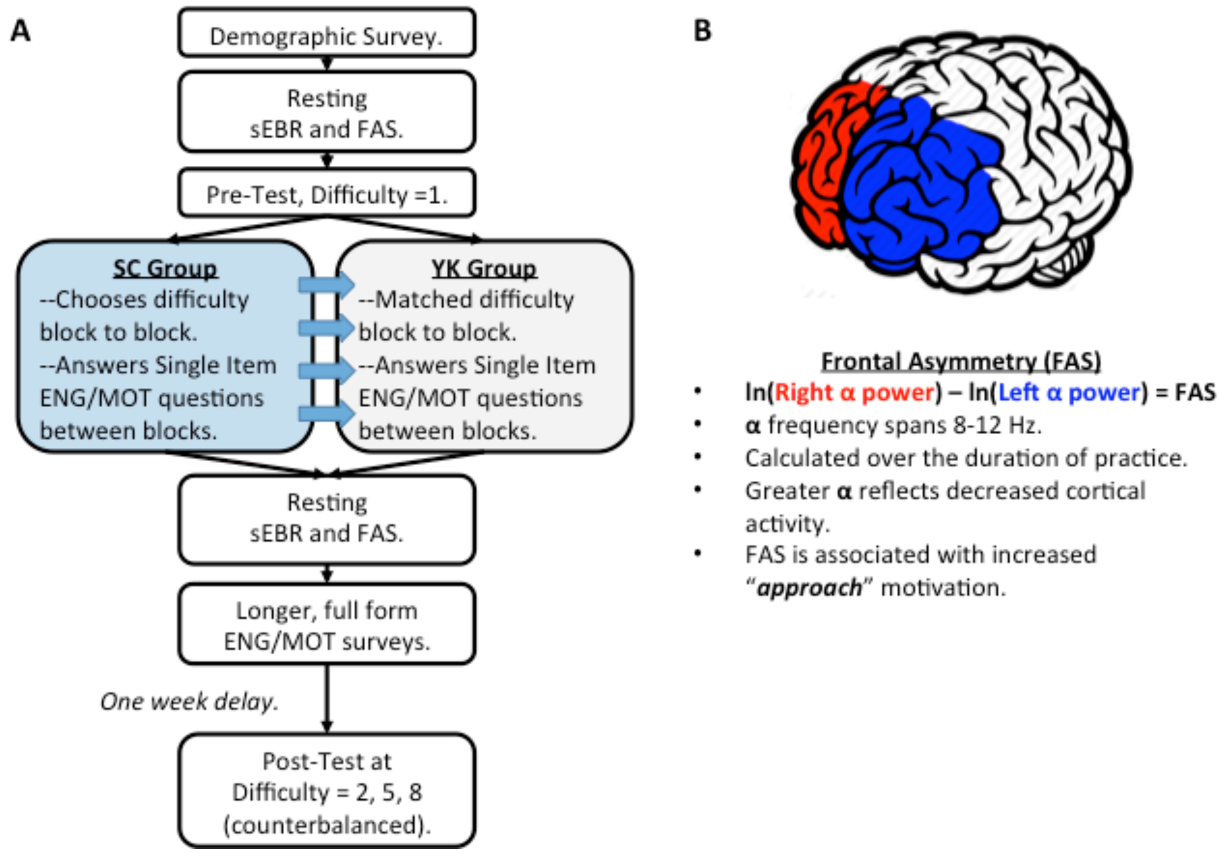

Figure 5. (**A**) Time course of Experiment 2. (**B**) Schematic showing the calculation of frontal asymmetry (FAS) in Experiment 2. SC = Self-Controlled Group; YK = Yoked Group; ENG = engagement; MOT = intrinsic motivation; sEBR = spontaneous eye-blink rate.

EEG processing and measures. Scalp EEG was collected from 32 channels of an EEG cap housing a 64-channel BrainVision actiCAP system (Brain Products GmbH) labeled in accord with an extended international 10-20 system (Oostenveld & Praamstra, 2001). Specific electrode sites included FP1, FP2, AF3, AF4, AF7, AF8, Fz, F3, F4, F5, F6, F7, F8, T7, T8, Cz, C3, C4, Pz, P3, P4, O1, O2, and a reference electrode on the right ear. EEG data were online-referenced to the left earlobe, and a common ground was employed at the FPz electrode site. Electrode impedances were maintained below 25 kΩ throughout the study, and a high-pass filter was set at 0.016 Hz with a sampling rate of 250 Hz. The EEG signal was amplified and digitized with a BrainAmp DC amplifier (Brain Products GmbH) linked to BrainVision Recorder software (Brain Products GmbH).

EEG data processing was conducted with BrainVision Analyzer 2.1 software (BrainProducts GmbH). Data were rereferenced to an averaged ears montage, band-pass filtered between 0.1 and 40 Hz with 24-dB rolloffs with a 60 Hz notch employing a zero phase shift Butterworth filter. Next, eye blinks were reduced employing the independent component analysis (ICA)-based ocular artifact rejection function within the BrainVision Analyzer software (electrode FP2 served as the vertical electrooculogram channel; BrainProducts, 2013). This function searches for an ocular artifact template in channel FP2 and then finds ICA-derived components that account for a user-specified (70%) amount of variance in the template-matched portion of the signal from FP2. These components were removed from the EEG signal, which was then reconstructed for further processing. Each practice block was recorded separately, but statistically, was concatenated together into groups of five blocks (Blocks 1-5, 6-10, 11-15, and 16-20). Next, data were epoched into 1-s segments. Trials with a change of greater than 100 µV in a moving 200 ms time window were removed at electrodes used in FAS calculations. A fast

Fourier transformation was applied with 0.997 Hz bins and a Hamming window with a 50% overlap. Segments were then averaged across the alpha frequency bandwidth (8-12 Hz) in blocks as previously noted (e.g., 1-5, 6-10, etc.). Before statistical analysis, a natural log transformation was calculated for 5 electrodes in the left frontal region (AF3, AF7, F3, F5, F7) and 5 electrodes in the right frontal region (AF4, AF8, F4, F6, F8). Next, we averaged across the 5 electrodes in the left frontal region, as well as the 5 electrodes in the right frontal region. Finally, we subtracted left from right to determine asymmetry. Therefore, higher scores (greater left frontal activity) were indicative of approach motivation, while lower scores (greater right frontal activity) were indicative of avoidance/withdrawal motivation.

Survey measures. In order to dynamically measure engagement and intrinsic motivation and to maintain the pace of the experiment, one question for each construct was given to participants after each of the 20 practice blocks. We then correlated these responses with the responses on the full engagement and motivation surveys given at the end of practice. At the end of the first block of practice, participants were read definitions for engagement and intrinsic motivation (see Appendix B). Following these definitions, and at the end of each subsequent block, participants responded with how engaged and motivated they were by that block on an 11-point scale (see Figure 4). Responses to these questions are referred to as single-item engagement and single-item intrinsic motivation.

Following the end of practice on Day 1, participants completed a post-training survey that included the full language-adapted version of the User Engagement Scale (O'Brien & Toms, 2008, 2010), and a language-adapted version of the Intrinsic Motivation Inventory, IMI (McAuley et al., 1989), which was edited to include only the interest/enjoyment, perceived competence, effort, and pressure/tension subscales. It should be noted that it is the interest/enjoyment subscale that is thought to specifically index intrinsic motivation, while the other subscales are correlates of motivation (Deci, Eghrari, Patrick, & Leone, 1994). Composite scores on the User Engagement Scale and the IMI are referred to as long-form engagement and long-form intrinsic motivation.

Participants also completed the Beck Depression Inventory-II (Beck, Steer & Brown, 1996) to control for a possible covariate of depression, as resting frontal asymmetry (specifically decreased left frontal activity) has been associated with depression (Harmon-Jones & Allen, 1997; Stewart et al., 2010; Thibodeau, Jorgensen, & Kim, 2006). See Appendix C.

Statistical analyses and power. The primary outcome of this study was that (1) participants in the self-controlled group will show superior learning (i.e., better performance on retention and transfer tests, based on the in-game score) compared to the yoked group. Replicating Leiker, Bruzi, et al. (2016), the primary outcome was defined as the effect of group (self-controlled versus yoked) on the delayed retention test, controlling for pre-test scores. Based on G*Power 3.1.9.2 (Faul, Erdfelder, Lang, & Buchner, 2007), the sample-size required to achieve 80% power for the effect of choice on learning was N = 55 (assuming $f^2 = 0.15$, $\alpha = 0.05$, tested predictors = 1, total predictors = 2). To allow for attrition/missing data, the decision was made to recruit N = 60 participants.

In exploratory analyses, we predicted that (2) participants who exhibit greater left frontal activation during practice will show superior learning compared to participants who exhibit more right frontal activation. Similarly, we also predicted that (3) participants who show greater resting sEBR at baseline will show superior learning on the delayed retention test. Both of these physiological correlates of dopaminergic activity were predicted to be positively associated with learning based on previous research (Pessiglione et al., 2006) and motor learning theories (Wulf

& Lewthwaite, 2016). Operationally, we tested these relationships in regression models predicting post-test performance, controlling for pre-test scores and group.

Outside of our primary hypotheses concerning learning, these data were also useful in exploring a number of hypotheses related to engagement and motivation during practice. Consistent with Leiker, Bruzi, et al. (2016), we predicted that (1) participants in the self-controlled group who change difficulty levels more often will report higher levels of engagement and motivation in post-practice surveys compared to those who choose not to change difficulty and (2) that the self-controlled group will, on average, report higher levels of intrinsic motivation than the yoked group. Furthermore, we predicted that (3) participants who exhibit greater left frontal activation will report higher levels of engagement and motivation in post-practice surveys compared to participants in the self-controlled group who exhibit more right frontal activation. We also predicted that (4) on average, participants in the self-controlled group will show greater frontal asymmetry than participants in the yoked group. A novel addition of the proposed study was the assessment of engagement and motivation following each block of practice. (5) To establish the concurrent validity of these single-item assessments between blocks we conducted Spearman Rank-Order Correlations between the average score of single-item between-block assessments and the composite scores of long-form post-training assessments. Finally, (6) to explore the relationships between performance, difficulty, engagement, and motivation, we used mixed-effect regression. A series of regression models were constructed in which we regressed performance on the current block onto pre-test performance and block number (Model 1), difficulty in the block (Model 2), motivation for that block (Model 3), and engagement on that block (added in Model 4).

Results

The effect of choice on learning. In order to test the primary outcome of choice on learning in Experiment 2, we conducted a RM ANCOVA controlling for Pre-Test. Unlike to the results found in Experiment 1, there was not a significant main effect of Group in Experiment 2, $F(1,57) = 1.22$, $p = 0.27$. The participants in the self-controlled group did not perform statistically better on the post-test than participants in the yoked group, controlling for pre-test scores. Additionally, there was no Group by Difficulty interaction for Experiment 2, $F(2,114) = 0.01$, $p = 0.99$, which was found in Experiment 1. There were no differences in post-test results between the groups for the different difficulty levels. There was, however, a significant main effect of Difficulty, $F(2,114) = 804.64$, $p < 0.001$, such that participants performed worse on the moderate difficulty test than the easy test, and worse on the high difficulty test than either of the other two, see Table 5. There was also a significant Pre-Test by Difficulty interaction, $F(2,114) = 3.60$, $p = 0.03$. For participants in the lower 25% of the pre-test, the scores were 1404.87, 744.60, and 83.8 on the easy, moderate, and high difficulty post-tests respectively. For participants in the upper 25% of the pre-test, the scores were 1569.33, 1074.27, and 183.00 points. As such, this interaction appears to be driven by the fact the differences between high and low-scoring participants (on the pre-test) were less pronounced on the easier post-tests and more pronounced on the difficult post-tests.

Table 5. **Descriptive statistics for participants' in-game scores across the different tests.**

	Overall	**SC Group**	**YK Group**
In-Game Scores			
Pre-Test	1167.68 (299.96)	1134.77 (291.62)	1200.6 (306.14)
Acquisition	741.82 (236.85)	758.11 (217.68)	725.53 (257.39)
Easy Post-Test	1493.68 (207.78)	1511.90 (187.96)	1475.47 (227.63)
Moderate Post-Test	980.92 (325.85)	994.30 (334.84)	967.53 (321.77)
Difficult Post-Test	113.03 (226.56)	135.00 (221.42)	91.07 (233.25)
User Engagement Scale			
Total Engagement	4.60 (0.82)	4.72 (0.74)	4.48 (0.89)
- Focused Attention	4.40 (1.02)	4.44 (0.89)	4.36 (1.14)
- Usability	4.29 (1.04)	4.27 (1.11)	4.31 (0.98)
- Aesthetics	4.80 (1.21)	5.05 (1.11)	4.54 (1.27)
- Endurability	4.49 (1.13)	4.71 (1.00)	4.27 (1.21)
- Novelty	4.43 (1.31)	4.56 (1.19)	4.31 (1.43)
- Involvement	5.18 (1.08)	5.29 (0.90)	5.08 (1.25)
Intrinsic Motivation Inventory			
Interest/Enjoyment	4.57 (1.00)	4.68 (0.89)	4.46 (1.10)
Competence	4.28 (1.21)	4.57 (0.82)	4.00 (1.46)
Effort	5.69 (0.91)	5.81 (0.86)	5.56 (0.96)
Pressure/Tension	4.75 (1.16)	4.75 (1.15)	4.76 (1.18)
Other Survey Measures			
Beck Depression Inventory-II	6.03 (7.37)	5.57 (6.04)	6.5 (8.58)
Single Item Engagement	8.15 (1.47)	8.57 (1.10)	7.73 (1.68)
Single Item Motivation	7.63 (1.65)	8.14 (1.46)	7.12 (1.69)
Physiological Measures			
Resting sEBR	41.18 (24.56)	41.93 (26.02)	40.43 (23.44)
Resting FAS	0.46 (1.23)	0.35 (1.14)	0.56 (1.33)
Practice FAS	0.36 (1.22)	0.29 (1.10)	0.42 (1.34)

Note. Values are shown as mean (SD) in on each test.

Because the results of the primary outcome differed between Experiment 1 and Experiment 2, we conducted a RM ANCOVA, controlling for Pre-Test, with the combined data from both experiments to test if the effect of group was significantly different from one experiment to the next. In the resulting Difficulty by Group by Experiment RM ANCOVA, with a covariate of pre-test, we did not find a statistically significant Group by Experiment interaction, $F(1,115) = 0.32$, $p = 0.58$. However, across the two experiments, there is a significant main effect of Group, $F(1,115) = 5.11$, $p = 0.03$.

Thus, even though the effect of Group was not statistically significant in Experiment 2, the lack of a Group by Experiment interaction in the combined analysis suggests the difference between the two experiments is within the difference we would expect due to sampling variability. Given that the main-effect of Group was statistically significant in the combined analysis, these results do support an advantage for self-controlled practice relative to a yoked control group. Additionally the combined effect size (merging Experiments 1 and 2) is probably a better estimate of the effect of Group for future studies as it is a more conservative estimate for the effect of Group.

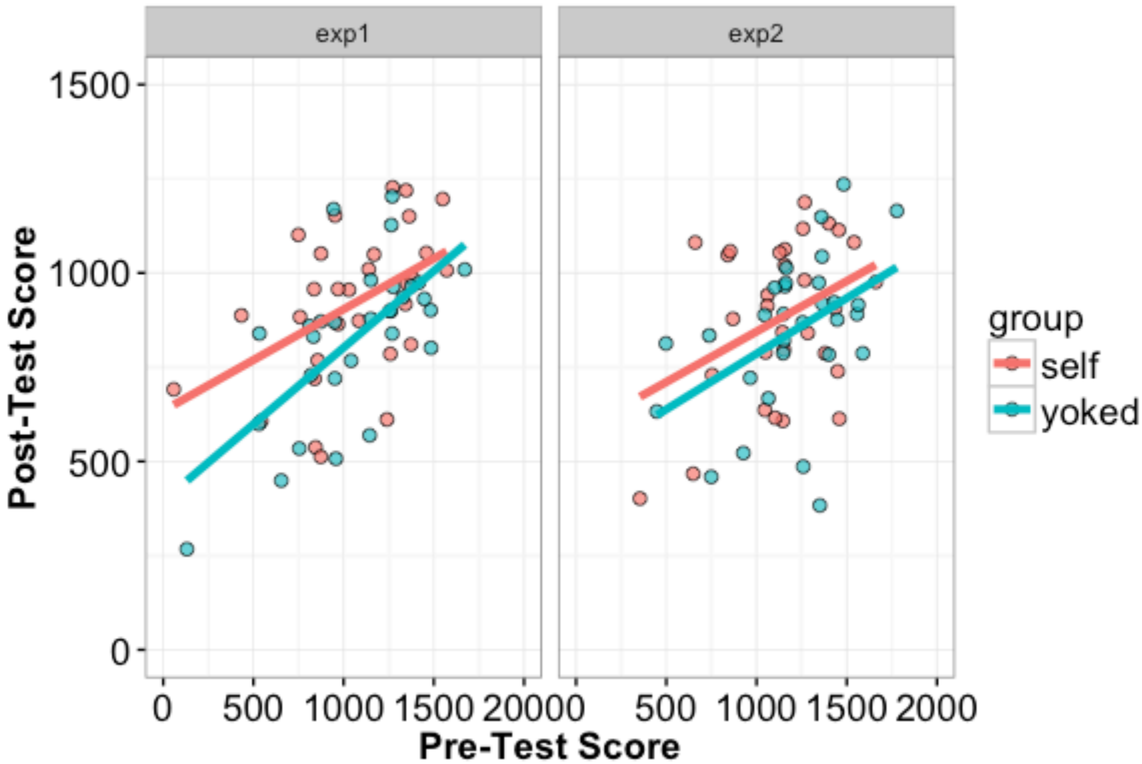

Figure 6. Post-test scores controlling for pre-test scores for self-controlled versus yoked groups in Experiment 1 and Experiment 2.

Effects of explanatory variables on learning. As there was no Group by Difficulty interaction in the RM ANCOVA for Experiment 2, we averaged across the three levels of difficulty to create a single post-test average score per participant, therefore reducing the number of regressions necessary. Consistent with the RM ANCOVA, the self-controlled group did not perform statistically better than the yoked group, as shown in the regression model predicting post-test averages, controlling for pre-test performance, $t(56) = 1.11$, $p = 0.27$, see Table 6. We then conducted a series of regressions adding the explanatory variables—long-form engagement (total engagement), long-form intrinsic motivation (interest/enjoyment), frontal asymmetry, and sEBR—to the regression model one at a time. See Figure 6. Controlling for Pre-Test and Group, there were no statistically significant relationships between post-test performance and total engagement, $t(56) = 0.89$, $p = 0.38$, interest/enjoyment, $t(56) = 0.47$, $p = 0.64$, frontal asymmetry, $t(56) = -0.06$, $p = 0.95$, or sEBR, $t(56) = 1.00$, $p = 0.32$.

As with the combined scores analyses, we also investigated the relationships between engagement, intrinsic motivation, and learning using the combined data from Experiment 1 and Experiment 2. As with each of the individual experiments, in the combined data engagement did not significantly predict post-test scores over both experiments, controlling for Pre-Test and Group, $t(116) = 1.46$, $p = 0.15$. Intrinsic motivation also did not significantly predict post-test scores in the combined data, controlling for Pre-Test and Group, $t(116) = 0.38$, $p = 0.70$. Thus, even with a larger overall sample size, we still do not see any engagement or motivation effects on learning.

Table 6. Parameters for the Regression Models Testing the Effects of Engagement, Intrinsic Motivation, FAS, and sEBR on Learning.

	Variable	**Beta**	***t*-value**	***p*-value**
Model 1	Pre-test	0.42	3.44	0.001
	Group	0.13	1.11	0.274
Model 2	Total Engagement	0.11	0.89	0.379
Model 3	Interest/Enjoyment	0.06	0.47	0.644
Model 4	FAS	-0.09	-0.06	0.949
Model 5	sEBR	0.12	1.00	0.321

Note that in Models 2-5, we controlled for Pre-Test and Group. The reported beta, t-value, and p-value thus correspond to the variable of interest, controlling for Pre-Test and Group.

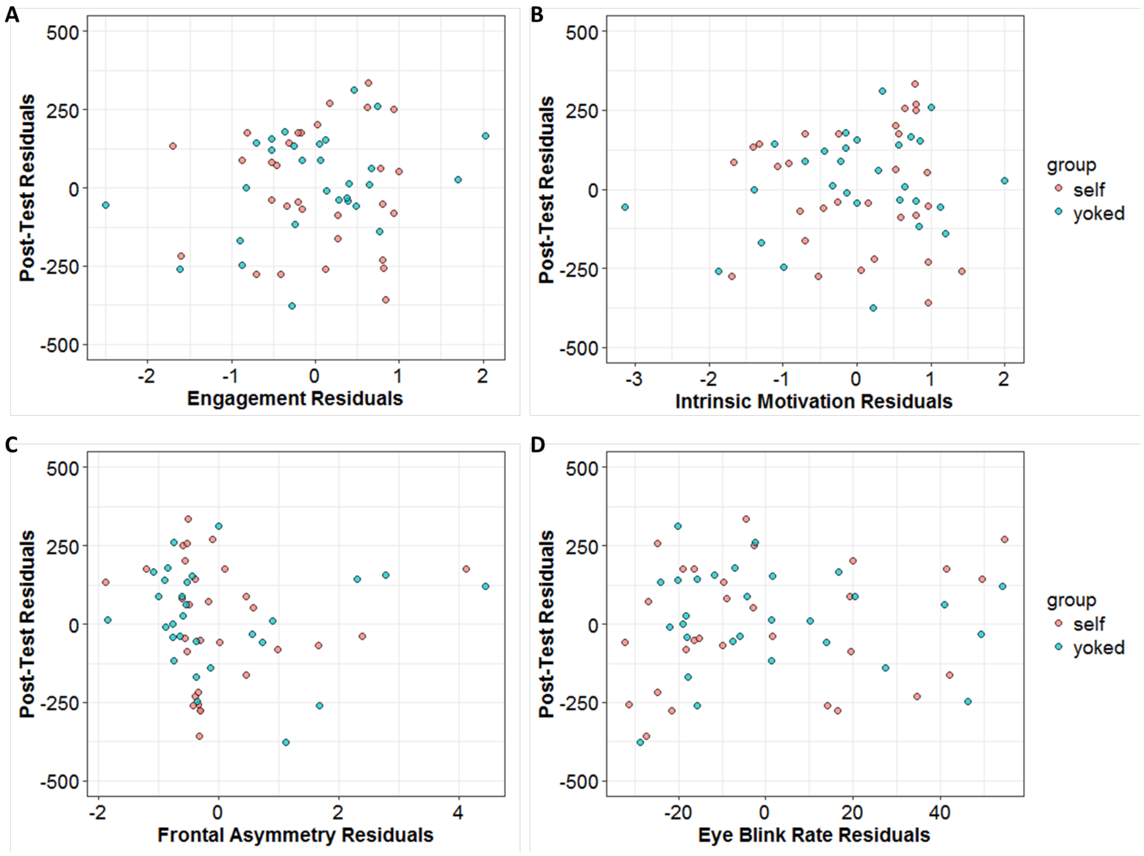

Figure 7. Scatter plots of the non-significant relationships between post-test average scores and explanatory variables. Plots are shown as the residuals of the post-score (controlling for Pre-Test and Group) plotted against the residuals of each explanatory variable (controlling for Pre-Test and Group). As such, positive values on the y-axis indicate post-test scores that are greater than would be predicted by a participant's pre-test score and group. On the x-axis, positive values indicate either greater engagement (**A**), intrinsic motivation (**B**), frontal asymmetry (**C**), or spontaneous eye-blink rate (**D**) than would be predicted by a participant's pre-test score and group. The distributions in these plots thus correspond to the betas, t-values, and p-values given for the explanatory variables in Table 6.

Relationships among survey measures and physiological variables. To examine the relationship between frontal asymmetry during practice and the post-practice engagement and motivation survey scores, we conducted a number of regressions controlling for Group. For the User Engagement Scale, there were no significant relationships found between practice frontal asymmetry and focused attention ($p = 0.60$), usability ($p = 0.33$), aesthetics ($p = 0.52$), endurability ($p = 0.14$), novelty ($p = 0.15$), involvement ($p = 0.77$), or total engagement ($p = 0.11$). For the Intrinsic Motivation Inventory, there were no significant relationships found between practice frontal asymmetry and interest/enjoyment ($p = 0.36$), competence ($p = 0.08$), effort ($p = 0.32$), or pressure/tension ($p = 0.99$). Thus, frontal asymmetry during practice was not related to any of the scales on the post-practice surveys. Frontal asymmetry may not be predictive of levels of engagement and motivation.

We also examined the relationship between practice frontal asymmetry and participants' average scores, average levels of difficulty, and changes in difficulty during practice, controlling for resting frontal asymmetry and group. There was no significant relationship between practice frontal asymmetry and average score during practice, $t(56) = -1.51$, $p = 0.14$. However, there was a significant relationship between practice frontal asymmetry and average level of difficulty, $t(56) = 2.65$, $p = 0.01$. There was also a significant relationship between practice frontal asymmetry and the standard deviation of difficulty during practice, $t(56) = 2.17$, $p = 0.03$. That is, participants who played at a higher level of difficulty or changed difficulty levels more often during practice tended to have greater frontal asymmetry, see Figure 7.

In a separate analysis, we investigated the relationship between practice frontal asymmetry and sEBR, as well as the relationship between resting frontal asymmetry and sEBR.

There were no significant relationships between sEBR and either resting FAS ($p = 0.62$) or FAS during practice ($p = 0.75$).

Additionally, we examined the relationship between sEBR and the post-practice engagement and motivation survey scores, using regressions controlling for Group. For the User Engagement Scale, there were no significant relationships found between sEBR and focused attention ($p = 0.93$), usability ($p = 0.23$), endurability ($p = 0.54$), novelty ($p = 0.33$), involvement ($p = 0.30$), or total engagement ($p = 0.39$). However, there was a significant relationship between sEBR and aesthetics, $t(57) = 2.17$, $p = 0.03$. For the Intrinsic Motivation Inventory, there were no significant relationships found between sEBR and interest/enjoyment ($p = 0.87$), competence ($p = 0.90$), or effort ($p = 0.65$), but there was a significant relationship between sEBR and pressure/tension, $t(57) = -2.38$, $p = 0.02$. Spontaneous eye-blink rate is unrelated to total engagement and intrinsic motivation, but is greater sEBR is associated with higher ratings of aesthetics and lower ratings of pressure/tension.

Finally, we examined the relationship between sEBR and participants' average scores, average levels of difficulty, and changes in difficulty during practice, controlling for group. There was no relationship between sEBR and average score during practice ($p = 0.58$), average level of difficulty ($p = 0.21$), or the standard deviation of difficulty during practice ($p = 0.73$).

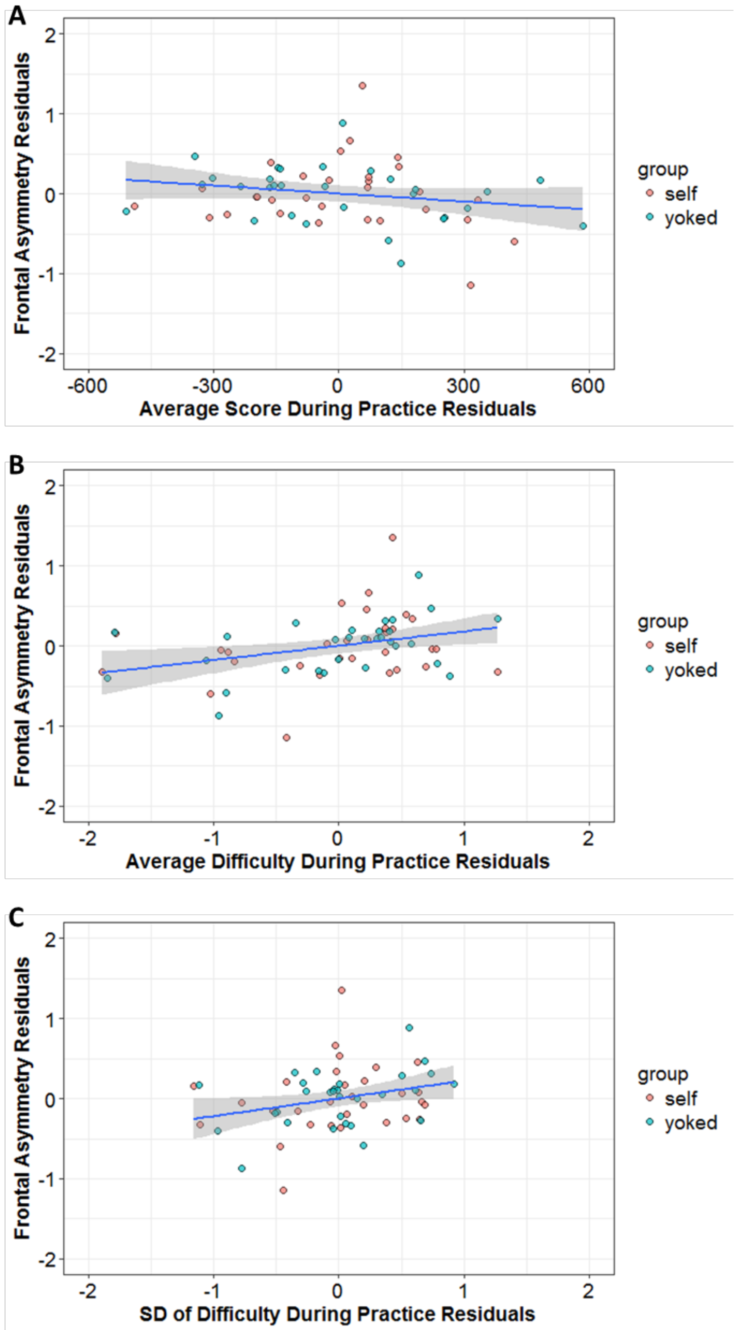

Figure 8. Scatter plots of the non-significant relationship between practice FAS and average practice score (A), the significant relationship between practice FAS and average practice difficulty (B), and the significant relationship between practice FAS and the SD of difficulty during practice (C). Plots are shown as the residuals of practice FAS (controlling for resting FAS and Group) plotted against the residuals of each practice variable (controlling for resting FAS and Group). As such, positive values on the y-axis indicate practice FAS values that are greater than would be predicted by a participant's resting FAS and Group. On the x-axis, positive values indicate either greater average practice score (A), average practice difficulty (B), or SD of difficulty during practice (C) than would be predicted by a participant's resting FAS and Group.

Relationship between intrinsic motivation and engagement. In accordance with our previous work, we conducted an analysis of the relationship between the long-form total engagement (User Engagement Scale) and the interest/enjoyment subscale of the Intrinsic Motivation Inventory. Similar to previous findings, the two surveys were highly related. The partial correlation between the two long-form scales was $r = 0.79$, $p < 0.001$, controlling for Group. We also tested the relationship between the single-item engagement and motivation scores with the long-form surveys. There was a significant partial correlation between the long-form User Engagement Scale to the average of the single-item engagement scores, $r = 0.54$, $p < 0.001$. There was also a significant relationship between the long-form Intrinsic Motivation Inventory to the average of the single-item motivation scores, $r = 0.61$, $p < 0.001$. The results suggest that the single-item questions are strongly predictive of the long-form survey responses.

Finally, we also investigated the effects of the intervention on long-form engagement, long-form motivation, single-item engagement, and single-item motivation. When controlling for Pre-Test scores, there were no significant differences between Group and long-form engagement, $t(57) = 1.20$, $p = 0.24$, or between Group and long-form motivation, $t(57) = 1.02$, $p = 0.31$. Interestingly, when controlling for Pre-Test score, there were significant differences between Group and single-item engagement, $t(57) = 2.51$, $p = 0.02$, as well as Group and single-item motivation, $t(57) = 2.69$, $p = 0.01$. See Figure 8. The self-controlled group reported significantly higher scores on the single-item measures compared to the yoked group. The non-significant findings for the long-form measures and the significant findings for the single-item measures are surprising because of the strong correlation between these measures (as discussed above). Dynamically measuring engagement and motivation throughout practice (single-item) may give us a better representation of actual engagement and motivation levels, as opposed to retrospective measurement (long-form). (It should also be noted that the statistical significance of these effects were the same whether pre-test scores were controlled for or not.)

Figure 9. Box plots of the differences in long-form and single-item engagement (**A**) and long-form and single-item motivation (**B**) as a function of Group. Although there were no group differences on the long-form measures, there were significant group differences on the single-item measures.

Discussion

Learning outcomes. Our goal for Experiment 2 was to replicate the learning effects found in Experiment 1, and to advance our understanding of how psychophysiological correlates of motivation and information processing mediate these learning effects. Unlike Experiment 1 (Leiker, Bruzi, et al. (2016) and previous motor learning studies (Andrieux, Danna, & Thon, 2012; Chiviacowsky & Wulf, 2002, 2005; Fairbrother, Laughlin, & Nguyen, 2012; Post, Fairbrother, Barros, & Kulpa, 2014), we did not find that self-controlled participants learned the task significantly better than yoked participants. However, we do not consider Experiment 2 a failure to replicate. The current study was only powered to achieve 80% statistical power and there was no Group by Experiment interaction in the combined analysis, suggesting the results of the two experiments are within what we could expect with sampling variability. The meta-analytic results combining the data from Experiment 1 and Experiment 2 are more telling, as there was a significant positive effect of choice over difficulty level on motor learning. The larger sample size of the combined experiments provides a better representation of the actual learning effect, as we gain more precision with an increased number of participants. In future studies, it may helpful to take these results into account when conducting power analyses for future experiments.

Further, the long-form engagement and motivation measures used in Experiment 1 showed no significant relationships with learning in Experiment 2. Even across the combined data from Experiment 1 and Experiment 2, there were no effects of engagement and motivation on learning. Corresponding to the results from previous motor learning studies (Leiker, Bruzi, et al., 2016; Leiker, Miller, et al., 2016; Lohse et al., 2015; Ste-Marie et al., 2015), individual differences in learning do not appear to be modulated by motivation, as suggested by Wulf and

Lewthwaite (2016). Again, these results do not refute the importance of motivation during motor learning, but motivational effects may only be mediated (e.g., by other affective or cognitive mechanisms), and not directly responsible for increases in learning.

To address the limitation in Experiment 1 of how to appropriately measure motivation (we may not have seen the learning effects of motivation because of the way we were measuring the construct), we chose to add two physiological variables in Experiment 2. As the combined results from Experiment 1 and Experiment 2 suggest, autonomy over difficulty affords an advantage to those in the self-controlled group. The goal of Experiment 2 to use these physiological and objective variables to explain this effect was relatively unsuccessful. There were no significant relationships between either of the physiological variables (frontal asymmetry or sEBR) and learning, and we were not able to predict learning based on these explanatory measures. We were also not able to better explain the positive effects of choice from the motivation hypothesis perspective. There is clearly a complicated relationship between autonomy and learning that was not explained by frontal asymmetry or sEBR. Different physiological variables may be better at parsing out the underlying mechanisms for this effect.

Performance outcomes. Our significant findings of average difficulty level and changes in difficulty level predicting practice frontal asymmetry in the self-controlled group supports the idea that frontal asymmetry is representative of approach motivation (Coan & Allen, 2004; Fox & Davidson, 1986; Fox & Davidson, 1988). Those participants who are more willing to engage in the game, through playing at higher difficulty levels and changing difficulty levels more often, have greater left frontal activity. As postulated by Harmon-Jones and Allen (1998), this effect could have been a result of enjoyment or anger while playing the game. Since approach motivation (as represented by frontal asymmetry) is not related to intrinsic motivation (as represented by the interest/enjoyment subscale on the IMI and single-item motivation question), it is quite possible that the approach motivation seen in these participants is due to frustration while playing the game. In this study, we were able to measure approach motivation using frontal asymmetry, but unable to use the physiological variable to measure intrinsic motivation. Although the relationships between practice frontal asymmetry and average difficulty level, and practice frontal asymmetry and changes in difficulty level are interesting, they do not provide any support for or against the motivation hypothesis of autonomy.

Although frontal asymmetry was related to performance measures during practice, we found no such relationships between sEBR and average score, average difficulty level, or changes in difficulty level. We did unexpectedly find a significant positive relationship between sEBR and a subscale of the User Engagement Scale (aesthetics), as well as a significant negative relationship between sEBR and a subscale of the IMI (pressure/tension). There has been evidence showing that stimuli rated higher in aesthetics enhance activation in areas of the brain related to striatal dopamine and reward value (Kawabata & Zeki, 2004; Reimann et al., 2010). However, there are no known studies that support the relationship between tonic dopamine levels and subsequent ratings of aesthetics or pressure/tension. Further research into these topics may be warranted.

Finally, the new single-item engagement and motivation measures used in the present study were significantly correlated with the long-form engagement and motivation surveys. This is an important finding, as these shorter survey methods allow us to dynamically measure engagement and motivation at multiple time points during practice with a lesser chance of retrospective amnesia. Additionally, while there were no differences between the self-controlled and yoked groups on the long-form survey responses, there were significant differences between the groups on the single-item survey scores. When measured with the single-item engagement and motivation questions, the self-controlled group reported greater engagement and intrinsic motivation during practice. This is an unexpected finding, as the long-form surveys and single-item questions were related. Measuring engagement and motivation dynamically may give us a better representation of perceived levels of engagement and motivation, as opposed to retrospective methods. Future studies can use these single-item measures of engagement and motivation in conjunction with the long-form User Engagement Scale and Intrinsic Motivation Inventory to assess fluctuations of these constructs throughout practice.

Limitations

One limitation of Experiment 2 is that self-controlled participants did not show the same learning effects as self-controlled participants in Experiment 1. We think it is unlikely that extraneous experimental factors (i.e., wearing an uncomfortable EEG cap) in Experiment 2 influenced learning effects significantly, as there was no Experiment by Group interaction in the combined data. However, there is still the possibility that this change in experimental paradigm could have distracted participants either emotionally or cognitively, and in turn, could have negatively affected learning.

A second limitation of the present study was the neurophysiological measures used in an attempt to quantify motivation and engagement (frontal asymmetry), as well as predict learning from dopaminergic activity (sEBR). These measures were largely unsuccessful at discovering the underlying neural substrates involved in autonomy. Future studies should investigate other physiological measures that may objectively index motivation and engagement, in addition to physiological information processing measures in order to gain a better understanding of why autonomy appears to be advantageous throughout motor learning research.

Finally, we were not able to fully address our original Aim #6 for Experiment 2 in the current results. Aim #6 was to explore the relationships between performance, difficulty, engagement, and motivation during practice itself. Our initial investigation into these effects is presented in Appendix C, but ultimately, these analyses are too detailed to be presented sensibly here and we think they require a separate study. As such, we are currently planning a second manuscript that will focus on analyses of the data from the practice session. The current dissertation focused on learning effects, but the subsequent study will focus on the practice session. Using mixed-effects linear regression, we will explore what factors predict intrinsic motivation and engagement in a given block of practice and how autonomy might moderate those relationships. Similarly, we will also explore what factors predict participants increasing or decreasing the difficulty of practice from block to block and how autonomy might moderate those relationships.

Conclusions

In conclusion, the combined data from Experiments 1 and 2 provide support for autonomy over difficulty level during practice. Choice during practice continues to deliver benefits in motor skill learning, but the mechanisms underlying this effect are still unclear. Our results suggest that intrinsic motivation stemming from self-control of difficulty during a motor task does not directly impact subsequent motor skill learning. See Figure 10. Although our attempts to discover the underlying mechanisms of this increased motor skill learning were unsuccessful using frontal asymmetry and sEBR, future research can benefit by choosing alternate neurophysiological measures while investigating autonomy. We suggest that these measures target the potential underlying cognitive mechanisms of autonomy (i.e., neurophysiological support for the information processing hypothesis).

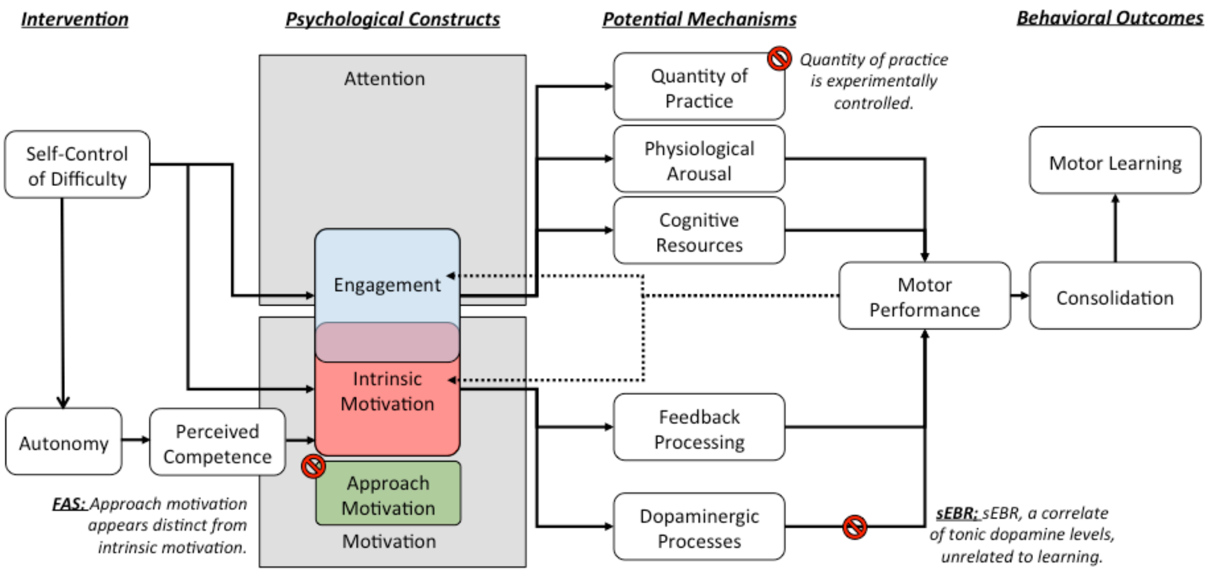

Figure 10. A retrospective look at the proposed mechanisms underlying task relevant choices following Experiments 1 and 2. Although the benefit of self-control over difficulty appears to improve learning, the underlying mechanisms are still unclear. The combined results of Experiments 1 and 2 show that engagement and motivation change coincident to changes in learning, but individual differences in these measures do not explain individual differences in learning. We need a finer approach to measuring motivation. Survey measures of motivation and engagement share significant variance and FAS indexes approach motivation, but this appears to be distinct from intrinsic motivation. Furthermore, sEBR, which is a correlate of tonic dopamine levels, was not related to motor learning. While other measures of dopaminergic processing might be more revealing, these data suggest differences in tonic dopamine do not explain learning effects. Finally, this model might suggest fruitful directions for future research by directing focus to cognitive mechanisms.

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Appendix A

Proportion of Asteroids Caught

As with our primary analysis, we used a RM ANCOVA with a between-subjects factor of Group (Self-Controlled versus Yoked), a within-subject factor of test Difficulty (easy, intermediate, or hard), and controlling for the proportion of asteroids caught on the pre-test as a covariate. Due to a computer error (in either data management or recording) pre-test proportion caught was missing for one participant and post-test proportion caught was missing for one participant from the easy Difficulty post-test. Thus, in this analysis Self Controlled n = 28 and Yoked n = 30. Following a correction for violating sphericity, there was significant main effect of test Difficulty, $F(1.81, 99.40) = 14.85$, $p < 0.001$, $\eta_p^2 = 0.21$, and a significant main effect of Group, $F(1,55) = 5.36$, $p = 0.02$, $\eta_p^2 = 0.09$. However, there was no significant test Difficulty by Group interaction, F(1.81, 99.40) < 1.0. The means and standard deviations for the proportion of asteroids caught are presented in Supplemental Table i.

Supplemental Table i. Proportion of asteroids caught as a function of group and test difficulty.

	Post-Test Difficulty		
Group	***Easy***	***Intermediate***	***Hard***
Self-Controlled	0.96 (0.05)	0.86 (0.09)	0.49 (0.14)
Yoked	0.94 (0.10)	0.81 (0.12)	0.47 (0.17)

Note. Data are shown as M(SD)

Time to Catch (for Successful Catches)

As above, we used a RM ANCOVA with a between-subjects factor of Group (Self-Controlled versus Yoked), a within-subject factor of test Difficulty (easy, intermediate, or hard), and controlling for time to catch (for successful catches) on the pre-test as a covariate. Time to catch was defined as the time, in seconds, from when an asteroid appeared on the screen to when it was successfully caught. Due to an error (in either data management or recording), pre-test time to catch was missing for one participant and post-test time to catch was missing for one participant from the easy Difficulty post-test. Thus, in this analysis Self Controlled n = 28 and Yoked n = 30. Following a correction for violating sphericity, there was a significant main effect of test Difficulty, $F(1.79, 98.60) = 3.77$, $p = 0.03$, $\eta_p^2 = 0.06$. The main effect of Group was not statistically significant, $F(1,55) < 1.0$, and there was no significant test Difficulty by Group interaction, $F(1.79, 98.60) < 1.0$. The means and standard deviations for the time to catch are presented in Supplemental Table ii.

Supplemental Table ii. Time to catch (for successful catches) as a function of group and test difficulty.

	Post-Test Difficulty		
Group	***Easy***	***Intermediate***	***Hard***
Self-Controlled	1.30 (0.13)	1.12 (0.08)	0.85 (0.07)
Yoked	1.32 (0.12)	1.12 (0.10)	0.88 (0.09)

Note. Data are shown as M(SD)

Proportion of Targets Hit (for Successful Catches)

As above, we used a RM ANCOVA with a between-subjects factor of Group (Self-Controlled versus Yoked), a within-subject factor of test Difficulty (easy, intermediate, or hard), and controlling for the proportion of targets hit (for successful catches) on the pre-test as a covariate. Due to a computer error (in either data management or recording) pre-test time to catch was missing for one participant and post-test time to catch was missing for one participant from the easy Difficulty post-test. Thus, in this analysis Self Controlled n = 28 and Yoked n = 30. Following a correction for violating sphericity, there was significant main effect of test Difficulty, $F(1.61, 88.59) = 3.71$, $p = 0.04$, $\eta_p^2 = 0.06$. The main effect of Group was not statistically significant, $F(1,55) < 1.0$, and there was no significant test Difficulty by Group interaction, $F(1.61, 88.59) < 1.0$. The means and standard deviations for the proportion of targets hit are presented in Supplemental Table iii.

Supplemental Table iii. Proportion of targets hit (for successful catches) as a function of group and test difficulty.

	Post-Test Difficulty		
Group	***Easy***	***Intermediate***	***Hard***
Self-Controlled	0.90 (0.09)	0.83 (0.13)	0.40 (0.21)
Yoked	0.89 (0.10)	0.77 (0.14)	0.42 (0.19)

Note. Data are shown as M(SD)

Regression Analyses Restricted to the Intermediate Difficulty Post-Test

Because the learning effects were strongest on the intermediate difficulty post-test, we reasoned that it would be appropriate to complement our primary analyses (averaging across test-type) with an exploratory analysis focused on the intermediate difficulty post-test specifically. Thus, in the first regression model, we tested the effect of group controlling for pre-test scores, shown in Supplemental Table iv.

Supplemental Table iv. Parameters for the Regression Model Testing the Effect of Choice on Learning, restricted to the intermediate difficulty post-test.

	Coefficient	**95% CI**	***p*-value**	**Model *F(2,57)***	**Model R^2**
Model:	--	--	--	17.59	0.38
Intercept	1058.32	991.60, 1125.03	<0.001		
Pre-Test Score	0.51	0.32, 0.71	<0.001		
Group	99.70	32.96, 166.44	0.004		

Note. Note that for the Group variable, Self-Control was coded as +1 and Yoked was coded a -1 and Pre-Test Score was centered around the average of 1,058.33 points.

As with our primary analyses, we were also interested in potential relationships between engagement and learning, and interest/enjoyment and learning. Thus, in the next two regression models, we regressed engagement on the intermediate difficulty post-test scores controlling for pre-test and group, and then interest/engagement onto intermediate difficulty post-test scores controlling for pre-test and group. As shown in Supplemental Table v, there was no statistically significant relationship between post-test performance and engagement during practice ($p = 0.51$) or interest/enjoyment during practice ($p = 0.64$), controlling for Group and pre-test performance. Thus, consistent with our primary analyses, these data show improvements in learning (Self-Controlled > Yoked) coincident to increased motivation (Self-Controlled > Yoked). However, there was no evidence that individual differences in motivation or engagement were related to individual differences in learning, even when we restrict our analysis to the intermediate difficulty post-test, where the learning effect was strongest.

Supplemental Table v. Parameters for the Regression Models Testing the Effects of Engagement and Intrinsic Motivation on Learning restricted to the Intermediate Difficulty Post-Test.

	Coefficient	**95% CI**	***p*-value**	**Model *F(3,56)***	**Model R^2**
Model 1:	--	--	--	11.75	0.39
Intercept	1058.24	991.16, 1125.31	<0.001		
Pre-Test Score	0.51	0.31, 0.71	<0.001		
Group	99.62	32.52, 166.72	0.004		
Engagement	26.44	-54.06, 106.94	0.51		
Model 2:	--	--	--	11.64	0.38
Intercept	1058.32	991.11, 1125.52	<0.001		
Pre-Test Score	0.51	0.31, 0.71	<0.001		
Group	105.06	32.03, 176.09	0.004		
Interest/ Enjoyment	-14.86	-78.36, 48.66	0.64		

Note. Note that for the Group variable, Self-Control was coded as +1 and Yoked was coded a -1, Pre-Test Score was centered around the mean of 1,058 points, Engagement was centered around the mean of 4.55, and Interest/Enjoyment was centered around the mean of 4.49.

Appendix B

Language Adapted User Engagement Scale

Participants were prompted with the following text:

Please answer the questions below using the 7 point scale below:

1	2	3	4	5	6	7
Strongly Disagree			**Neutral**			**Strongly Agree**

… and then answered the following questions. Note that question order was randomized and participants did not see to which subscale questions belonged.

Focused Attention Subscale

1. I forgot about my immediate surrounding while in the game. ___ **[Enter a number 1-7 here.]**
2. I was so involved in the game that I ignored everything around me. _____
3. I lost myself in this gaming experience. _____
4. I was so involved in my gaming experience that I lost track of time. _____
5. I blocked out things around me while I was playing this game. _____
6. When I was playing, I lost track of time and the world around me. _____
7. During the game, I let myself go. _____
8. I was absorbed in playing the game. _____

Usability Subscale

9. I felt frustrated while playing this game. _____
10. I found this game confusing to use. _____
11. I felt annoyed while playing this game. _____
12. I felt discouraged while playing this game. _____
13. Using this game was mentally taxing. _____
14. Playing the game was demanding. _____
15. The game was quite restrictive and I could not do some of the things I wanted to do in the game. _____

Aesthetics Subscale

16. The game environment was attractive. _____
17. The game's layout was aesthetically appealing. _____
18. I liked the graphics and images used in the game. _____
19. The game's layout appealed to me visually. _____

Endurability Subscale

20. Playing this game was worthwhile. _____
21. I consider my gaming experience a success. _____
22. This game was not as fun as I had hoped. _____
23. I would recommend playing this game to my friends and family. _____

Novelty Subscale
24. I would continue to play this game for fun. _____
25. The content of the game incited my curiosity. _____
26. I was interested in the game. _____

Perceived Involvement Subscale
27. I was really drawn into playing the game. _____
28. I felt involved while playing the game. _____
29. This gaming experience was fun. _____

Language Adapted Intrinsic Motivation Inventory

Participants were prompted with the following text:

Please answer the questions below using the 7 point scale below:

1	2	3	4	5	6	7
Strongly Disagree			**Neutral**			**Strongly Agree**

… and then answered the following questions. Note that question order was randomized and participants did not see to which subscale questions belonged.

Interest/Enjoyment Subscale

1. I enjoyed doing this activity very much _____
2. This activity was fun to do. _____
3. I thought this was a boring activity. _____
4. This activity did not hold my attention at all. _____
5. I would describe this activity as very interesting. _____
6. I thought this activity was quite enjoyable. _____
7. While I was doing this activity, I was thinking about how much I enjoyed it. _____

Competence Subscale

8. I think I am pretty good at this activity. _____
9. I think I did pretty well at this activity, compared to other students. _____
10. After working at this activity for awhile, I felt pretty competent. _____
11. I am satisfied with my performance at this task. _____
12. I was pretty skilled at this activity. _____
13. This was an activity that I couldn't do very well. _____

Effort Subscale

14. I put a lot of effort into this. _____
15. I didn't try very hard to do well at this activity. _____
16. I tried very hard on this activity. _____
17. It was important to me to do well at this task. _____
18. I didn't put much energy into this. _____

Pressure/Tension Subscale

19. I did not feel nervous at all while doing this. _____
20. I felt very tense while doing this activity. _____
21. I was very relaxed in doing these. _____
22. I was anxious while working on this task. _____
23. I felt pressured while doing these. _____

Standardized Game Instructions

"In this game, you are going to use your left hand to control the motion of a spaceship on the screen. You will steer the spaceship around to catch asteroids that fly onto the screen. In order to catch the asteroids, you simply need to move the spaceship over the center of them and they will be caught. After you catch the asteroid, you will need to throw it at a yellow target that will appear on the top, bottom, or side of the screen. In order to throw the asteroid, you need to be moving your hand pretty fast, so you might find it helps to "flick" the asteroid at the target. You will score points based how many targets you hit, but you will lose points for every second you haven't hit the target, so your goal is to catch the asteroids as fast as you can and hit as many targets as you can. Your score will be shown at the top left of the screen. Today you will be completing 20 blocks, each consisting of 20 asteroid catches and throws. Does that make sense?"

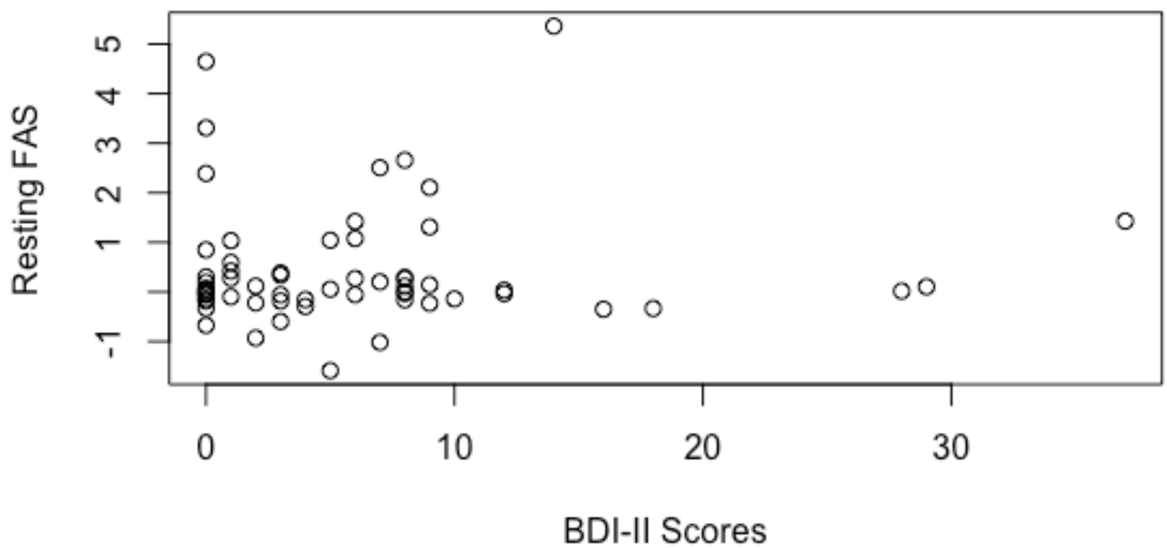
Practice Engagement/Motivation Survey (given every block):
Ask the participant to rate their response to each question on a 10-point scale

Engagement: How engaged were you by the game? ____
"The goal today is to measure how engaged you are by this game. Engagement refers to the extent to which you feel involved and "immersed" in the activity. On a scale of 0 to 10, how engaging would you rate this activity?"

Intrinsic Motivation: How motivated were you by the game? ____
"Intrinsic motivation is defined as performing an action or behavior because you enjoy the activity in itself. On a scale of 0 to 10, how intrinsically motivating would you rate this activity?"

Appendix C

Possible Covariate of Depression on Resting Frontal Asymmetry



Supplemental Figure i. Scatter plot showing the non-significant relationship between Beck Depression Inventory-II scores and resting frontal asymmetry, $r = 0.06$, $p = 0.66$.

Changes in Difficulty Level Not Related to Engagement or Motivation

In Experiment 2, we found that an increase in switching behavior (changes in difficulty level) is positively related to practice frontal asymmetry, $t(56) = 2.17$, $p = 0.03$. To assess if participants in the self-controlled group in Experiment 2 showed the same switching-related engagement as in Experiment 1, we conducted a regression model, controlling for Pre-Test. In Experiment 2, there was no relationship between changes in difficulty level and engagement, $t(27) = -0.80$, $p = 0.43$. We also conducted a regression model, controlling for Pre-Test, to examine the relationship between changes in difficulty level and intrinsic motivation. Similarly, we found no relationship, $t(27) = -0.63$, $p = 0.53$.

However, when we investigated these relationships with participants in the yoked group, the relationship between changes in difficulty level and engagement approached significance, $t(27) = -1.98$, $p = 0.0584$. Further, the relationship between changes in difficulty level and intrinsic motivation was significant, $t(27) = -2.06$, $p = 0.0489$. Changing difficulty levels more often actually decreased engagement and motivation in participants that were in the yoked group.

We also applied the same regression models across both the self-controlled and yoked groups. The relationship between changes in difficulty level and engagement approached significance, $t(55) = -2.00$, $p = 0.0503$, while the relationship between changes in difficulty level and intrinsic motivation was significant, $t(55) = -2.03$, $p = 0.0474$. Overall, participants who changed difficulty level more often rated lower levels of engagement and motivation than those participants who did not. This effect seems to be largely driven by the near significant engagement and significant motivation relationships found among participants who changed difficulty levels more often in the yoked group.