Anticipating Explicit Motor Learning by Assessing Arousal Levels using HRV and GSR

A thesis presented to the academic faculty

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Abstract

Biometrics, including heart rate variability (HRV) and galvanic skin response (GSR), are already used to gauge autonomic regulation, emotional reactivity, attention, and flow, a concentration state. Given the role of arousal seen in motor learning factors such as optimal stress, anxiety, and task engagement, this study investigates whether HRV and GSR show distinguished patterns in those who explicitly learn a hidden sequence in a motor task as compared to those who only learn implicitly. This is done using a serial reaction time task (SRTT) and the collection of electrocardiogram (ECG) and GSR data throughout the task then comparing qualitative data across subjects. HRV decrease and GSR increase are noted at serval instances of explicit motor learning emergence, and even in instances when the shift is not exaggerated, it is never found varying in the opposite direction as the hypothesized pattern. Despite a low participant sample size and a low sampling frequency for ECG and GSR, the results tentatively support the concept of using HRV and GSR to gauge whether or not a person's current state is conducive to explicit motor learning. This biometric monitoring holds the potential for real-time biofeedback and could be useful in physical rehabilitation settings due to the relative ease of implementation.

Introduction

Motor learning can be both implicit, outside of conscious awareness, and explicit, within conscious awareness. Motor learning can be detected through increased accuracy and decreased reaction times in a serial reaction time task (SRTT) where subjects push keys corresponding to boxes that light up on a screen in front of them. Even when subjects are not aware that a sequence is repeating, almost everyone shows improved response times. If the latencies are low enough, implicit and even explicit motor learning can be inferred. Despite task improvement, not everyone makes explicit connections so that they are fully aware of what is happening and can remember the repeated sequence.

Motor learning can be influenced by several factors. Motivation can enhance working memory (Wulf & Lewthwaite, 2016) as well as the “accessibility of goal relevant knowledge” (Ferguson et al., 20018). Working memory was found to be a predictor of explicit motor learning in the study that preceded this study (Turner 2020). A higher self-efficacy correlates with better attention, accuracy, and response times for difficult motor tasks (Wulf & Lewthwaite) while stress and anxiety can reduce performance. However, if the task at hand doesn’t use up all information-processing resources, then motivation by stress may actually positively affect performance (Liao & Masters, 2001). This suggests that an appropriate level of arousal increases task performance until arousal gets so high as to overload the subject, which is intuitive when thinking about life experiences. For example, for a player to achieve optimal performance in and engagement with a video game, the game needs to be challenging enough not to be boring but not so difficult that the player is overloaded.

Considering the role of motivation and attention in motor learning as well as the benefit of an optimal level of stress, arousal levels could potentially be predictive of motor learning performance. Heart rate variability (HRV) is the variability in the timing between heartbeats. It is a useful indicator of autonomic regulation and therefore of stress and arousal levels. A high resting HRV is indicative of synchronization of the sympathetic and parasympathetic nervous systems, and HRV tends to drop during task performance, indicating increased arousal (Asprey & Porges, 2019). Indeed, HRV has already been applied to study cognitive domains, such as attention, in studies like Porges & Coles (1982) and those reviewed in Forte et al. (2019). Galvanic skin response (GSR), the sweatiness and electrical conductance of the skin, increases with arousal. GSR has been found to increase with task difficulty (Nourbakhsh, 2012), further indicating that arousal is tied to task performance. Because HRV and GSR can gauge arousal, which is intertwined with many cognitive and emotional influencers of motor learning, this study attempts to build a bridge from these biometrics to motor learning.

This study seeks to collect HRV and GSR during a SRTT to see if differences can be distinguished between those who learn explicitly and those who do not. The question is whether or not HRV and GSR can gauge the stress and engagement of the subject during the SRTT in which there is a repeating sequence that the subject is not privy to and whether arousal shows characteristic fluctuations as people undergo motor learning. If a pattern emerges, these metrics may prove not only predictive of explicit motor learning but also applicable to rehabilitation training. HRV and GSR may provide the opportunity to use biofeedback to facilitate optimal motor learning in real time for those who are learning to use a prosthetic or otherwise recovering motor function after a traumatic injury. Based on the literature reviewed below, it is hypothesized that those who learn explicitly will have a high resting HRV and that they will show a subsequent decrease in HRV and increase in GSR during the task, particularly when they begin to explicitly discover the hidden sequence, which will most likely increase engagement with and excitement about the task.

Literature Review

This study explores the use of HRV and GSR to predict explicit motor learning in a SRTT. The reasoning is that optimal arousal promotes motor learning, and HRV and GSR can gauge arousal and stress and can even be predictive of attention and cognition in task performance. Forte et al. states that the cognitive domains of attention, processing speed, visuospatial skills, and memory studied in the context of HRV have many qualitative and quantitative methodological limits to date, and this study will help to fill that gap (2019). If HRV and GSR prove promising in ascertaining the engagement of subjects and in predicting motor learning, then they can be paired with or substituted for other variables currently under study for the same function, such as working memory, EEG, and eye-tracking. HRV and GSR collection could potentially be applied in a rehabilitation setting to enable patients to get the most out of their training with real-time biofeedback.

Motivation, whether implicit or explicit, can affect motor learning through several avenues. Expectancies affect working memory, which was found to be predictive of explicit motor learning in the study preceding this experiment (Turner, 2020), as well as cognition, attention, long term memory, and biasing towards expected stimuli (Wulf & Lewthwaite, 2016). Goal priming, when subjects are cued to goals without their knowledge, can improve implicit learning without an accompanying increase in explicit motivation, knowledge, or performance (Eitam et a., 2008). In this experiment, the presence of the repeating sequence is not made known to the subject, and this study is assessing what separates those who can grasp this sequence implicitly and then make a subsequent explicit connection from that implicit awareness. Motivational concerns, whether implicit or explicit, at the time of the task can affect the "accessibility of goal relevant knowledge," which can then affect goal pursuit (Ferguson et al., 2008). Motivation to avoid loss increases performance only while the manipulation is present, indicating "that motivation enhanced knowledge expression through performance, not learning" (Chon et al. 2018). Perhaps learning did not increase when the motivation was due to a potential loss because that is an inherently stressful situation, and self-efficacy, anxiety, and stress have also been shown to affect motor learning.

Self-efficacy, stress, and anxiety tie into optimal arousal levels because experiencing extreme stress or anxiety arouses subjects past their optimal arousal levels and begins to impair task performance. A higher self-efficacy is associated with increased attention to task error cues, increased response accuracy, and faster reaction times during difficult tasks (Wulf & Lewthwaite, 2016). If the task at hand leaves plenty of information-processing resources available, then the motivation induced by stress may have a positive influence on performance (Liao & Masters, 2001), indicating that there is an optimal level of stress arousal for task performance. Anxiety may play a role in task performance, attention, or motivation due to its high level of arousal and since highly anxious people don't do as well in "testing situations" (Mathis, 1967). If mood and arousal changes can be accurately assessed by HRV and GSR in real time and those changes coincide with explicit motor learning, HRV and GSR may provide the ability to tailor rehabilitation paradigms for optimal arousal, and therefore optimal motor learning. HRV is already used in biofeedback training through organizations such as the HeartMath Institute to help reduce stress and regulate emotions.

A high baseline HRV indicates better autonomic and parasympathetic balance and regulation, and it is predictive of reduced HRV and faster reaction times during task performance (Asprey & Porges, 2019). During task performance, when people become focused, HRV drops, indicating increased sympathetic arousal (Asprey & Porges, 2019). Similarly, GSR increases during a flow state, also indicating increased arousal (Ulrich et al., 2015). If subjects show a high baseline HRV followed by a subsequent decrease in HRV and increase in GSR during the task, this biometric shift may indicate an appropriate level of arousal and engagement with the study as long as the arousal does not increase so much that the subject is overloaded. This is not only consistent with Porge's research on the Polyvagal Theory but also with the Neurovisceral Integration Model, which links the autonomic nervous system with executive and emotional function (Thayer & Lane, 2009). It postulates that sympathetic hyperactivation decreases prefrontal activation, disinhibiting the amygdala, which substantiates the idea of overarousal decreasing performance as exhibited in anxiety and/or stress overload (Thayer & Lane, 2009).

Both increased sympathetic activity and decreased parasympathetic activity led to worse cognitive performance, even in healthy people with no heart disease or mental illness, in Forte et al.'s review of HRV and cognitive function (2019). Most of the experiments in the Forte et al. review predict better attentional performance with higher HRV, but the distinction between baseline HRV and task HRV is not made like in Porges' research. Similarly, a higher resting HRV was significantly correlated with attentional maintenance (resistance to distractors) in the Siennicka et al. study (2019). From Porges, we know that a high baseline HRV, which denotes autonomic homeostasis, can predict better attentional performance but that those same individuals showed a decrease in HRV during the task, indicating increased arousal during the task (2019). These sources do not necessarily contradict; the key is having the appropriate arousal at the appropriate time. The people exhibiting better attention in the Porges study are well-regulated, experiencing increased arousal only when necessary for the task at hand (1982).

A qualitative look at HRV and GSR throughout the SRTT and between subjects, especially between those who learn explicitly and those who only learn implicitly, may prove more revealing than a direct comparison of values. The timing of the HRV change may be more important than its magnitude (Porges, 1982). Similar trends are seen with GSR data in a study by Nourbakhsh et al. showing substantial variation between subjects so that no significance could be found without preprocessing although there was a general positive trend between task difficulty and GSR (2012). A sine wave HRV indicates a proper balance between parasympathetic and sympathetic activity (McCraty, 2005; Asprey & Porges, 2019). Better synchronicity between the branches of the autonomic nervous system occurs with a genuine positive emotional state, and one can use biofeedback training to improve cognitive, emotional, and behavioral outcomes (McCraty, 2005). Two measures emerge as expected when comparing explicit learners with implicit only learners: a healthy, well-regulated baseline before task initiation and appropriate arousal levels brought on by task performance. Biofeedback training has been able to improve emotional outcomes in the McCraty study and even in independent use through interventions as simple as breathing exercises, so biofeedback training may have a potential application in rehabilitation if arousal proves predictive of motor learning in this study (2005).

High resting HRV, which is indicative of a positive emotional state and effective autonomic regulation, has been shown to predict better performance in cognitive domains important for motor learning while stress, anxiety, and overload decrease performance. Because of this, the ability to generally assess the mood and arousal of subjects in a motor learning paradigm through HRV and GSR could be predictive of their success in explicit motor learning and could have applications in rehabilitation. Collecting these biometric measures may prove a valuable tool to gauge a subject's engagement or general mood during a motor learning paradigm, which may become boring due to its repetitive nature. This study will collect HRV and GSR during a SRTT in an effort to make this connection between arousal and explicit motor learning. Instead of varying the difficulty of this study to fit the individual, the study is attempting to assess how engaged the subject is with this potentially boring task. If HRV and GSR can successfully gauge mood and arousal and predict explicit motor learning up to or above the standards of other experimental methods, such as EEG, they would prove much more practical to implement.

Methods

Participants

The criteria for subjects to be eligible to participate in the study are age, handedness, and musical training. All subjects are between the age of 18 and 35. All subjects are right-handed as determined by the Edinburgh Handedness Inventory (Oldfield, 1971). This criterion is kept for consistency's sake and is particularly important for branches of the study using EEG due to differential brain activation between left and right-handed participants. Participants cannot have 3 or more years of formal musical training due to differential performance in patterned motor tasks. Under normal conditions, students are recruited at Georgia Institute of Technology through flyers and word of mouth although the Covid-19 pandemic has hampered data collection. All four participants complete the same SRTT paradigm. Participants are sorted into groups after experiment completion based on their learning classification, whether or not they learned explicitly.

Working Memory Assessment

After completing the Edinburgh handedness inventory to confirm eligibility, subjects are given an n-back test at the 2-back level to assess working memory. The test is administered through the website cognitivefun.net. Recorded results include the percentage correct and the average response time. The n-back test is given because working memory is indicated to be a predictor of explicit motor learning based on preliminary data in the study from which this research budded and may even be necessary for sequential motor learning (Turner, 2020; Lawson & Wheaton, 2018).

Experimental Design

<u>SRTT</u>. The Serial Reaction Time Task comprises the bulk of the experiment. SRTT is an ideal choice for this experiment because it not only indicates motor learning through decreased reaction times and increased accuracy, but it is also repetitive like learning to do a task in physical rehabilitation (Lawson, et al., 2017). The SRTT is run through Matlab using PsychToolbox to display the stimuli and using a 4-key response pad to record the participant's responses. Participants respond on the keypad using their right hand to push buttons corresponding to four rectangles on the display, leaving one finger on each key. Subjects have a maximum of 750 ms to response to the stimuli. Blocks are separated by 10 second rests with every 10th rest being 30 seconds. The SRTT is split into two main parts. A random sequence block is presented at the beginning of the paradigm, between the two repeating sections, and at the end of the paradigm in order to acquire response time baselines. Based on these baselines, the

program calculates the participant's threshold for learning. Z-scores can be calculated using the averages and standard deviation from the baseline blocks in order to compare response times in repeating blocks with the threshold.

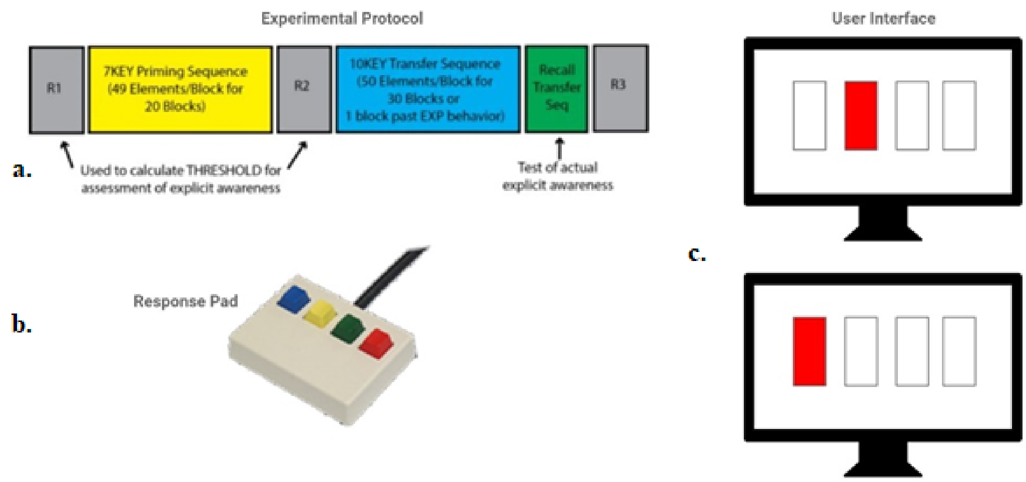

Figure 1 (Turner, 2020). SRTT setup. Part **a.** shows the overarching progression of the task. Part **b.** shows a 4-key response pad. Part **c.** illustrates what the participant sees and reacts to during the SRTT presentation.

The first section of the SRTT presents 20 blocks that repeat in sequence every 7 stimuli, and the second section presents up to 30 blocks that repeat in sequence every 10 stimuli. Importantly, the participant is not made aware by the experimenter that the program contains a repeating pattern. In the 10-sequence portion, the participant can complete the experiment in under 30 blocks if his/her performance improves enough to indicate explicit motor learning. The threshold for explicit learning is a z-score of -1.85 twice in a row (Turner, 2020; Lawson, et al., 2017). The basis for this cutoff is improved reaction time and accuracy to a level that suggests the participant was anticipating the coming stimulus. Once the participant either finishes the full second section of the experiment or reaches the sufficiently low z-score, the presentation asks the participant about the repeating sequence. The prompt inquires if the participant noticed the repeating sequence, and if so, whether he/she can recall it. The SRTT program is the same code used in the research of an adjacent study in the lab (Turner, 2020).

Biometric Assessment. For the duration of the SRTT, ECG and GSR are collected using an Arduino Uno run through Matlab on a second computer. A pulse sensor is attached to the volar surface of the left second digit, and two GSR sensors are attached to the volar surfaces of the third and fourth digits of the left hand. The left hand is unused in the SRTT portion of the experiment, so the sensors do not interfere with task participation. A separate computer is used to run the biometric collection through the arduino because the computer presenting the SRTT display cannot be interacted with for the duration of the presentation. Matlab records voltages from the ECG and GSR sensors through the arduino approximately five times per second. The data collection code and the arduino are adapted from a project in visualizing heart rate and galvanic skin response during emotionally evoking videos (Pollock & JafariNaimi, 2017). The adaptation of this set-up was practical as opposed to starting from ground-zero. The Matlab version of the code was used instead of a second version run through Processing so that the data could be easily integrated with the SRTT data if desired and to minimize the number of different software needed to run the experiment.

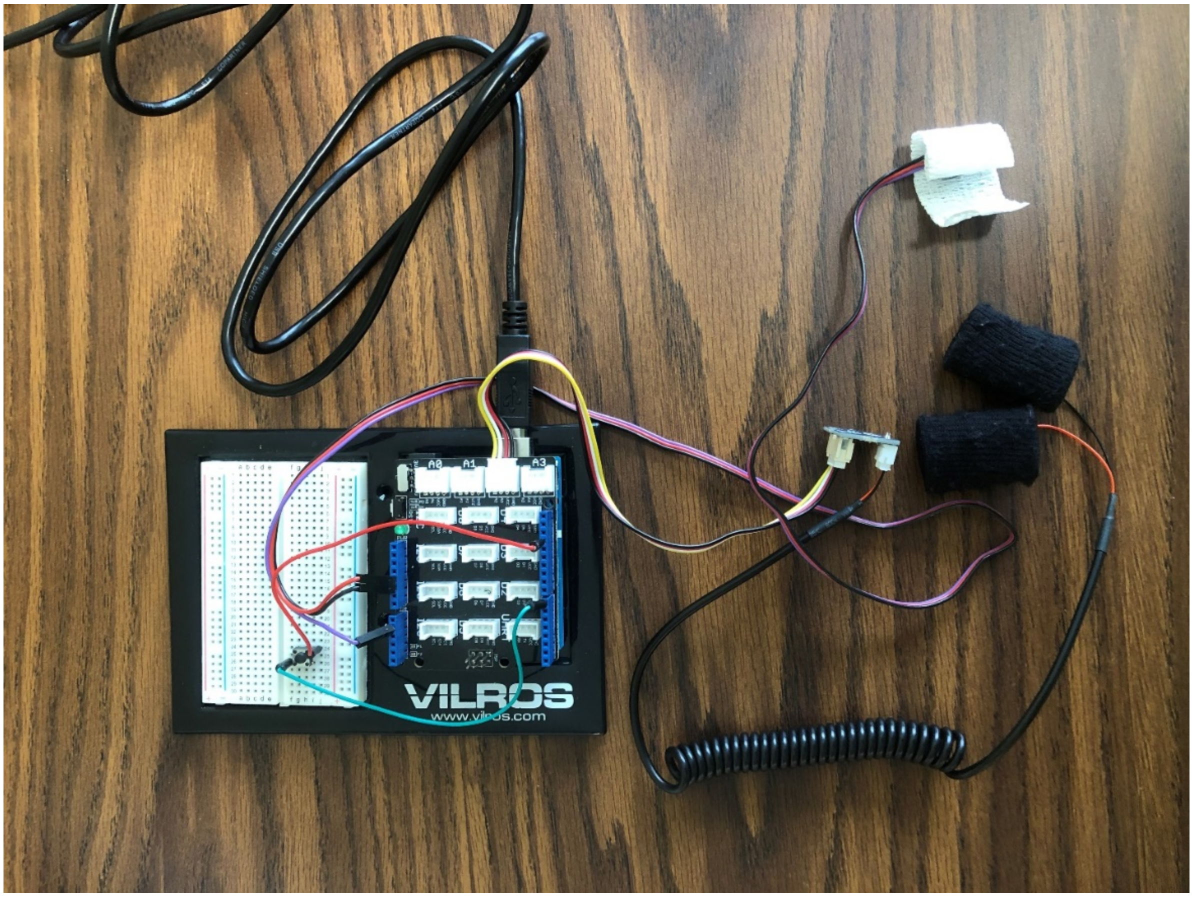

Figure 2. This is the Arduino Uno used to collect ECG and GSR data. The thick black cord at the top connects the arduino with a computer. The two sensors with the black finger cuff are for GSR, and the pulse sensory has a white wrap on the end. The button on the breadboard is used to manually start and then stop data collection after the code is running.

Data Analysis

After saving the data from the biometric collection, they are written to a csv file. A csv file is created with time data in one column and ECG data in a second column. This file is imported into separate Matlab code. The data is extrapolated to help see past the low frequency of sampling (5Hz) from the pulse sensor. The findpeaks function is used as a filter in an effort to mark only the R peaks in the ECG data. The times of each R peak are written to a CSV file and run through Kubios HRV Standard software to calculate the RMSSD of the RR intervals from the ECG data. The RMSSD of the RR intervals reveals how consistent the timing of heartbeats is with a higher RMSSD indicating higher HRV. Analysis of HRV can be done for a participant's entire data collection or within portions of interest, such as fluctuations in GSR or response times passing the explicit learning threshold. GSR is plotted and assessed qualitatively. Because of high individual variation, a straight comparison of numbers is not useful for the goal at hand.

Participants' performance and observations during the SRTT are used to determine their motor learning status. Implicit learning is indicated as their reaction time and accuracy improve throughout the study and by any comments the participants make about suspecting a pattern in the task. Explicit learning is indicated by passing the threshold of two or more sequential z-scores of -1.85 or lower. Additionally, the subjects are asked if they noticed a repeating sequence and given an opportunity to enter it, or a portion of it, on the response pad. Explicit learning status hinges upon surpassing the response time threshold and whether or not the participant can accurately recall the repeating 10-stimuli sequence.

Looking across all data, HRV, GSR, SRTT, and working memory, grants a glimpse into the state of the participant during the motor learning task. Differences can then be compared and interpreted between subjects, especially between those who did and who did not learn explicitly. Formal statistics were not run due to the low participant sample size and to the qualitative nature of the data. GSR, and to some extent HRV, numbers are not meaningfully compared across subjects, but they can be compared across time within an individual, and any emerging trends can be compared across subjects.

Results

SRTT

The SRTT presentation during the testing of the first subject glitched despite prior trial runs. It did not present the repeating 7-sequence or 10-sequence portions of the presentation. Instead, the code became stuck in the first random priming block, and it looped this block over and over indefinitely. To end the experiment, the program had to be crashed. Despite having a sequence of 40 stimuli repeating instead of 7 or 10 stimuli repeating, subject 1 was the only of the four subjects to explicitly recall a pattern. At the end of the experiment, subject 1 could recall the first 3 keys and the last 6 keys of the block. The SRTT progressed correctly for all other subjects although it did not kick out the participant who reached the explicit learning threshold in the 10-sequence portion. Subjects 2, 3, and 4 showed signs of implicit learning through decreasing reaction times and comments about suspecting a pattern or about noticing their fingers working faster on their own.

In addition to implicit learning, subject 2 met the threshold for explicit learning during the 7-sequence portion of the SRTT (Figure 4). Explicit recall is not tested for the 7-sequence portion to avoid drawing attention to the pattern in the second half of the SRTT. Although subject 3 did suspect a pattern at the end of the experiment and did show some decrease in reaction times, subject 3 never quite reached the threshold for explicit motor learning. All instances of 2 or more adjacent z-scores below -1.85 for subject 3 included incorrect button presses, so they were not accepted as explicit learning markers. Subject 3 had uncharacteristic forearm pain during sizable portions of the SRTT, perhaps from tensing his muscles too much as it didn’t bother him before or after the experiment. Subject 4 met the threshold criteria for both portions of the experiment but did not enter the sequence when prompted. The threshold was met many times, so the learning classification is not likely a fluke.

GSR

When zooming out to look at GSR across the whole SRTT, trends were more easily spotted. Areas of interest were selected based on improvements in reaction time in the SRTT. However, since subject 1's SRTT data could not be salvaged, notable spikes and periods of increase in GSR were isolated. This guided the targeted analysis of HRV in lieu of the missing reaction time and accuracy data. Subject 1 displayed an early period of GSR increase as well as a couple prominent spikes after the general GSR level had fallen. The HRV during these periods is discussed later.

Subject 2 met the explicit learning threshold multiple times during the 7-sequence section. The first block reaching the explicit learning threshold is concurrent with the first distinct increase in GSR which continued to rise through the next few blocks (Figure 4). The next isolated instance of explicit-level reaction times during blocks 10 and 11 also coincides with an increase in GSR (Figure 4). Blocks 15-20 show pervasively decreased reaction times crossing the threshold but GSR decreases by this point (Figure 4).

Subject 3 never met the criteria for explicit learning. The closest block was block 16 which contained two z-scores of low enough value but that were far from each other within the block. GSR was elevated at this time (Figure 5). Block 9 in the 10-sequence portion presented a similar situation, two low, non-adjacent z-scores. GSR was elevated in this block, but no clear pattern emerged in the blocks presenting with just one low z-score.

Subject 4 met the reaction time threshold in both portions of the SRTT. From block 8 onward during the repeating 7-sequence, the threshold was met many times (Figure 6). There is no clear GSR pattern across this broad section although block 8 does occur within a group of local GSR peaks. The first instances of the threshold being met in the 10-sequence portion are blocks 3 and 7. Block 3 occurs around some smaller, local GSR peaks, and block 7 occurs during a period of GSR increase (Figure 6). The threshold is passed multiple times during the last 3 blocks of the 10-sequence portion. The end of the experiment does show a relatively elevated GSR with a sudden drop during the last 2 minutes, which is during the explicit learning prompt and the final random sequence.

HRV

For subject 1, the RMSSD of the RR intervals across the entire experiment was 644 ms. Relatively early in the experiment an initial elevation of GSR occurred as well as two large spikes after GSR started to decline a bit. During these portions of interest, HRV was 641 ms and 568 ms, respectively (Figure 3). These are both lower than the average across the whole experiment, especially the HRV during the two GSR spikes. About ¾ of the way through the hour of recording, there was a prominent spike in subject 1's GSR. The HRV at this time was 635 ms, also lower than the average RMSSD (Figure 3).

Subject 2's RR interval RMSSD across the whole SRTT was 589 ms. During and directly before block 5 of the 7-sequence portion, the first block in which the explicit learning threshold was met, the HRV was 544 ms (Figure 4). Reaction times were very low during the last 5 blocks of the 7-sequence portion. Although GSR appeared to decrease overall, HRV was 533 ms during this time (Figure 4). Blocks 3, 4, 8, and 10 of the 10-sequence portion are the only blocks to have a reaction time reach the threshold level, but none of them had the required two instances. HRV around blocks 3-4 was 620 ms and around blocks 8-10 was 733 ms (Figure 4).

As noted earlier, subject 3 did not meet explicit learning criteria in either the 7 or 10-sequence portions of the SRTT despite some signs of implicit motor learning. Block 16 during the 7-sequence and block 9 during the 10-sequence were the closest to explicit learning. The HRV around these blocks were 574 ms and 543 ms respectively (Figure 5). The RR interval RMSSD across the entire SRTT for subject 3 was 575 ms.

The overall RMSSD for subject 4 was 671 ms. Although subject 4 hesitated at the prompt regarding the repeating 10-sequence and subsequently did not answer, the subject met the reaction time criteria for explicit learning in both portions of the experiment. Starting at block 8, every block in the 7-sequence met the threshold at least once. During and just before block 8, the HRV was 684 ms, but during and just after block 8 HRV was 629 ms (Figure 6). Blocks 3 and 7 during the 10-sequence portion were the first to meet the threshold, each containing one instance. HRV at these blocks were 546 ms and 573 ms respectively (Figure6). The final three blocks of the 10-sequence met the threshold multiple times each. The average HRV here was 651 ms (Figure 6).

Working Memory

Subject 1, the explicit learner, had the highest percentage of correct answers in the 2-back test at 73.33% (Table 1). Subject 3 had an accuracy on par with subject 1, scoring 73% correct (Table 1). Subjects 2 and 4 had lower percentages correct, 61.53% and 50%, respectively (Table1). Subject 2 was the quickest responder, taking an average of 920 ms. Notably, subject 4, who had the lowest 2-back accuracy, also had markedly higher repones times. Her average response time was 1321.09 ms, which is 348 ms higher than the next highest average response time. The other subject's average response times were all within 60 ms of each other, between 920 ms and 973 ms.

	Subject 1	*Subject 2*	*Subject 3*	*Subject 4*
Learning status	Explicit sequence recall for 9 out of the 40 digits	Explicit learning of 7-seq	Implicit only	Passed explicit threshold for both 7-seq & 10-seq; didn't recall
n-back accuracy	73.33% correct	61.53% correct	73.00% correct	50.00% correct
Average RMSSD for HRV	643.51 ms	588.85 ms	574.91 ms	671.16 ms

Table 1. This is a comparison of key data across subjects for each portion of data collection. The first row categorizes participants as explicit learners or implicit learners regarding the hidden sequence in the SRTT motor learning paradigm. The second row shows the participants' respective performance in the 2-back working memory assessment. The bottom row gives the RMSSD of the RR intervals from the ECG data of each subject across the whole SRTT duration. A higher RMSSD is indicative of a higher HRV.

Key for Figures 3-6:

= repeating sequence

= random baseline block

= block when z-score threshold was passed

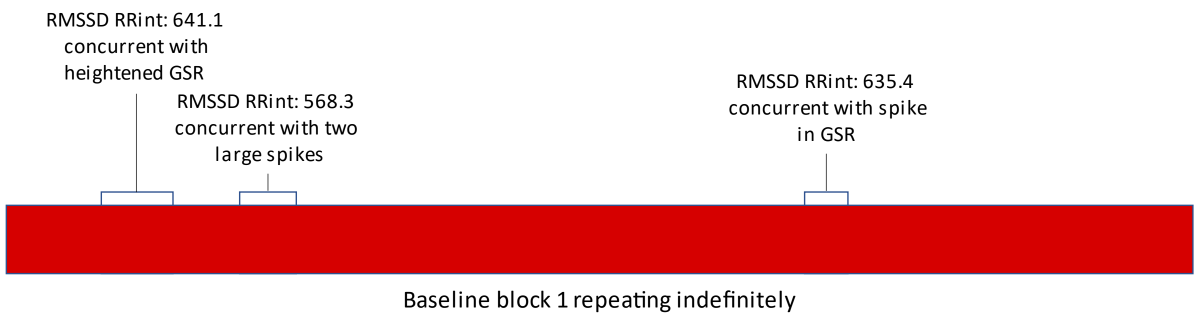

Figure 3. Subject 1 SRTT. The overall HRV (RMSSD for the RR intervals across the whole task) was 643.5 ms. Notable shifts in HRV and GSR that occurred together during the task are reported. Subject 1's SRTT responses were not recorded due to malfunctioning code, but the subject still learned part of the repeating 40 sequence block explicitly. HRV was assessed according to notable GSR changes since z-scores could not be calculated.

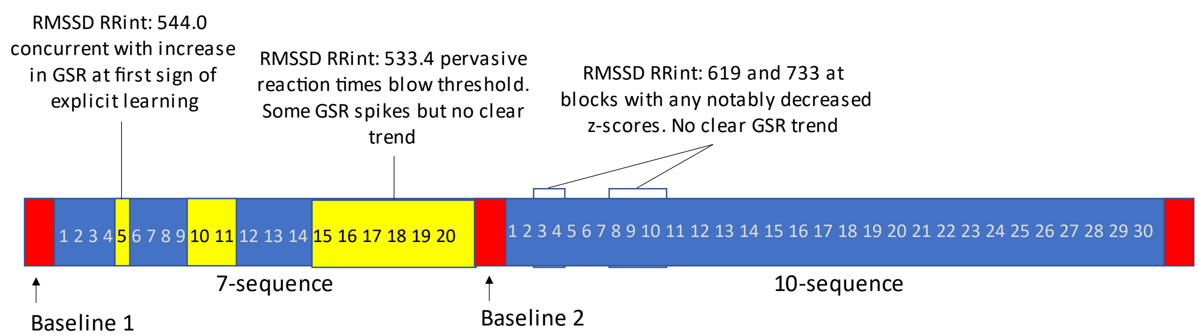

Figure 4. Subject 2 SRTT. The overall HRV (RMSSD for the RR intervals across the whole task) was 588.9 ms. Subject 2 met the threshold for explicit motor learning during the repeating 7-sequence portion of the SRTT but not during the repeating 10-sequence portion. HRV and GSR for important blocks are indicated.

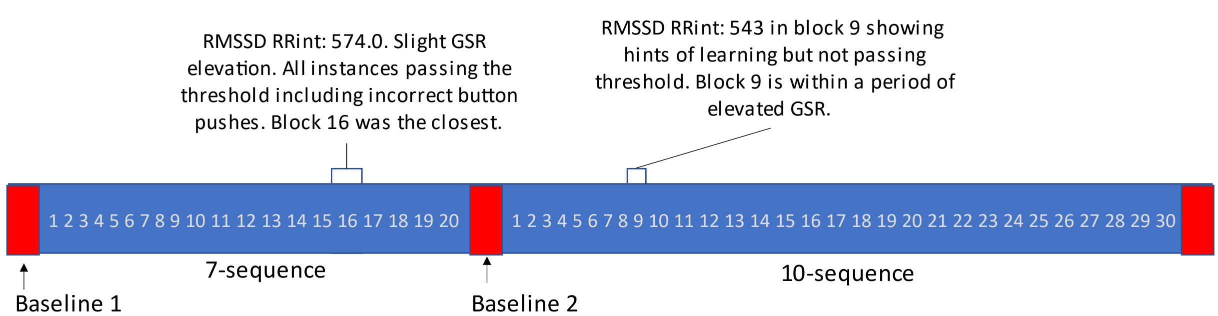

Figure 5. Subject 3 SRTT. The overall HRV (RMSSD for the RR intervals across the whole task) was 574.9 ms. Subject 3 did not learn explicitly in either the 7 or 10-sequence portions of the SRTT. Every group of reaction times low enough to pass the threshold included incorrect button presses. HRV and GSR for important blocks are indicated in blocks that were closest to meeting the threshold.

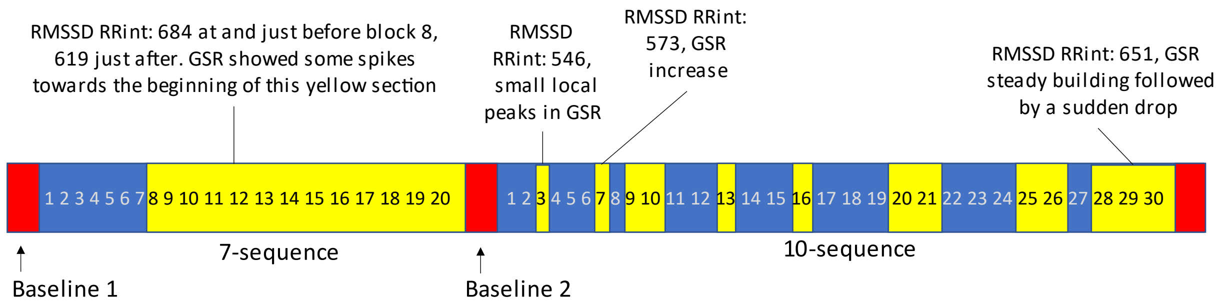

Figure 6. Subject 4 SRTT. The overall HRV (RMSSD for the RR intervals across the whole task) was 671.9 ms. Subject 4 met the reaction time criteria to be classified as an explicit learner in both the 7 and 10-sequence portions of the SRTT although the subject did not enter the sequence when prompted. HRV and GSR for important blocks are indicated above.

Discussion

Arousal Biometrics as Predictors of Motor Learning

All participants learned implicitly as shown through decreasing reaction times even when they did not meet the threshold for explicit learning. Accordingly, the participants made comments about suspecting a pattern or about their fingers getting faster on their own. Only subject 1 answered the prompt about the sequence which is impressive considering that the code malfunctioned during that SRTT so that a block of 40 random stimuli repeated continuously instead of 7 or 10 stimuli repeating. After terminating the malfunctioning code, subject 1 could explicitly recount the first 3 and last 6 digits of the 40-digit priming sequence. Despite not being able to assess subject 1's reaction time and accuracy during the SRTT, subject 1 did display periods of increased GSR concurrent with drops in HRV, indicating increasing arousal, attention, and engagement with the SRTT (Figure 3).

When the SRTT worked correctly, subject 2 met the reaction time threshold for explicit motor learning in the 7-sequence portion, and subject 4 met the criteria for the both the 7 and 10-sequence portions despite not entering an answer in the prompt. Subject 4 may have frozen or blanked when asked the question so that the box disappeared before she could type anything. Admittedly, this happened to me when I tested the code prior to running the experiment even though I knew what was going to happen and knew the sequence.

At the first sign of explicit learning during the 7-sequence portion, subject 2 exhibited both an increase in GSR and a relatively low HRV (Figure 4). However, only a few blocks during the 10-sequence contained even one z-score lower than the threshold, and none contained the required 2 in a row. HRV was higher than the average during these blocks, and no pattern in GSR emerged (Figure 4). The block closest to explicit learning during subject 3's 7-sequence exhibited an average HRV and only slight GSR elevation while the block closest to learning in the 10-sequence exhibited a decreased HRV and a relatively elevated GSR (Figure 5). Subject 3 never met the threshold for explicit learning during the SRTT and, accordingly, could not recall the sequence. These findings indicate that when subject 2 was first discovering the 7-sequence, subject 2 was at a state of arousal higher than the average for the duration of the study. However, this arousal pattern was not seen in blocks during the 10-sequence which didn't meet the explicit learning threshold. The data also indicates that subject 3 never reached a sufficiently high level or arousal, focus, or task engagement to learn the sequence explicitly. This supports the hypothesis and is consistent with the idea that appropriately increased arousal and focus go hand in hand (Asprey & Porges, 2019; Ulrich et al., 2015).

As mentioned previously, subject 4 passed the explicit learning threshold in both portions of the SRTT. The 10-sequence portion fits the pattern mentioned in the preceding paragraph. The first couple blocks meeting the threshold display decreased HRV and increased GSR (Figure 6). Threshold hold was met first in block 8 then in every subsequent block through the end of the 7-sequence portion. Interestingly when looking at block 8 and before, HRV was higher than average, 684 vs 671 ms, but when looking at block 8 and after, HRV was lower than average, 619 vs 671 ms (Figure 4). This is different from some of the other blocks when the threshold was met. Perhaps the difference arises because the threshold was met more and more for the remainder of the 7-sequence instead of occurring once then a occurring again several blocks later before increasing in prevalence. Because of this finding, it is still unclear whether the arousal precedes the focus and learning or vice versa.

Although comparing strict HRV and GSR values between subjects isn't helpful to detect motor learning, it may be worth noting that the two subjects who learned harder sequences had higher overall HRV than the other two subjects. Subject 1 learned 9 values of a 40-sequence repetition and had a RR interval RMSSD of 645 ms across the whole task. Subject 4 met the explicit learning threshold in both the 7-sequence and 10-sequence halves of the SRTT and had an RR interval RMSSD of 671 ms across the entire task. Subject 2 learned only the 7-sequence portion and had an RR interval RMSSD of 589 ms across the entire task. Subject 3 had the lowest average HRV at an RR interval RMSSD of 575 ms and failed to learn either sequence explicitly. Values can be compared in Table 1. This correlation is consistent with the literature review on HRV and cognitive domains by Forte et al. (2019) and with research about HRV effects on reaction times (Siennicka et al., 2019; Asprey & Porges, 2019). This is why the hypothesis included not only an HRV drop but a high baseline HRV.

These results tentatively support the hypothesis. Qualitative observation supports the biometric prediction, but there is no statistical power in this experiment. The main finding that indicates consistency with the hypothesis and with previous research is a high baseline HRV and a subsequent drop in HRV and rise in GSR activity. Subject 4 displayed a high baseline HRV, explicit learning of both sequences, and a drop in HRV and rise in GSR at the emergence of explicit motor learning. This occurred during the 7-sequence portion of subject 2's task and is implied in subject 1's task based on biometric assessment but cannot be confirmed due to loss of SRTT data. This is consistent with both Porges' Polyvagal Theory and with the literature reviewed by Forte et al (2019) which helped to establish the hypothesis.

Subject 1 had the highest working memory and learned explicitly. Subject 3 had a working memory on par with subject 1, but his biometrics and reaction times indicate that he did not experience the proper arousal and engagement to learn explicitly. Subject 4, on the other hand, did show expected instances of GSR increase and HRV decrease corresponding with the emergence of explicit motor learning, but subject 4 only had a working memory of 50% accuracy, compared to 73% in subjects 1 and 3. This suggests that either working memory, sufficient arousal, and task engagement are all important for explicit motor learning, and the working memory threshold is lower than 50% accuracy of the 2-back test, or that working memory isn't as strong of a predictor as reaction time threshold and arousal.

Ferguson et al. found that motivation affects how accessible goal-relevant knowledge is to the participant (2008). The sequence in this study was only presented implicitly, but the Ferguson study accounts for both implicit and explicit priming and effects (2008). Subject 3 appears to have lacked the proper motivation to learn the sequence explicitly given absence of distinct biometric signs of focus. After the experiment, subject 3 made a comment about noticing repetition but not caring enough to try and learn it. Participants were not surveyed regarding their stress or anxiety levels either. Subject 2, however, did comment on expecting her heart rate to increase when the task started due to the “testing” nature of the task. This is consistent with the idea that anxiety plays a role in task performance, attention, and motivation due to its accompanying high level of arousal.

In the literature review, studies were cited which investigated the influence of mood and of motivation on motor learning and which investigated the use of HRV and GSR to assess mood, arousal, and even attention. This study attempts to start the bridge between these ideas, making the two-step leap from biometrics to cognitive and emotional domains to motor learning.

Limitations

Increased sample size is always desired for generalizability to the population at large, but the need for more subjects is exaggerated in this study due to the limitations posed by Covid-19. Only four subjects were able to participate in the study, and the SRTT program did not repeat properly for one participant. A low biometric sampling frequency of 5 Hz of calls into question the sensitivity of the HRV data. The ECG data did not look like clear cardiac cycles due to the low sampling frequency, so R peaks were hard to pinpoint. Extrapolating and filtering the ECG data helped tremendously, but the low sampling frequency has most likely influenced the HRV data in an unknown way since even a few additional or missing R peaks can change HRV results.

Tertiary factors like whether or not the subject slept sufficiently the night before the experiment can potentially influence performance in the motor learning task. In addition to factors involving the subjects' day-to-day lives, the environment in which the experiment was conducted was not as controlled as a lab setting since the lab was suspended from use during the Covid-19 pandemic. This means that the environment was not the same for each participant, and extraneous distractions, such as a barking dog or a person walking through the room, could not be completely eliminated. These factors could potentially influence attention and focus.

Future Directions

Repeating this paradigm with improvements could yield more robust results. Increasing the sample size so that more explicit learners can be studied, especially ones that learn with the appropriately repeating SRTT, is prudent. Including total time elapsed in the SRTT data sets would make comparison with the biometric data simpler. Collecting ECG at a higher sampling frequency, would allow for a clearer ECG trace and therefore more reliable HRV calculations. Further experimentation running the SRTT procedure while collecting all the potential predictors of motor learning, such as working memory, EEG, eye tracking, HRV, and GSR, could present the opportunity to begin teasing out the relationship between these predictors. At this point, it is not clear if and how these factors all depend on each other.

Assessing if any of these predictors are more reliable or even more practical to implement in certain situations than other methods would have useful implications for application not only in personal performance improvement but also in physical rehabilitation. Particularly, HRV and GSR seem to be the most promising if they can match or surpass the predictive power under investigation in the realm of EEG for two reasons. One, ECG and GSR are cheaper, quicker, and easier to collect than EEG. Two, heart rate, HRV, and GSR can be more easily assessed in real time. If, during rehabilitation, the patient's biometrics indicate increased stress arousal to the point of inhibiting performance, breathing exercises can be implemented to calm heart rate and to reduce emotional reactivity so that the patient can continue that rehab session with the potential to get the most out of the session. Besides direct application in motor learning, collection of heart rate and skin conductance information can be applied in any situation for which arousal and autonomic regulation are informative, such as sleep and health monitoring. Products like the Oura Ring and Fitbit already ultilize this realm of technology.

Conclusion

The research question was whether or not HRV and GSR can gauge the arousal and engagement of a subject during a SRTT in which there is a hidden sequence so that explicit motor learning can be detected. This was hypothesized to be observed as a higher general HRV in explicitly learning participants with a subsequent drop in HRV and a rise in GSR during times of explicit motor learning and therefore heightened task engagement. The results are promising as the known instances of explicit motor learning emergence, detected through reaction times, generally showed this pattern of HRV decrease and GSR increase. Moreover, this pattern was either not pronounced or completely non-existent during periods of implicit learning only. And, the subjects who learned more difficult sequences had higher HRV across the whole task in addition to well-timed dips in HRV. Arousal levels also trump working memory as a predictor of explicit motor learning since one of the two highest scoring subjects in working memory did not learn explicitly at all, but the subject with the poorest working memory performance learned both sequences to the explicit level.

Arousal levels as assessed by HRV and GSR may provide a window into both task engagement and the emergence of explicit motor learning. Despite a small sample size and low frequency ECG collection in this study, HRV and GSR emerge as promising not only for predicting explicit motor learning but for real time biofeedback in motor learning. HRV and GSR are certainly easier to implement than EEG, and companies already have rings and bracelets that can collect biometric data and communicate it to a phone. Going forward, these results should be confirmed (or refuted) with a better ECG sampling frequency, a larger participant population, and a more controlled environment. If the results hold true to the hypothesis after further testing, then HRV and GSR can be confidently implemented in further motor learning research as well as by physical therapists and even by the general population.

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References

Asprey, D. (producer, host) & Porges, S. W. (guest). (2019, March 7). Episode "573. The Nervous System Circuitry of Safety, Sound, and Gratitude – Stephen Porges Ph.D." *Bulletproof Radio* [Audio podcast]. https://blog.daveasprey.com/stephen-porges-573/

Chon, D., Thompson, K. R., & Reber, P. J. (2018). Motivation to avoid loss improves implicit skill performance [Abstract]. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *44*(2), 327–333. https://doi.org/10.1037/xlm0000456

Eitam, B., Hassin, R. R., & Schul, Y. (2008). Nonconscious Goal Pursuit in Novel Environments. *Psychological Science*, *19*(3), 261–267. https://doi.org/10.1111/j.1467-9280.2008.02078.x

Ferguson, M. J., Hassin, R., & Bargh, J. A. (2008). *Implicit motivation: Past, present, and future.* In J. Y. Shah & W. L. Gardner (Eds.), *Handbook of motivation science*, 150–166. The Guilford Press.

Forte, G., Favieri, F., & Casagrande, M. (2019). Heart Rate Variability and Cognitive Function: A Systematic Review. *Frontiers in Neuroscience*, *13*, 1–11. https://doi.org/10.3389/fnins.2019.00710

Lawson, R., Gayle, J., & Wheaton, L. A. (2017). Novel behavioral indicator of explicit awareness reveals temporal course of frontoparietal neural network facilitation during motor learning. *PLOS ONE*, *12*(4), e0175176. https://doi.org/10.1371/journal.pone.0175176

Lawson, R. & Wheaton, L. A. (2018, November). *Successful transfer of recently acquired motor skills may be dependent on enhanced visuomotor error monitoring during initial learning*. 2018 Society for Neuroscience Annual Meeting, San Diego, California.

Liao, C.-M., & Masters, R. S. W. (2001). Analogy learning: A means to implicit motor learning. *Journal of Sports Sciences*, *19*(5), 307–319. https://doi.org/10.1080/02640410152006081

Mathis, B. C. (1967). Motivation and Emotion in Learning. *American Journal of Physical Medicine*, *46*(1), 468–479. Retrieved from https://journals.lww.com/ajpmr/Citation /1967/02000/Motivation_and_Emotion_in_Learning.31.aspx

McCraty, R. (2005). Enhancing emotional, social, and academic learning with heart rhythm coherence feedback. *Biofeedback*, 33(4), 130–134. Retrieved from http://humancair.com /image/pdf/Enhancing%20Learning%20%20with%20heart%20coherence%2014-10-10.pdf

Nourbakhsh, N., Wang, Y., Chen, F., & Calvo, R. A. (2012). Using galvanic skin response for cognitive load measurement in arithmetic and reading tasks. *OzCHI '12: Proceedings of the 24th Australian Computer-Human Interaction Conference*, 420–423. https://doi.org/10.1145/2414536.2414602

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113. https://doi.org/10.1016/0028-3932(71)90067-4

Pollock, A., & JafariNaimi, N. (2017, November). *Heart Time: Reflections on Physiology and Embodiment*. 2017 Meeting of the Society for Literature, Science and the Arts (SLSA), Tempe, Arizona.

Porges, S. W., & Coles, M. G. H. (1982). Individual differences in respiratory-heart period coupling and heart period responses during two attention-demanding tasks. *Physiological Psychology*, *10*(2), 215–220. https://doi.org/10.3758/bf03332939

Siennicka, A., Quintana, D. S., Fedurek, P., Wijata, A., Paleczny, B., Ponikowska, B., & Danel, D. P. (2019). Resting heart rate variability, attention and attention maintenance in young adults. *International Journal of Psychophysiology*, *143*, 126–131. https://doi.org/10.1016/j.ijpsycho.2019.06.017

Thayer, J. F., and Lane, R. D. (2009). Claude Bernard and the heart–brain connection: further elaboration of a model of neurovisceral integration. *Neurosci. Biobehav. Rev.* 33, 81–88. doi: 10.1016/j.neubiorev.2008.08.004

Turner, E. (2020). Implicit Awareness During Skilled Motor Learning and the Implications for Rehabilitation, 1-19. Undergraduate Thesis at Georgia Institute of Technology.

Ulrich, M., Keller, J., & Grön, G. (2015). Neural signatures of experimentally induced flow experiences identified in a typical fMRI block design with BOLD imaging. *Social Cognitive and Affective Neuroscience*, *11*(3), 496–507. https://doi.org/10.1093/scan/nsv133

Wulf, G., & Lewthwaite, R. (2016). Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning. *Psychonomic Bulletin & Review*, *23*(5), 1382–1414. https://doi.org/10.3758/s13423-015-0999-9