

Measuring Investment in Learning: Can Electrocardiogram Provide an Indication of Cognitive Effort During Learning?

Perceptual and Motor Skills

2016, Vol. 122(2) 375–394

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DOI: 10.1177/0031512516633348

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Abstract

Heart rate variability (i.e., low frequency:high frequency ratio) was measured to differentiate invested cognitive effort during the acquisition and retention of a novel task. Participants (12 male, $M = 25.1$ year, $SD = 3.6$; 12 female, $M = 22.8$ year, $SD = 1.1$) were required to produce Braille equivalents of English letter primes on a standardized keyboard in proactive or retroactive conditions (groups, each $n = 12$). The correct Braille response was either provided before (i.e., proactively) or after (i.e., retroactively) the participant's response. During acquisition, participants in the proactive group demonstrated shorter study time, greater recall success, and reported lower cognitive investment. Participants in the proactive and retroactive groups did not statistically differ in heart rate variability. For retention, the retroactive group showed greater recall success, lower perceived cognitive effort investment, and lower heart rate variability. The results highlight the usefulness of

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heart rate variability in discriminating the cognitive effort invested for a recently acquired skill.

Keywords

learning, practice, heart rate variability

Introduction

Researchers have demonstrated that holding the content of augmented information constant, but changing the timing of its delivery to either before (termed proactive) or after (termed retroactive) a motor action, has paradoxical effects on performance and learning (e.g., Patterson & Lee, 2005, 2008; Richardson & Lee, 1999). Specifically, presenting augmented information about how to perform a task *after* an attempt at the task (i.e., retroactively) can improve retention of the skill, but often is accompanied by poor performance during the acquisition period. In contrast, presenting augmented information about the task performance *before* an attempt (i.e., proactively) leads to superior performance, but poor retention of the skill compared with presenting the task information retroactively. For example, Richardson and Lee (1999) showed that participants who received task information proactively demonstrated superior and near perfect recall success during practice. However, during the immediate and 48-hour delayed retention tests, greater recall success was exhibited by participants who were provided the same task information after their motor action (i.e., retroactively). The learning benefits associated with providing augmented information retroactively have been observed during the acquisition of personal digital assistant or English alphabet pairings (Patterson & Lee, 2005, 2008).

The effectiveness of a practice condition in relation to learning is attributed to the relative permanence of the motor memory that is formed through encoding of the requisite task information in memory and retrieval of that information from long-term memory (Kantak & Winstein, 2012). Lee et al. (Patterson & Lee, 2005, 2008; Richardson & Lee, 1999) attributed the learning advantages of augmented information presented retroactively to the differential demands placed on long-term memory compared with the demands placed on working memory when that same information is presented proactively. Augmented information presented retroactively engages the learner in retrieval practice, believed to be a potent learning variable such that repeated retrieval attempts subsequently facilitates future retrieval attempts (Bjork, 1988, 1994; Kornell, Klein, & Rawson, 2015). When augmented information is presented proactively, the necessary information to produce the correct motor action is readily available in working memory, and therefore, retrieval processes are circumvented. As a result, the learning advantages associated with the retroactive placement of

augmented information over proactive placement are attributed to the increased cognitive effort of retrieval practice (e.g., Patterson & Lee, 2005, 2008).

Cognitive effort has been defined as the mental processing invested by the learner in the cognitive processes related to the anticipation, planning, regulation, and interpretation of motor performance (Guadagnoli & Lee, 2004; Lee, Swinnen, & Serrien, 1994; Schmidt & Bjork, 1992). Researchers have attempted to identify behavioral and psychological methods capable of assessing the cognitive effort invested during the performance of both cognitive and motor tasks (e.g., Tyler, Hertel, McCallum, & Ellis, 1979). Physiological measures of attention have gained prevalence within experiments investigating cognitive effort because the measurements can be collected throughout performance (Abernethy, 2007; Mitchell & Hunt, 1989). Some of these psychophysiological measures include glucose metabolism, pupillary responses, electroencephalography, heart rate (HR), and heart rate variability (HRV; see Fairclough & Mulder, 2012 for a review).

An increase in psychophysiological research identifying connections between HRV and cognitive systems such as attention and working memory has been an area of focus over the past decade (e.g., Hansen, Johnsen, Sollers, Stenvik, & Thayer, 2004; Thayer, Hansen, Saus-Rose, & Johnsen, 2009). In these studies, power spectral analysis of HRV has been used to identify changes in cognitive effort. During the analysis, the power spectrum is split into a very low frequency (LF) band (≤ 0.04 Hz) thought to reflect thermoregulation, a low frequency band (0.04–0.15 Hz) thought to reflect manipulations in mental workload demands, and a high frequency (HF) band (0.15–0.4 Hz) thought to represent momentary respiratory influences or respiratory sinus-arrhythmia (Fairclough & Mulder, 2012). The ratio between the LF and HF frequency (i.e., LF:HF ratio) has been used to provide an indication of the relative contributions of the sympathetic and parasympathetic nervous system to the activity of the heart during cognitive effort (e.g., Tattersall & Hockey, 1995). An increase in parasympathetic activity produces a lower LF:HF ratio, whereas an increase in sympathetic activity produces a higher LF:HF ratio (Pomeranz et al., 1985). The work of Tattersall and Hockey (1995) demonstrated that cognitively effortful problem-solving phases of simulated flight resulted in an increased LF:HF ratio compared with less demanding phases. More recent research supports the notion that an increased LF:HF ratio is associated with greater cognitive investment (e.g., De Rivecourt, Kuperus, Post, & Mulder, 2008; Hansen, Johnsen, & Thayer, 2003; Luft, Takase, & Darby, 2009). Although researchers have provided considerable support for the use of frequency-based measures of HRV as an index of cognitive effort, research involving motor tasks have focused exclusively on changes in HRV as a function of cognitive effort during motor performance (e.g., Mullen, Faull, Jones, & Kingston, 2012; Mullen, Hardy, & Tattersall, 2005; Neumann & Thomas, 2009). What remains unknown is whether LF:HF ratio can be used as a useful metric to infer learning of a

motor task during the retrieval phase (i.e., delayed retention test) of motor skill acquisition (Kantak & Winstein, 2012).

In this study, the change in the LF:HF ratio was investigated as an index of cognitive effort engaged during the acquisition and retention of learning English–Braille pairings when presented task-related augmented information either proactively or retroactively. Traditional behavioral and psychological measures of cognitive effort were also collected (e.g., NASA task load index). Conceptual compatibility was operationally defined as the spatial and motor relatedness between an English prime and the corresponding Braille sequence (Sanders & McCormick, 1993). A pre-test determined the English–Braille pairings considered to have a low level of conceptual compatibility (i.e., not guessable on the first attempt) to subsequently be utilized as the experimental stimuli.

The LF:HF ratio was used to capture differences in cognitive effort as a function of practice condition. Based on previous works by Lee et al. (e.g., Patterson & Lee, 2005, 2008; Richardson & Lee, 1999), participants in the retroactive group were expected to demonstrate inferior performance during acquisition, but superior retention of the English–Braille pairings due to the increased cognitive effort invested during the encoding (i.e., acquisition portion of practice) to retrieve the requisite task information during the delayed retention test (Kantak & Winstein, 2012; Patterson & Lee, 2008). Increased cognitive effort should be indicated by a high LF:HF ratio (Fairclough & Mulder, 2011; Neumann & Thomas, 2009). A lower LF:HF ratio was predicted for the retroactive group in the retrieval period (i.e., retention period) suggesting decreased investment of cognitive effort to successfully retrieve the requisite motor task information (Kantak & Winstein, 2012; Neumann & Thomas, 2009; Patterson & Lee, 2005, 2008). In comparison, participants in the proactive group were expected to demonstrate superior recall success of the pairings accompanied by lower LF:HF ratio (i.e., lower investment of cognitive effort) during acquisition period as a function of the requisite task information presented before the trial (i.e., information readily available in working memory). However, because participants in the proactive condition were not required to retrieve the requisite task information until the retention period of the experiment, their recall success was expected to decline at the expense of investing greater cognitive effort, evidenced by a higher LF:HF ratio compared with the participants in the retroactive condition.

Therefore, the purpose of the present experiment was to examine whether the placement of augmented information (either retroactive or proactive) would differentially effect cognitive effort invested by participants during the acquisition and retention test of a novel task. To assess whether invested cognitive effort and subsequent learning was modulated by the timing of task information, a behavioral measure (i.e., recall success), a self-report (self-reported cognitive

load), and a psychophysiological measure (i.e., HRV) were administered during both the acquisition and retention periods.

Hypothesis 1. Placement of augmented information during acquisition will differentially impact invested cognitive effort during acquisition as indexed from behavioral, self-report, and psychophysiological measures.

Hypothesis 2. Placement of augmented information during the acquisition period will subsequently affect learning of the task, inferred from behavioral, self-report, and psychophysiological measures from the retention period.

Method

Participants

Twenty-four self-declared right-handed volunteers from the undergraduate and graduate student population (12 male, $M = 25.1$ year, $SD = 3.6$; 12 female, $M = 22.8$ year, $SD = 1.1$) with normal or corrected-to-normal vision volunteered to participate in the experiment. Exclusion criteria included the following: left-handed; prior experience or knowledge of Braille; and individuals with heart or anxiety disorders (Thayer et al., 2009). Individuals with heart disorders were excluded since lower resting LF:HF ratio has been reported (Sztajzel, 2004). High-level athletes were excluded from this experiment and were defined as those athletes who self-reported engaging in aerobic exercise 15 hours or more per week. Previous research has shown differences in HRV of individuals who were considered to have a high-fitness level compared with those who did not (see Plews, Laursen, Stanely, Kidling, & Buchheit, 2013 for a review outlining factors that influence HRV). Participants who self-reported to be right-handed, with no prior knowledge or experience with Braille, and were not a high level/varsity athletes were included in the experiment. The participants were equally distributed (balanced for gender) and quasi-randomly assigned to one of the two experimental conditions. Participants' inclusion in the experiment was based on self-reported information collected from participants prior to their participation in the experiment. Participants provided informed consent and received no financial compensation. Guidelines of the University's Research Ethics Board were followed.

Instrument and reliability

Perceived workload of participants was assessed by the NASA Task Load Index (NASA-TLX; Hart, 2006; Hart & Staveland, 1988). The NASA-TLX is a multi-dimensional rating-scale that requires participants to self-report their perceived

workload based on six subscales: mental demand, physical demand, performance, effort, and frustration (Hart, 2006; Hart & Staveland, 1988). Typically, participants self-report their perceived workload on each subscale separately ranging from very low (i.e., 0) to very high (i.e., 20). An overall mean is computed from these subscales to provide insight into the perceived workload of participants for a particular task (see Hart, 2006 for a review). The NASA-TLX is a well accepted and common approach to assessing perceived workload of participants in laboratory tasks and task performed in naturalistic settings (Hart, 2006). The NASA-TLX has extensive support for its psychometric properties of validity and reliability (Hart, 2006; Rubio, Diaz, Martin, & Puente, 2004) in group (Braarud, 2001; Cronbach's alphas .83 and .81) and individual task settings (e.g., see Safari from Habibi, Cronbach's alpha = .83). Scores have shown to be sensitive to changes in mental workload placed on participants (Mehta & Agnew, 2015) and is commonly used in combination with other measures (e.g., physiological see Hart, 2006 for a review). The NASA-TLX has shown to be sensitive to perceived workload demands in such contexts as medical (e.g., Surgeons, Zheng, et al., 2012), construction (masonry; Mitropoulos & Memarina, 2013), complex tasks performed in the laboratory (Haga, Shinoda, & Kokubun, 2002), and with different populations such as children (Laurie-Rose, Frey, & Zaman, 2014). Other contexts include the military, virtual reality, and human-computer interactions (Hart, 2006).

For the present experiment, participants self-reported their perceived workload immediately after completion of the acquisition period and immediately upon completion of the delayed retention test. An overall mean was calculated to assess perceived workload demands of participants as a function of learning the English-Braille pairs in one of two experimental conditions (e.g., Proactive or retroactive; see Hart, 2006).

Only three subscales (performance, effort, and frustration) of the assessment was utilized for statistical analysis, previously suggested to directly assess the participants perceived workload demands with their interaction with the task. Portions of the NASA-TLX are commonly utilized by researchers (see Hart, 2006). The Cronbach alpha for the NASA-TLX for the present experiment was 0.84.

Apparatus and task

Participants were required to enter a series of key pressing sequences on a number pad that consisted of a Braille sequence, accompanied by the associated English prime (i.e., English-Braille pairings) (Figure 1). Braille consists of six cells, separated into two columns, with three cells in each column. Braille is typically read from top to bottom, beginning in the left column then to the right column. Seven keys (0-1-2-4-5-7-8) on a standard keyboard's number pad were used to emulate the typical Braille layout. The 0 key was colored

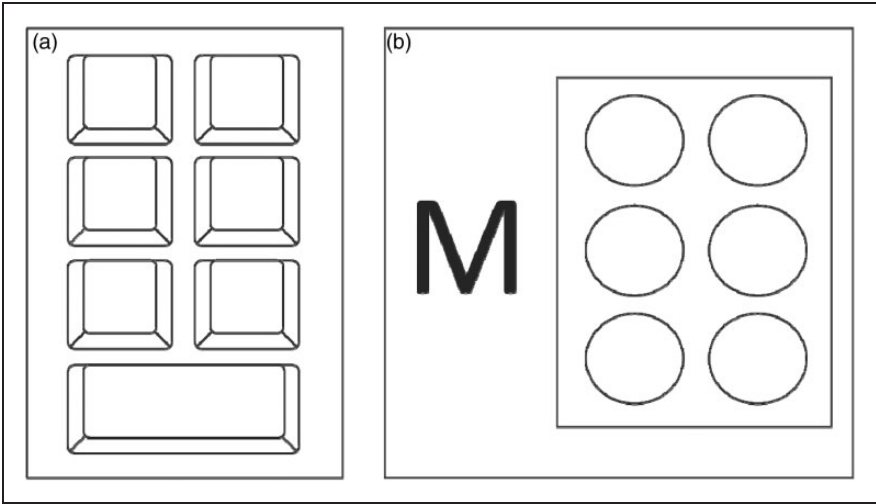


Figure 1. (a) Schematic of the number-pad layout that participants used to complete their motor responses. The “zero” key at the bottom was used as the home position. (b) Example of an English prime and a blank Braille cell.

green and used as the home button. The remaining six keys were colored pink and visually represented the Braille cell. The English–Braille pairings were presented on a 19" LCD monitor, and the timing of the presentation of all stimuli was controlled using E-Prime v2 (Psychology Software Tools Inc., Sharpsburg).

A pre-test determined the conceptual compatibility between an original set of 43 English–Braille pairings. High and low compatibility was determined when pairings were guessed correctly or incorrectly, respectively. Six participants who did not engage in the current experiment (three men, *M* age = 24 year) completed one repetition of all 43 pairings without feedback. Success rate of each guess was recorded. Results revealed that the majority of the English–Braille pairings had low conceptual compatibility (i.e., required key pressing sequence not guessed on the first attempt). The pairings for H, X, Q, 8, single quotation, and dash were all guessed correctly at least once and were, therefore, excluded from the experiment. Although the pairing for the number 1 was guessed correctly once, it was subsequently included in the experiment to equate six experimental stimuli in the keystroke categories. Overall, stimuli for the current experiment consisted of six English–Braille pairings in three keystroke categories (2, 3, and 4 strokes) for a total of 18 pairs. In each category, there was at least one presentation of an English letter, a number, and a special character.

Electrocardiogram (ECG) data were collected with a Powerlab system (AD Instruments, Colorado Springs, Colorado) with gelled electrodes. The following

procedure was used: The ground lead was placed superior to the heart, the positive lead was placed inferior to the heart, and the negative lead was placed directly across from the positive lead on the right side of the chest (Hansen et al., 2003). ECG data were sampled at 1000 Hz (Fairclough & Houston, 2004).

Procedure

Prior to participation, individuals refrained from vigorous exercise, smoking, alcohol, or caffeine consumption for at least 24 hours and refrained from eating for 2 hours (Fairclough & Houston, 2004). Electrode sites were cleaned using alcohol swabs and underwent gentle skin abrasion. Participants sat in a dark and quiet room with eyes closed while wearing acoustic impeding devices for 10 minutes (Hansen et al., 2003). Five-minute baseline readings were obtained at the beginning of each experimental session. ECG data were collected for the duration of each session. Participants were randomly assigned to either the proactive ($n = 12$) or retroactive group ($n = 12$). Sex of participant and time of day were counterbalanced across groups (Bonnemeier et al., 2003).

Participants were seated 48.5 cm from the computer monitor. Prior to data collection, they were instructed how to properly enter their keystroke sequences. Participants completed two familiarization trials with pairings that were not used during data collection. A familiarization trial began with presentation of a "Ready" screen for 2 seconds before appearance of the English prime. An English prime would appear with a blank Braille cell on the right. A response began with the depression of the home button. Subsequently, a blank navy blue screen remained until the response was completed by a second depression of the home position. Afterward, a "Trial Complete" screen appeared for 2 seconds before the next trial.

The practice phase consisted of depressing the requisite buttons corresponding to the English–Braille pairing. For the proactive group, the English prime was presented with the required Braille sequence before entering the required key pressing sequence on the keypad. The participants in the retroactive group were required to enter the requisite key pressing sequence after viewing only the English prime. Upon completion of their response, the complete English–Braille pairing was presented to the participant. Immediately following the presentation of the complete pairing in the retroactive condition and the last key press in the proactive condition, both groups received 3 seconds of qualitative feedback on a screen that stated "your response was (correct/incorrect)" (Figure 2). During practice, the 18 English–Braille pairings were repeated eight times for a total of 144 trials. The ordering of each pairing was constant across participants and no pairings requiring the same number of keystrokes were performed consecutively. After the practice phase, participants completed the NASA task load index (NASA-TLX; Hart & Staveland, 1988) to assess perceived cognitive effort

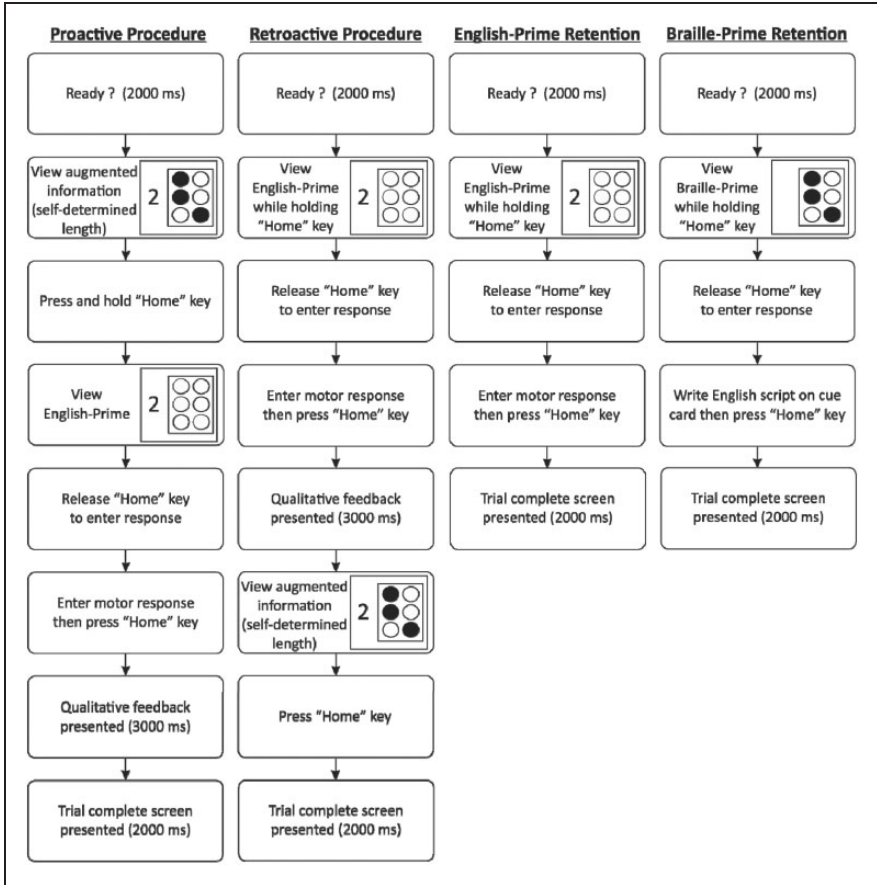


Figure 2. Representations of the order of events for the proactive and retroactive conditions during practice and the order of events for both groups in the English prime and Braille prime retention tests.

invested during the acquisition of the English–Braille pairings as a function of augmented feedback condition.

Retention of the pairings was assessed in a 15-minute and 24-hour retention test without the augmented information. The presentation order of the stimuli in the retention period differed from the acquisition period to eliminate an order effect. Participants were required to produce the required key pressing sequence while viewing the English prime (similar to acquisition) and also the English character while viewing the Braille sequence (i.e., transfer test) to assess the presence of any practice specificity effects associated the order of presentation of the stimuli within the practice conditions. The proactive group practiced with

the English prime and Braille sequence appearing before the movement in comparison to the retroactive group who had the English prime only before making the response. Therefore, the retroactive group could have an advantage in the English prime retention test when the participants were asked to perform in the manner in which they practiced. In contrast, the proactive group could have had an advantage in identifying the English equivalent of a Braille prime as the participants saw both pieces of augmented information before performing the responses (Figure 2). The NASA-TLX was completed after each retention test. The order of events for practice and retention are outlined in Figure 2.

Dependent variables and data analysis

Dependent variables were recall success, study time, NASA-TLX scores, and proportional LF:HF ratio. Study time (ST) was defined as the length of time individuals observed the screen with both the English prime and Braille sequence. In order to acquire the LF:HF ratios, the time of the R-spikes were identified in the ECG recording and then a tachogram was created and submitted to a fast Fourier Transform using the PowerLab software in order to obtain the power spectrum values. The LF:HF ratios from each block were divided by the baseline LF:HF ratio to acquire a proportional LF:HF ratio.

Practice phase data were analyzed in separate 2 Group (Proactive, Retroactive) \times 8 Block (18 trials each) analyses of variance (ANOVA) with repeated measures on the final factor. Retention data for the English prime and Braille prime tests were separately analyzed using 2 Group \times 2 Time (15-minute/24-hour) ANOVAs with repeated measures on Time. Tukey's HSD was employed *post hoc* with a significance level of $p < .05$.

Results

Acquisition

There was a significant Group \times Block interaction for recall success, $F(7,154) = 57.07$, $p < .001$, $\eta_p^2 = 0.72$. The proactive group had superior recall success in Blocks 1–7 (Figure 3(a)). Analysis of study time revealed main effects of Block, $F(7,154) = 36.27$, $p < .001$, $\eta_p^2 = 0.62$, and Group, $F(1, 22) = 49.31$, $p < .001$, $\eta_p^2 = 0.69$. The main effects were superseded by a significant interaction of Block and Group, $F(7,154) = 15.24$, $p < .001$, $\eta_p^2 = 0.41$. The proactive group took less study time in Blocks 1 to 4 compared with the retroactive group (Figure 3(b)). There were no significant effects or interaction for LF:HF ratio (Figure 3(c)). A main effect of Group, $F(1, 22) = 34.79$, $p < .001$, $\eta_p^2 = 0.61$, for NASA-TLX scores revealed that the retroactive group ($M = 30.17$, $SD = 11.52$) self-reported investing greater effort than the proactive group ($M = 9.17$, $SD = 4.41$; Figure 3(d)).

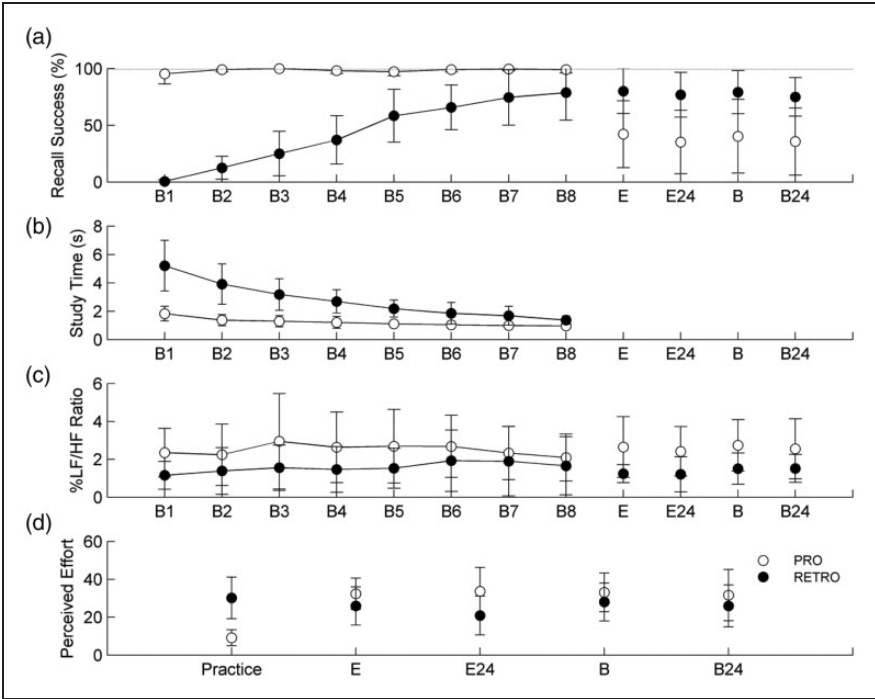


Figure 3. (a) Recall success rate (%) for the proactive (open circles) and retroactive (closed circles) as a function of practice block (1–8) and retention test (E = English prime after 15 minutes; E24 = English prime after 24 hour; B = Braille prime after 15 minutes; B24 = Braille prime after 24 h). (b) Study time (seconds) as a function of group and practice block (c) LF:HF ratio as a function of practice block and retention test. (d) Perceived effort scores as a function of practice and the four retention tests.

Retention

English prime. Main effects of Group, $F(1, 22) = 14.75, p < .001, \eta_p^2 = 0.40$, and Time, $F(1, 22) = 8.34, p < .01, \eta_p^2 = 0.27$, were found for recall success. *Post hoc* tests indicated superior recall success for the retroactive group ($M = 0.78, SD = 0.19$) compared with the proactive group ($M = 0.39, SD = 0.30$). The 24-hour test ($M = 0.56, SD = 0.33$) was performed with less recall success than the 15-minute test ($M = 0.61, SD = 0.32$).

There were also main effects of Group for the NASA-TLX, $F(1, 22) = 5.49, p < .05, \eta_p^2 = 0.20$, and LF:HF ratio, $F(1, 22) = 10.22, p < .005, \eta_p^2 = 0.32$. *Post hoc* comparisons revealed lower self-reported investment of cognitive effort by the retroactive group ($M = 23.38, SD = 10.62$) compared with the proactive group ($M = 33.00, SD = 10.90$) and a lower increase in LF:HF ratio for

the retroactive group ($M = 1.23$, $SD = 0.75$) than the proactive group ($M = 2.53$, $SD = 1.50$).

Braille prime. Main effects for Group, $F(1, 22) = 13.47$, $p < .01$, $\eta_p^2 = 0.38$, and Time, $F(1, 22) = 5.31$, $p < .02$, $\eta_p^2 = 0.19$, were found for recall success. *Post hoc* tests indicated superior recall success for the retroactive group ($M = 0.77$, $SD = 0.19$) than the proactive group ($M = 0.38$, $SD = 0.32$). The 24-hour test ($M = 0.55$, $SD = 0.32$) was performed with less recall success than the 15-minute test ($M = 0.60$, $SD = 0.34$). There were no group differences for the NASA-TLX scores. However, a main effect of group, $F(1, 22) = 10.33$, $p < .004$, $\eta_p^2 = 0.32$, was found for LF:HF ratio where the retroactive group ($M = 1.51$, $SD = 0.80$) had a lower increase in LF:HF ratio than the proactive group ($M = 2.65$, $SD = 1.51$).

Discussion

Presenting augmented information proactively facilitated superior recall success during the acquisition period, while presenting augmented information retroactively showed superior recall success during the retention period. In fact, participants provided augmented information retroactively demonstrated superior recall success of the Braille sequences based on the presentation of an English prime (retention test) and had better recall of English characters based on the presentation of a Braille prime (transfer test). These findings are congruent with previous work suggesting motor learning is optimized when augmented information, that is held constant in precision and content, is presented retroactively rather than proactively (e.g., Patterson & Lee, 2005, 2008; Richardson & Lee, 1999). The learning advantages have been attributed to the amount of cognitive effort invested by participants to retrieve the requisite task information. Specifically, motor skill retention is perpetuated when augmented information is provided retroactively (i.e., greater cognitive effort), subsequently heightening the encoding and retrieval strength of the required motor actions in long-term memory (Bjork, 1988; 1994; Kantak & Winstein, 2012).

In this context, working memory is conceptualized as a functionally active construct that temporarily maintains and stores information providing a limited capacity interface between perception, long-term memory, and action (Baddeley, 2001, 2003, 2012; Baddeley & Hitch, 1974). When presenting augmented information proactively, the pertinent visuospatial information for a successful response was immediately available in working memory and only needed to be held in memory long enough to produce the motor action on the upcoming performance trial (i.e., low cognitive effort). In comparison, participants provided augmented information retroactively were required to invest greater cognitive effort based on the fact they were required to guess the correct solution for each English–Braille pairing on the first attempt (i.e., Block 1), then attempt a

retrieval of the requisite motor action on subsequent practice trials. The gradual retrievability (i.e., recall success) of the requisite task information over the course of the acquisition period for the retroactive condition is consistent with the notion that *retrieval attempts* rather than *retrieval success* enhances learning (Kornell et al., 2015). In summary, the processing differences highlighted between presenting augmented information retroactively or proactively are distinct and have been shown to induce differing perceived cognitive effort (e.g., Patterson & Lee, 2005, 2008).

This study attempted to extend previous research that has examined presenting task information either retroactively or proactively by differentiating invested cognitive effort by using a psychophysiological measure (i.e., LF:HF ratio), extensively reported as being sensitive to increasing and decreasing mental work load demands (e.g., Fallahi et al., 2016) during the performance of a motor task (e.g., Mullen et al., 2012; Neumann & Thomas, 2009). Specifically, increased mental work load shows increased LF:HF ratio compared with contexts of low mental workload (i.e., lower LF:HF ratio). The purpose of the present experiment was to extend this research by determining whether the LF:HF ratio would be a sensitive measure highlighting changes in invested cognitive effort by participants during skill acquisition as a function of their respective practice context. Previous research has shown the LF:HF ratio to be sensitive to a motor task that still require attention to perform (i.e., yet to be learned, novice performers) and performed automatically (i.e., already learned, expert performer; Fallahi et al., 2016; Neumann & Thomas, 2009). This is commensurate with more recent neuroscience theoretical discussions regarding motor skill acquisition that highlight differing demands placed on cortical (i.e., primary motor cortex) and sub-cortical (i.e., basal ganglia) areas of the brain as a function of the skill progressing from considerable cognitive effort to perform (encoding phase) to a degree of automaticity (retrieval phase, low cognitive effort; Kantak & Winstein, 2012).

The results of the acquisition phase for the LF:HF ratio period did not support the prediction in regard to an expected difference between experimental conditions in invested cognitive effort. This prediction was premised on the expectation that those participants in the retroactive condition would invest greater cognitive effort in their attempts to retrieve the requisite task information, whereas those in the proactive condition were expected to avoid this process by utilizing information already stored in working memory from the task information being presented proactively. This finding is curious, since participants in the retroactive group self-reported greater investment of cognitive effort in the acquisition period compared with those in the proactive group. To reconcile this finding, because the participants were all naive to the task and experimental procedure, perhaps their anxiety similarly affected HRV during the acquisition phase, regardless of the self-reported investment of cognitive effort and the practice condition experienced. Although speculative, since participants'

anxiety was not measured, this notion is consistent with previous research that has shown anxiety experienced by participants can differentially affect HRV (Bradley et al., 2010). Perhaps, a lengthened familiarization period to circumvent the anxiety associated with experimental testing would be one method of reducing this variable during measurements of HRV. In summary, the acquisition data suggest that HRV was not sensitive to potential changes in invested cognitive effort during skill acquisition as a function of practice condition. However, future research should explore other methods of capturing the changing psychophysiological process during the acquisition of a motor skill.

The behavioral and physiological indices from the retention period for the proactive and retroactive conditions provided support for the hypotheses. Specifically, the LF:HF ratio for the retroactive group suggested lower investment of cognitive effort in the retention phase accompanied by lower self-reported measures of invested cognitive effort and superior recall success compared with the proactive condition. The LF:HF ratio is consistent with other research suggesting that when a performer is skilled at a motor task, the demands of the task demand less attention and utilized more automatic cognitive processing, compared with those individuals who have not acquired the motor task (Neumann & Thomas, 2009). As suggested by previous research, the proactive and retroactive presentation of augmented information during practice requires place differential demands on the cognitive processes of the learner during skill acquisition (Patterson & Lee, 2005, 2008). Although the expected differential cognitive demands of the augmented information conditions during acquisition were not evidenced in the LF:HF ratio, the perceived higher cognitive demands reported by participants in the retroactive condition as well as their inferior recall success and longer study of the complete pairings was consistent with past research. However, the results extend previous research by showing the cognitive processes engaged in by participants during the acquisition phase differentiated psychophysiological measures in the retention period. Although, the LF:HF ratio was seemingly insensitive to changes in cognition occurring during practice, it was a good indicator differentiating the cognitive effort invested once a task was learned (Mullen et al., 2005, 2012; Neumann & Thomas, 2009).

Limitations and conclusions

One method of inferring the cognitive demands invested by a participant during task performance is through the assessment of HRV. HRV, as a function of task demands, is commonly assessed in one performance instance of the task by the performer (i.e., one day). However, the present experiment offers a novel contribution to current understanding of motor learning such that HRV was assessed over successive days and utilized to infer the acquisition and retention of a novel task as a function of practice condition. However, there are some identified limitations that limit the generalizability of the findings.

There is some controversy pertaining to the use of the LF:HF ratio. Specifically, there is mounting evidence to suggest that, despite its common usage, the LF:HF ratio may not be a valid measure of cardiac autonomic regulation (Billman, 2013; Cotie, St Amand, McMillan, Picton, & Ditor, 2010; Sharif, Millar, Incognito, & Ditor, in press). While the authors agree with this criticism, such a shortcoming of the LF:HF ratio does not preclude its use as an index of mental workload. In fact, a great deal of recent work continues to successfully use the LF:HF ratio in such a manner and has demonstrated LF:HF increase as mental workload becomes greater, and LF:HF decrease in a more relaxed state (Fallahi, Motamedzade, Heidarimoghdam, Soltanian, & Miyake, 2016; Heemskerk et al., 2016).

The sample size was relatively small and consisted primarily of younger adults in a university setting. Future research should examine a more diverse sample population varying in age, task experience, and perhaps cognitive processing capabilities. Such research would extend understanding of the variables differentially modulating HRV during motor skill acquisition.

Previous research has shown motor learning advantages for presenting task-related information retroactively (i.e., after a response) from the recall success of participants during tests of retention (Patterson & Lee, 2005, 2008). The results of the present offer further support and extend this previous research by evidencing skill acquisition from a psychophysiological index (LF:HF ratio) during the retention period. Participants provided information retroactively during the acquisition period demonstrated greater recall success and a lower LF:HF ratio in the retention period compared with those provided task information proactively during the acquisition period. The present findings are similar to Neumann and Thomas (2009), who also showed that participants who previously acquired the motor skill (i.e., experts) invested less cognitive effort to perform the task, evidenced by HRV, compared with those considered inexperienced (i.e., novices). The present study differs from previous research since all participants in the present experiment were inexperienced with the task and the task goal. Further, the findings from the present experiment also support future experiments utilizing behavioral measures (i.e., recall success) and perceived cognitive effort scales (i.e., NASA Task Load Index) to identify and quantify the cognitive effort invested by participants during skill acquisition.

The findings from the present experiment offer some practical implications. The results suggest that HRV, based on the LF:HF ratio, changes as function of the cognitive effort invested by the participant during the acquisition and retention period of the experiment. The results of the present experiment highlight a future direction of inquiry in regard to knowing when the learner's information processes are being optimally challenged during skill acquisition (see Guadagnoli & Lee, 2004). Optimally challenging the information processes of the learner by manipulating the difficulty of the practice context throughout skill acquisition is recommended as one method of perpetuating learning

(see Guadagnoli & Lee, 2004). A study by Thurber, Bodenhamer-Davis, Johnson, Chesky, and Chandler (2010) examined the use of biofeedback training regarding HRV. Thurber et al. (2010) showed that musicians provided biofeedback training regarding their HRV (i.e., told to maintain a certain HRV criterion) effectively reduced their music performance anxiety and improved their music performance. These findings from Thurber et al. (2010) offer insight into the effect of allowing participants the opportunity to self-monitor their HRV during task acquisition, and the modulating impact of HRV on skill acquisition. Utilizing HRV as feedback to participants and information to the practitioner in regard to the complexity of the practice context could potentially distinguishing between a practice context that is either optimally challenging or not challenging enough to the learner and could, therefore, be modified accordingly.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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