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The Neural Mechanisms of Optimal Human Performance

prepared by Helene M. Sisti
Norwich University
Northfield, Vermont

under contract W911SR_15-2-0001

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14. ABSTRACT
Training for optimal human performance is an essential component of military operations. Military personnel undergo extensive training in a broad range of cognitive skills. The manner in which skills are practiced can impact how well they are executed at a later time point. A critical factor that may influence later execution is the practice schedule. In this study, two different practice schedules are compared to determine the effect on memory and the neural dynamics that drive it. The purpose is to determine how to train military personnel for optimal human performance. The model that is used is a hand–eye coordination task. Participants must rotate two dials using their left and right hands to track a moving target on a screen. Brainwaves are captured in real-time before and after practice. The task models complex bimanual coordination and the visuomotor and cognitive load that underlies it. Participants demonstrated successful memory retrieval 1 week after training. Analysis of neural dynamics revealed that the post-movement beta-rebound was evident in the sensorimotor cortex both before and after practice.

15. SUBJECT TERMS
Humans in Complex Systems; optimal human performance; learning; memory; electroencephalogram; EEG

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1. Introduction

Training for optimal human performance is an essential component of military operations. Learning and retention of skills that require diverse physical and cognitive task demands depend on a myriad of factors, one of which is practice organization during training. Practice organization refers to the manner in which a skill is learned. For example, a skill may be practiced using either a blocked or randomized schedule. In the blocked schedule, a specific task is performed repeatedly before moving on to the next one, whereas in a randomized schedule, all task variants are practiced within each session. Paradoxically, long-term retention is often superior in the group that practices using a randomized schedule, despite inferior performances during acquisition. These observations have important implications for how military personnel are trained. The objective of the present study is twofold: (1) determine optimal practice organization using a model of visuomotor bimanual coordination and (2) elucidate the neural mechanisms underlying it.

2. Methodology

2.1 Participants

Participants (n = 36) were 18 years of age or older and were students of Norwich University. All completed the Oldfield (1971) handedness questionnaire, as well as questions regarding previous history with activities that require bimanual coordination, including video games, driving manual transmission automobiles, or playing a musical instrument. Participants were fitted with an electroencephalogram (EEG) Quik-Cap (Compumedics Neuroscan) during only the pre- and posttest. Posttest refers to the retention test done 1 week after the last day of practice. EEG data were not collected during the three practice sessions. All procedures were approved by the Norwich University Institutional Review Board Ethics Committee and in accordance with the 1964 Declaration of Helsinki (revised in 2008). All participants signed the informed consent form.

2.2 Apparatus and Task Description

Participants were comfortably seated at a table in front of a computer monitor with both lower arms resting on two custom-made adjustable ramps. At the end of each ramp, a dial was mounted and could be rotated by holding an upright peg between the thumb and index finger. The two dials controlled movement of a red cursor (a flexible line segment 1 cm long) on the monitor. When the left dial was rotated clockwise, the cursor moved up; when it was rotated counterclockwise, the red cursor moved down. When the right dial was rotated clockwise, the cursor moved to the right; when it was rotated counterclockwise, it moved to the left. The right dial controlled horizontal movement. The objective of the task was to use the two dials simultaneously to track the moving target. The target was a white dot that moved along a stationary path, either a curved line (pre- and posttest) or a jagged line (acquisition period).

During the 3-day acquisition period, the path was a jagged line. To introduce task variants, the starting position and orientation of the jagged line changed between tasks. The starting position was either at the left of the screen, so the cursor moved towards the right; the right of the screen, so the target cursor moved to the left; or the bottom of the screen, so the target cursor moved upwards. A novel transfer test was done at retention, i.e., the line was curved instead of jagged. Participants from both blocked and randomized groups had the same pre- and posttest. This was done to control for temporal interval differences between the end of training and the retention test between the blocked and randomized schedules, i.e., the blocked group would have only practiced Task A on Day 1 and would have recently practiced Task C on Day 3, whereas the randomized group would have practiced all three tasks on Day 3. The three practice sessions included a similar path, with the exception that it was a jagged line rather than curved.

The entire experiment included five sessions, beginning with a pretest, followed by three consecutive practice sessions, each on a different day, and finally a posttest, which occurred 1 week after the last practice session. Each session included 20 trials. In the randomized practice schedule, the starting position was randomized within a training day. In the blocked practice schedule, the starting position remained constant each day. The sample sizes across the two conditions were unequal, as a result of the blocked practice schedule requiring additional recruitment for counterbalancing procedures.

2.3 Behavioral Analysis

The x- and y- coordinates of both the target and the participant's cursor were captured every 10 ms by LabView 2020. Task performance was assessed by calculating the Euclidean distance between the participant's cursor and the target cursor during each trial and summed. A value of zero indicates the participant finished the trial precisely on the target. The mean Euclidean distance across the 20 trials was calculated. Calculations are done in MS Excel and formatted for statistical analysis using SPSS software.

2.4 Neurophysiological Analysis

During the pre- and posttest (1-week delayed retention test) sessions, participants were fitted with a 32-electrode Quik-Cap. The central electrode, Cz, was placed at the midpoint between nasion and inion. The ground electrode was at the top of the forehead anterior to Fz and equidistant between Fp1 and Fp2. Soluble electrolytic gel was inserted into each electrode using a blunt-edge syringe. Gel was inserted until the impedance values were less than 5 kΩ. Once impedance values were less than 5 kΩ, instructions for the behavioral task were administered. Neuroscan Curry8 was used for signal acquisition and off-line processing. Triggers were manually delivered to signal the start (keyboard press 1) and end (keyboard press 2) of every trial. Manual triggers are marked in the software with both a time stamp and a visual cue, i.e., a purple vertical line in the data acquisition window. EEG data were collected with a sampling rate of 1,000 Hz.

The following steps were applied to each participant's data in the same sequence: bandpass filter of 1.0–30 Hz to remove non-physiological artifacts. The upper limit of the bandpass filter was 30 Hz, which obviates the need for the 60-Hz notch filter. Ocular artifacts were removed using Independent Component Analysis; removal of other residual artifacts (e.g., muscular) was performed using a voltage threshold (+100 μV, +200 ms). We focused our analysis on the post-movement beta rebound (PMBR) in the sensorimotor cortices. This frequency has been the target of successful deep brain stimulation therapeutic intervention as well as modulation by users who control an actuator via a brain computer interface. The sensorimotor cortex corresponds with C3 and C4 electrodes, left and right hemisphere, respectively.

Signals were averaged across the 20 trials for the pre- and the posttest. Conversion of signals from the time to the frequency domain was done by applying the fast-Fourier transform using the same software that was used for both acquisition and preprocessing (Curry 8, Compumedics). A 2-s interval was selected during the last 2 s of movement, and the first 2 s of the intertrial interval. This criterion was selected based on prior research examining task-related power during bimanual coordination (Andres et al. 1999; Serrien and Brown 2002). Further rationale for this interval included both control for nonlinear drift of the signal and selection of a temporal interval comparable with task demand characteristics. Mean values across subjects were calculated for each condition. Data were then exported as .txt files to MS Excel and formatted for statistical analysis in SPSS.

2.5 Statistical Analysis

The effect of practice organization on learning and memory was analyzed using a 2 × 5 ANOVA, in which the first factor was practice organization (blocked or randomized) and the second factor was practice session (pretest, practice session 1, practice session 2, practice session 3, posttest). The dependent measure was the performance error. To determine the effect of PMBR on learning, a 2 × 2 ANOVA was calculated; the first factor was movement termination (before vs. after movement), and the second factor included the electrodes corresponding with the sensorimotor cortex (C3 and C4).

3. Results and Discussion

Task performance improved in both groups from pre- to posttest following three practice sessions [$F_{(1,4)} = 13.51$, $p < .001$, $\eta^2 = .241$] (Figure 1). Mean performance error for the blocked group was 9.41 ± 0.87 at pretest and 4.86 ± 0.76 at posttest. Mean performance error for the randomized group was 7.80 ± 1.21 at pretest and 3.41 ± 0.58 at posttest. There was no main effect of practice condition [$F_{(1,4)} = 2.09$, $p = .14$, $\eta^2 = .012$]. There was no significant interaction between practice condition and practice session [$F_{(1,4)} = 1.67$, $p = .15$, $\eta^2 = .0138$].

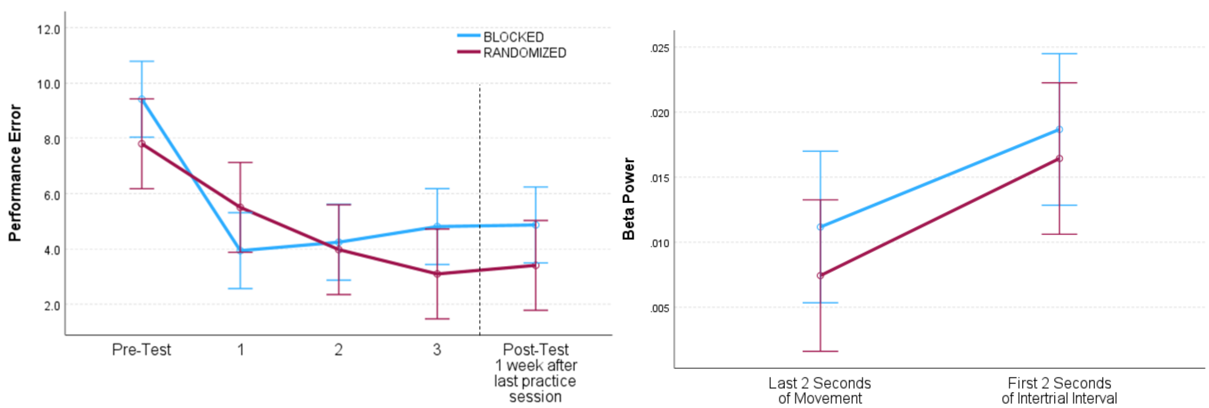

Figure 1. Participants improved across three practice sessions in both the blocked and randomized practice schedules (left). Beta power in the sensorimotor cortex (right) increased upon movement termination (right).

Beta power of the sensorimotor cortex before and after movement termination (i.e., the end of the trial) was analyzed using a 2 × 2 ANOVA; the first factor was movement termination (before vs. after), and the second factor was the electrode corresponding with the left and right sensorimotor cortex (C3 and C4). This was done for both pre- and posttest. The previous behavioral analysis revealed no effect of practice condition; therefore, blocked and randomized groups were collapsed. At pretest, there was a main effect of movement termination [$F_{(1,1)} = 7.85$, $p = 0.006$, $\eta^2 = .056$]; no main effect of electrode [$F_{(1,1)} = 1.02$, $p = 0.31$, $\eta^2 = .008$]; and no significant interaction of movement termination by electrode [$F_{(1,1)} = 0.065$, $p = 0.79$, $\eta^2 = .001$]. At posttest, 1 week after the last practice session, there was a main effect of movement termination [$F_{(1,1)} = 8.42$, $p = 0.004$, $\eta^2 = 0.64$]; no main effect of electrode [$F_{(1,1)} = .01$, $p = 0.99$, $\eta^2 = .001$]; and no significant interaction of movement termination by electrode [$F_{(1,1)} = 0.23$, $p = 0.62$, $\eta^2 = .002$]. Because there was no significant effect of electrodes, C3 and C4 were collapsed. A 2 × 2 ANOVA of movement termination (before vs. after) × practice session (pretest vs posttest) was computed. There was a significant main effect of movement termination [$F_{(1,1)} = 16.43$, $p < .001$, $\eta^2 = .059$]; no main effect of practice session [$F_{(1,1)} = 0.04$, $p = 0.83$, $\eta^2 = .01$]; and no significant interaction [$F_{(1,1)} = .013$, $p = 0.91$, $\eta^2 = .01$]. The PMBR was evident before 3 days of practice and 1 week later at the retention test.

4. Conclusion

A rich body of work, both theoretical and empirical, has characterized the impact of practice organization on the retention of motor skills (Schmidt 1975; Lage et al. 2015; Raviv et al. 2022; Czyż et al. 2022, 2024; Panzer et al. 2024). One rationale for this study was to increase ecological validity for military settings while still maintaining rigorous experimental control over the independent variables. To this end, a reductionist model of a complex bimanual coordination skill was used.

Brainwaves were recorded before and after practice. Participants in both groups successfully learned the task and demonstrated retention of it 1 week after practice. Furthermore, the increase in beta power upon movement termination was also evident in both groups. This speaks to the complexity of developing effective training programs and the challenges of understanding the neural oscillations that drive optimal human performance. The practice schedules adopted here resulted in similar patterns of acquisition and retention. The underlying neurophysiology examined here, the PMBR of the sensorimotor cortex, was a consistent match with the behavior. In other words, when participants were either naive (pretest) or trained on the task across several days and tested 1 week later, posttest, the PMBR was present. The robustness of this component of a potential "neural signature" is important in the eventual development of a robust biomarker for motor control (Cohan et al. 2019). Future research will include a more comprehensive analysis across multiple frequencies and brain regions. Of particular interest are functional connectivity approaches, which may yield new insight of whole brain communication during learning under variable practice conditions that lead to optimal human performance.

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List of Symbols, Abbreviations, and Acronyms

ANOVA	Analysis of Variance
EEG	Electroencephalogram
PMBR	Post-Movement Beta Rebound

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