

# Neurophysiology of Visual-motor Learning during a Simulated Marksmanship Task in Immersive Virtual Reality

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## ABSTRACT

Immersive virtual reality (VR) systems offer flexible control of an interactive environment, along with precise position and orientation tracking of realistic movements. Immersive VR can also be used in conjunction with neurophysiological monitoring techniques, such as electroencephalography (EEG), to record neural activity as users perform complex tasks. As such, the fusion of VR, kinematic tracking, and EEG offers a powerful testbed for naturalistic neuroscience research. In this study, we combine these elements to investigate the cognitive and neural mechanisms that underlie motor skill learning during a multi-day simulated marksmanship training regimen conducted with 20 participants. On each of 3 days, participants performed 8 blocks of 60 trials in which a simulated clay pigeon was launched from behind a trap house. Participants attempted to shoot the moving target with a firearm game controller, receiving immediate positional feedback and running scores after each shot. Over the course of the 3 days that individuals practiced this protocol, shot accuracy and precision improved significantly while reaction times got significantly faster. Furthermore, results demonstrate that more negative EEG amplitudes produced over the visual cortices correlate with better shooting performance measured by accuracy, reaction times, and response times, indicating that early visual system plasticity underlies behavioral learning in this task. These findings point towards a naturalistic neuroscience approach that can be used to identify neural markers of marksmanship performance.

## 1 INTRODUCTION

The ability to coordinate visual information with motor output is essential to a great number of human endeavors. In particular, activities such as sports, surgery, and law enforcement often rely on

efficient reciprocal interactions between visual perception and motor control, allowing individuals to execute precision movements under time-limited, stressful situations. As such, developing a better understanding of the neurophysiological mechanisms that underlie precision visual-motor control, and characterizing how these change with practice, will offer fundamental new insight into skilled performance and may be useful for the development of better training programs that have the potential to accelerate learning.

Relationships between brain activity and motor proficiency have been studied for tasks such as marksmanship [7, 13–15], golf putting [4, 5], and archery [18, 27]. However, these tasks are typically performed as self-paced tasks that require minimal movement to acquire a static target. Tasks that require large movements to engage with a dynamic target introduce additional brain processes that allow for perception, motor planning, control, and execution. Therefore, experiments that limit mobility may not be capturing the cognitive processes involved with performing a natural, full-body motor action.

Until recently, approaches to investigate the brain dynamics of actively behaving participants in a complex 3D environment have been considered infeasible. In most natural environments, conditions cannot be controlled (e.g., wind speed/direction) and are difficult to replicate between experiments. Additionally, experiments using non-invasive modalities for recording brain activity, such as electroencephalography (EEG), have long considered muscle-related activity to be artifacts and, therefore, limit participants movement to avoid them. However, recent advancements in simulation technology, tracking, and mobile EEG have contributed to the development of mobile brain/body imaging (MoBI), a new imaging approach that investigates the links between distributed brain dynamics and natural behavior using synchronized recordings of movement tracking and EEG [21]. Simulation technologies such as immersive virtual reality systems allow for complex tasks to be performed in a controlled indoor 3D environment without sacrificing ecological validity, providing a strong platform for naturalistic neuroscience research. For example, past research has implemented the MoBI EEG approach for investigating the sequence and timing of rhythmic finger movements [26], the mechanisms of cognitive control during gait adapted locomotion [28], and physical exertion during high-intensity cycling [10].

In this study, we synchronize kinetic movement tracking with recordings of the brain's electrical activity using EEG while participants perform a simulated marksmanship task in immersive virtual reality, modeled after the Olympic Trap Shooting event. This marks-

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manship task is particularly useful for studying psychophysiological patterns of skill acquisition because it produces discrete measures of performance while still requiring high mental and physical coordination. EEG data were analyzed to calculate visual evoked potentials (VEPs) [20], centered over the left and right visual cortices, thereby giving an acute, high-temporal resolution marker of visual information processing in the brain that could be quantified over practice sessions and linked to performance on the task.

The specific neurophysiological framework under consideration in this study utilizes the time-locked responses induced by the launch of the target pigeon. By considering the temporal evolution of the neural response (EEG) in the visual hemisphere that is contralateralized to a target stimulus (VEPs in the left hemisphere for right launches and vice versa), ocular response (horizontal electrooculography), and kinematic response (head and hand tracking), we will be able to derive a process model of the sequence of brain and behavioral process that unfolds over time, allowing visual processing and motor tracking in this task. This EEG approach is modeled after past EEG studies that have exploited neurophysiological contralateralization of the sensory and motor systems to derive lateralized potentials indexing high-temporal resolution measures of neural activity. For example, past research investigating visual search has used this approach to understand sensory and attentional processing [6, 8], while other studies have used this approach to investigate cognitive control [3] and visual working memory [17]. The current protocol expands upon previous research to study early visual processing and behavior during a full-body orienting task over three days of practice. Furthermore, this protocol builds upon past behavioral research by Rao et al. [24], which demonstrated that improvements on this task were accompanied by systematic changes in the kinematic chain over one day of practice.

## 2 METHODS

### 2.1 Participants

Twenty-four healthy participants (13 female) from Duke University were recruited for this study. Four participants were excluded from analyses: two left-handed participants (due to differences in visual processing when compared to right-handed participants [19]), one participant with extensive marksmanship experience, and one participant who did not complete the experiment. The ages of the remaining twenty participants ranged from 18 to 35 years and all were right-handed. Participation was voluntary, and participants were compensated for their involvement in the study.

### 2.2 Equipment

The study was conducted in the Duke immersive Virtual Environment (DiVE), a six-sided CAVE-like VR system [9], where participants stood in the center of the room-size cube with projectors directed at each of the cube's six walls. The back-facing wall of the DiVE display was not active during the study, effectively making it a 5-wall system. The projectors were run at 120 Hz with a total resolution of 1920 x 1920 pixels per wall.

Participants wore 3D shutter glasses operating at 60 Hz to display stereoscopic graphics. A head tracking device, which was mounted on the shutter glasses, controlled the system viewpoint according to the participant's head movements. An Xbox Top Shot Elite firearm game controller was used for target shooting. The controller, furnished with a 6-DOF tracking sensor, was held in the participants right hand and stabilized with the opposite hand placed along the barrel of the controller (see Fig. 1). An Intersense IS-900 tracking system was used to record the position and orientation of the controller and the head throughout the experiment. Data from both the controller and head tracking sensors were sampled at 60 Hz.

Participants' EEG signals were recorded using actiCAP active electrodes connected to a computer via a 16-channel BrainVision V-Amp system. Thirteen active electrode channels (F3, Fz, F4, C3,

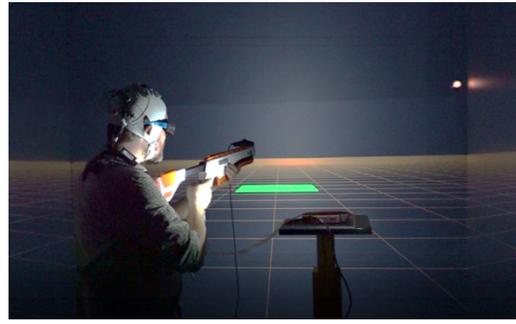


Figure 1: Participant performing the simulated marksmanship task in the Duke immersive Virtual Environment (DiVE), a six-sided CAVE-like VR system. For clarity, the picture was taken with monoscopic graphics.

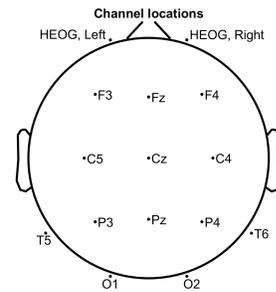


Figure 2: Electrode montage consisting of 13 EEG electrodes and 2 HEOG electrodes, placed according to the 10/20 International Electrode Placement system.

Cz, C4, T5, T6, P3, Pz, P4, O1 and O2) were placed along the scalp according to the 10-20 Electrode Placement system with a linked mastoid reference [16]. Two additional electrodes were placed on the right and left outer canthi of the eyes to record horizontal eye movements using horizontal electrooculography (HEOG). Fig. 2 displays the electrode configuration. All electrode impedances were kept below 10 k $\Omega$ . Data were sampled at 1000 Hz. The dominant electrical artifact at 60Hz (power line frequency) was attenuated using a 0.1-30 Hz bandpass filter. Furthermore, the use of active electrodes containing built-in amplifiers reduced environmental noise at the recording site by converting high impedance input signals into low impedance output signals.

### 2.3 Experimental Task

The marksmanship task used in this study was modeled after International Shooting Sport Federation standards [11]. To mimic realistic target flight times, trajectories, and distances observed in real trap shooting events, the design of the simulation incorporated the physics of projectile motion such as gravitational pull, air resistance, and lift force.

Participants entered the DiVE wearing the EEG cap and the 3D shutter glasses. To begin a trial, the participant aimed the controller towards a trap house, which was displayed as a rectangle on the ground 16.46 m in front of them in simulated space. After an initial 500 ms waiting period, the trap house changed color from red to green and a second waiting period began (variable between 1 and 1.5 s). During the initial waiting period, if the participant aimed the controller away from the trap house before the color changed from red to green, the timer was reset and did not begin again until the participant aimed the controller back towards the trap house. At the

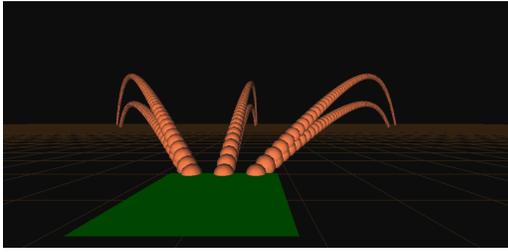


Figure 3: Six target trajectories (shown slightly off-center to improve visibility) showing the orange spherical target in flight (all frames included) and the green trap house from which the targets were launched.

end of the second waiting period, a target was launched in one of six possible trajectories.

The six target trajectories, illustrated in Fig. 3, consisted of three horizontal directions relative to the center of the trap house (left = -45°, center = 0°, right = 45°) and two elevations relative to the ground plane (upper = 25.17°, lower = 12.95°). To increase ecological validity (e.g., fluctuations in outdoor environmental conditions such as wind currents), a random horizontal jitter, ranging from -3° to 3°, was added to each trajectory.

The target was displayed as an orange sphere of radius 0.3 m that traveled at a speed of 28.75 m/s. The maximum flight times for the target were 1.772 s and 3.085 s for the upper and lower elevations, respectively.

## 2.4 Experimental Procedure

Each participant completed the simulated marksmanship task on three separate days within one week. On each day, the experiment was split into 8 blocks of 60 trials each. Before each block, participants stood with their eyes open for 30 seconds to record resting state EEG data prior to beginning the task. Within a block, all six target trajectories were presented 10 times in a random order.

The target acquisition task was done by a raycasting technique [23], but rather than a visible ray, only a white dot was shown at the target depth, to mimic a laser sight. For a given trial, participants were allowed one attempt to hit the target. If the controller's ray was in contact with the target at the time of the shot, the screen would freeze and the target would change color from orange to green. If the ray was not in contact with the target at the time of the shot, the screen would freeze and the target would change color from orange to red. After each shot, the participant's shot location and the target were displayed on the screen until they indicated that they were ready for another target by aiming the controller back over the trap house. The participant was also given feedback on their cumulative accuracy for the block and how many trials remained in that block via text on the screen.

## 2.5 Performance Measures

The independent variables for this study were day, trajectory elevation, and trajectory horizontal direction. The dependent variables (i.e., the measured variables affected by the independent variables) were accuracy, reaction time, response time, and EEG component amplitude.

Accuracy was defined as the number of target hits out of the total number of shots taken. Reaction time was defined as the elapsed time from the target launch to the start of movement. Reaction times were calculated for three different movements: head, controller, and eyes. Head and controller reaction times were calculated offline using 10% of the peak acceleration, measured with the Intersense trackers. Acceleration was calculated as the derivative of the velocity trace, after the velocity trace was smoothed with a 7th order

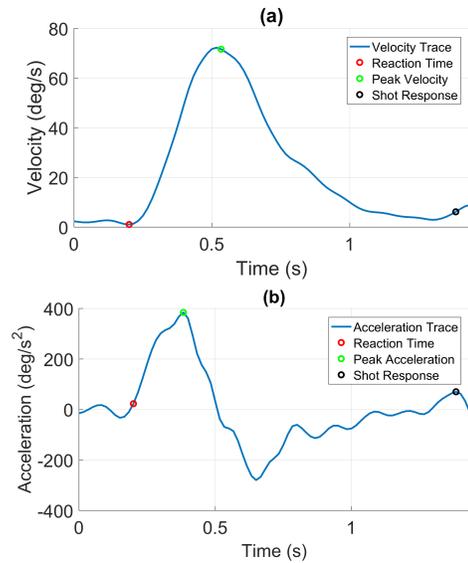


Figure 4: (a) The smoothed velocity trace and (b) the acceleration trace for the firearm controller during a single trial, time-locked to the target launch at 0 ms. The dependent variables are indicated by the circular markers along trace.

FIR filter. Eye reaction times were calculated using a rectified sum of the two HEOG channels, where the beginning of a voltage deflection resulting from changes in eye position was detected when a threshold of 3 standard deviations above the baseline mean ([0 100] ms post-launch) was reached. Due to the lack of a vertical eye measurement, eye reaction times were only computed for the left and right trajectories. Shot response time was defined as the elapsed time from the target launch to the trigger pull. Fig. 4 illustrates these dependent variables along the velocity and acceleration traces for a single trial.

EEG data were analyzed in epochs to calculate the VEPs in the 200 ms following target launch. For this purpose, data epochs were extracted time-locked to the target launch and baseline corrected using the mean value from a 50 ms pre-launch baseline. Channels P3 and P4 were selected for analyses due to the posterior locations of the electrodes over the left and right hemispheres of the visual cortex, respectively. Epochs were averaged over trials for a given participant in order to attenuate noise so that the brain signal can be seen more easily.

## 2.6 Statistical Analysis and Trial Removal

Statistical differences were computed using 3-way repeated measures analysis of variance (ANOVA), where the main effects were computed across independent variables (i.e., days, trajectory elevations, and trajectory horizontal directions). Data were tested for sphericity using Mauchly's Test for Sphericity and, if the assumption of sphericity was violated, a Greenhouse-Geisser correction was used. ANOVA results are reported in the format [F(DOF<sub>conditions</sub>, DOF<sub>error</sub>) = F-statistic, p-value > or < threshold], where the F-statistic was calculated by dividing the mean sum of squares for the independent variable by the mean sum of squares for error. Correlations were computed and tested for statistical significance using Pearson's correlation coefficient.

Trials were excluded from both behavioral (movement) and EEG analyses if the participant did not shoot (1.67%, 482 trials). If movement was initiated too quickly for a given trial, defined as less than 16.667 ms, the trial was removed from the behavioral analyses (0.39%, 23 trials).

Trial removal for EEG was based on two calculations done within a very specific spatial (contralateral visual responses in P3/P4) and temporal (launch-locked before the HEOG response) window. This corresponded to the VEP and was done to test panned hypotheses relating to the role of visual processing in this complex motor protocol. Trials were removed from the EEG analyses if they exceeded a threshold of  $40 \mu V$  (3.02%, 580 trials) or contained data outside of 5 standard deviations of the joint probability distribution observed at each time point (0.35%, 67 trials). The use of artifact correction techniques (as opposed to rejection) would have been severely challenged due to the lack of clear biological templates (e.g. ocular artifact correction) to base removal on. Moreover, based on the low prevalence of rejected trials (3.37%), we are convinced that the signal under consideration offers a strong and unimpeded view of the neural activity that is meant to be scrutinized in these planned hypothesis tests.

### 3 RESULTS

#### 3.1 Shot Accuracy and Error

The overall accuracy (i.e., number of hits out of total shots taken) for the 20 subjects was 67.01%. Significant main effects of day ( $F(2, 38) = 71.355, p < .01$ ), elevation ( $F(1, 19) = 13.032, p < .01$ ), and horizontal direction ( $F(2, 38) = 196.03, p < .01$ ) were observed. Participants showed a significant improvement in accuracy across days. The best performance occurred in the upper and central trajectories and symmetrically decreased for the left and right side horizontal directions. Fig. 5 displays the average accuracy results across days and trajectories, respectively. The accuracy values for each day are listed in Table 1.

A significant interaction effect of horizontal direction with day for shot accuracy was also observed ( $F(4,76) = 3.476$  with  $p < .05$ ), indicating that improvements over days were not uniform across trajectories. This interaction is illustrated in Fig. 6. Larger increases in accuracy over days were observed for the left and right trajectories when compared to the center trajectories. The mean accuracy for the side trajectories increased by 14.6% from day 1 to day 3, while the mean accuracy for the center trajectories increased by 10.35%.

Shot error – the Euclidean distance between the shot and the center of the target – decreased across days ( $F(2, 38) = 23.854, p < .01$ ). The mean error values are displayed across days in Fig. 7a

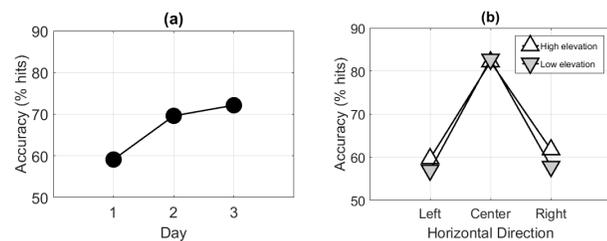


Figure 5: Accuracy results displayed across (a) days and (b) trajectories. The minimum accuracy for a single participant was 32.3%; therefore, the y-axis has been scaled to show small trends. Significant improvements ( $p < .01$ ) were observed over days, with better performance occurring in the central and upper trajectories.

Table 1: Average values of shot accuracy (in % hits) and shot error (in meters) across days

variable	Day 1	Day 2	Day 3
Shot Accuracy	59.12 %	69.61 %	72.15 %
Shot Error	0.312 m	0.254 m	0.243 m

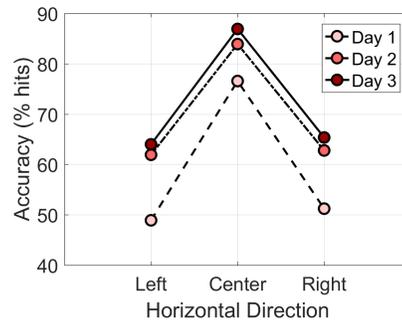


Figure 6: Accuracy is displayed for the 3 days on separate lines across horizontal directions. A significant interaction between day and horizontal direction was observed ( $p < .05$ ), indicating that greater improvements occurred in the left and right horizontal trajectories.

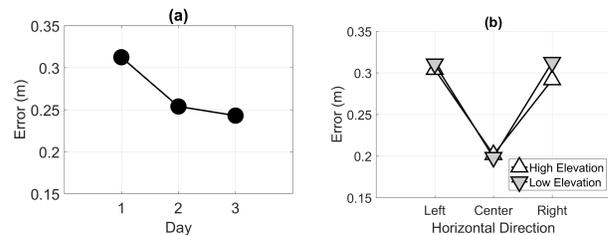


Figure 7: Shot error expressed as the Euclidean distance from the center of target, where a lower number indicates better performance, and displayed across (a) days and (b) trajectories. The maximum distance for a hit was 0.3 m (i.e., the radius of the target); therefore, the y-axis has been scaled to show small trends around this threshold. A significant decrease in error ( $p < .05$ ) was observed across days, with lower error in central and lower trajectories.

and listed in Table 1. Significant main effects were also observed for elevation ( $F(1, 18) = 56.762, p < .01$ ) and horizontal direction ( $F(2, 38) = 125.024, p < .01$ ). Fig. 7b shows that better performance (i.e., lower error) occurred in the upper and central trajectories.

#### 3.2 Reaction and Shot Response Times

Reaction times – the elapsed time between the target launch and the start of movement – were computed for horizontal eye movement (via HEOG), controller rotation, and head rotation. The average reaction times across days, displayed in Fig. 8, were  $0.194 \pm 0.04s$  for eye movement,  $0.206 \pm 0.04s$  for controller rotation, and  $0.287 \pm 0.12s$  for head rotation. A significant decrease in the reaction time of the controller was observed across days ( $F(2, 38) = 28.247, p < .01$ ), indicating that faster hand movements occur with practice. There were no main effects of day for eye or head reaction times.

Shot response times – the elapsed time between the target launch and the time the trigger was pulled – were also recorded and the results are displayed in Fig. 9. Significant main effects of day ( $F(2, 38) = 4.218, p < .05$ ), elevation ( $F(1, 19) = 46.86, p < .01$ ), and direction ( $F(2, 38) = 116.886, p < .01$ ) were observed. Response times decreased across days, with trigger pulls occurring sooner for the central and lower trajectories. Table 2 lists the average values for the reaction and response times across days. A significant interaction of elevation with day ( $F(2, 38) = 5.745, p < .01$ ) was also observed, with larger decreases in shot response times occurring over days for the upper trajectories when compared to the lower trajectories.

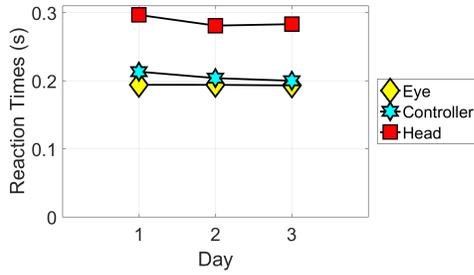


Figure 8: Reaction times of the eyes (diamonds), controller (hexagrams), and head (squares) displayed across days. On average, the eyes moved first after a target launch, followed by the controller and head. A significant decrease in the reaction time of the controller ( $p < .01$ ) was observed across days.

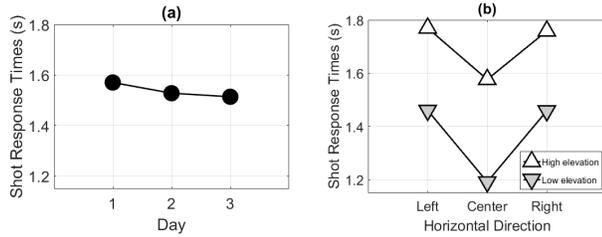


Figure 9: Shot response times displayed across (a) days and (b) trajectories. Participants rarely shot before 1.0 s (3.1% of trials); therefore, the y-axis has been scaled to show small changes in response times. A significant decrease in response time ( $p < .05$ ) was observed across days, with faster response times occurring in the central and lower trajectories.

Table 2: Average values of the reaction and response times (in seconds) across days.

variable	Day 1	Day 2	Day 3
Reaction Time (eyes)	0.194 s	0.194 s	0.193 s
Reaction Time (controller)	0.213 s	0.204 s	0.199 s
Reaction Time (head)	0.297 s	0.284 s	0.288 s
Response Time	1.571 s	1.529 s	1.514 s

### 3.3 Visual Evoked Response

In order to quantify neural responses elicited by the launch of the target, EEG data were analyzed using the time window between the target launch and the onset of eye movement for each trial (0 ms to 200 ms). During this timeframe, an early positive ipsilateral VEP followed by a late negative contralateral VEP was observed over the visual cortex for the left and right trajectories. This simply means that if the target was launched leftward, a positive potential could be seen over the visual cortex in the left hemisphere of the brain followed by a negative potential in the right hemisphere. Conversely, if the target was launched rightward, a positive potential could be seen over the visual cortex in the right hemisphere of the brain followed by a negative potential in the left hemisphere.

Fig. 10 displays the grand average VEPs (averaged across subjects and days) on separate lines for the left and right trajectories, time-locked to the target launch. Electrodes P3 (Fig. 10a) and P4 (Fig. 10b) are located over the left and right hemispheres of the brain, respectively. Parametric statistical tests, corrected for multiple comparisons using Bonferroni correction, show that significant differences ( $p < .05$ ) between the VEPs for the left and right trajec-

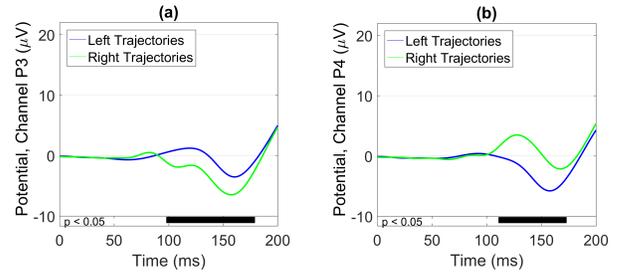


Figure 10: Grand average VEPs for the left and right target trajectories displayed in (a) channel P3 and (b) channel P4, located over the left and right cortices, respectively. Significant amplitude differences ( $p < .05$ ) between left and right trajectories are indicated by black bars below each VEP.

tories exist in the range of ~100 ms and ~175 ms. These differences are displayed in black below the VEPs in Fig. 10.

Fig. 11 displays the grand average scalp topographies for the left trajectories (Fig. 11a) and the right trajectories (Fig. 11b) over 10 ms intervals, ending at the onset of large eye movements around 190-200 ms. The early ipsilateral positive VEP appears to begin at ~100 ms, followed by the larger late contralateral negative VEP at ~110-120 ms.

The mean amplitudes are displayed across days in Fig. 12. Mean amplitudes were determined by averaging over a window of 50 ms in the subject average VEPs. The window ranges were [100 150] ms for the ipsilateral positive VEP and [125 175] ms for the contralateral negative VEP. Significant decreases in mean VEP amplitude were observed from the first day to the third day ( $p < .05$ ).

### 3.4 EEG Correlates

An important goal of this study was to link EEG biomarkers to behavioral performance on the shooting task. In order to assess this, the mean VEP amplitudes were evaluated in channels P3 and P4 for the contralateral target launches. These values were then correlated with shot accuracy, reaction time, and response time by averaging across trials on a given day for each participant, producing 20 (subjects) by 3 (days) data points for each dependent variable. Correlations between the positive ipsilateral VEP amplitudes and these variables were not observed and, therefore, are not reported in this paper.

Fig. 13, Fig. 14 and Fig. 15 illustrate the correlations between VEP amplitude (along the x-axis) and accuracy, reaction time and response times (along the y-axis) respectively. In each figure, the correlations for P3 are shown for the right trajectories in panel a, while the correlations for channel P4 are shown for the left trajectory directions in panel b. In all but one case, significant correlations were observed ( $p < .05$ ) with better performance (higher accuracy or lower reaction/response times) seen for more negative amplitudes.

## 4 DISCUSSION

In this study, a simulated trap shooting task was used to investigate the behavioral and brain processes underlying motor skill learning. Repeated natural movement patterns were measured using kinematic tracking while brain activity was measured with EEG as participants shot at moving targets.

Over 3 days of training, participants improved their accuracy by an average of 13.03%. Faster hand reaction times accompanied this improvement and shots were taken sooner, indicating that less time is needed for motor planning and execution. A similar marksmanship task without EEG was performed in Rao et al. [24], where improvements in accuracy were observed over 7 blocks in a single day experiment for 20 participants. Our results show that these

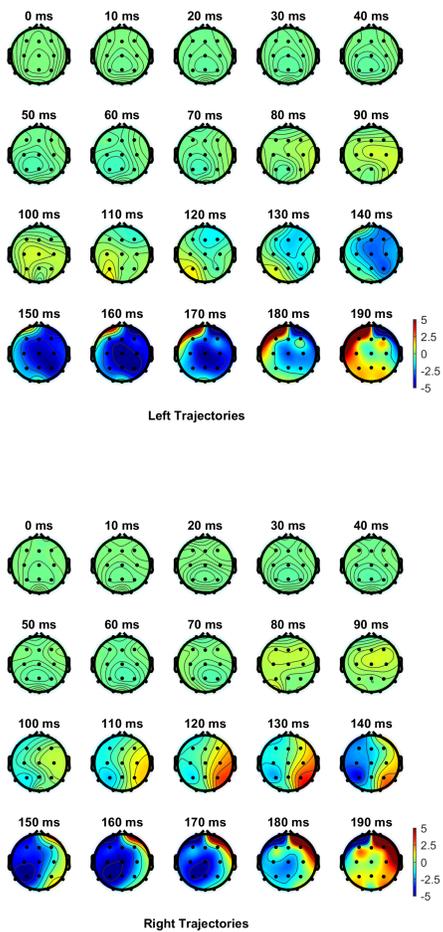


Figure 11: Topographic maps of the VEPs, shown in 10 ms intervals, for left target trajectories (top) and right target trajectories (bottom). Electrodes are displayed as black dots on the scalp. The color axis displays the voltage (in  $\mu\text{V}$ ), where the values are mapped to a color according to the color bar on the bottom right.

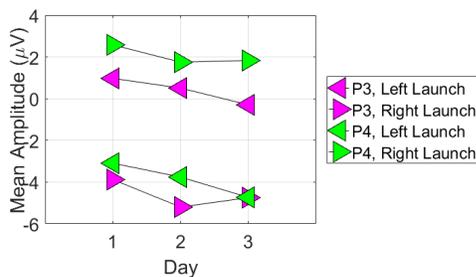


Figure 12: Mean amplitude values for left target trajectories (left-pointing triangles) and right target trajectories (right-pointing triangles) across days. Electrode channels P3 (magenta) and P4 (green) are located over the left and right hemispheres of the brain, respectively.

trends continue over days, with the addition of faster reaction and response times.

The current study also revealed important new insights into the

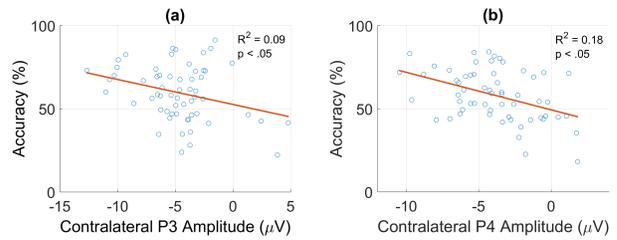


Figure 13: Scatter plots of accuracy (y-axis) and the contralateral VEP amplitude in microvolts (x-axis) in (a) channel P3 for the right trajectories, (b) channel P4 for the left trajectories. A line of best fit illustrates the correlation between the variables.

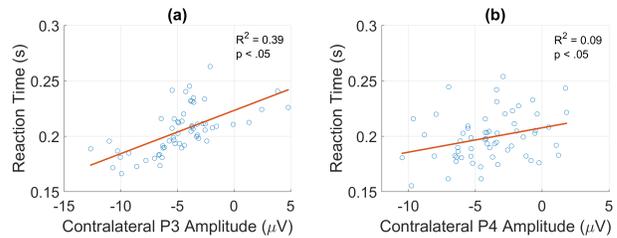


Figure 14: Scatter plots of controller reaction time in seconds (y-axis) and the contralateral VEP amplitude in microvolts (x-axis) in (a) channel P3 for the right trajectories, (b) channel P4 for the left trajectories. A line of best fit illustrates the correlation between the variables.

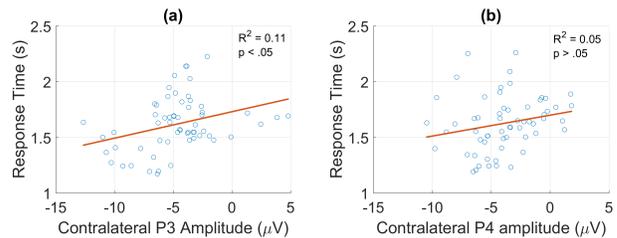


Figure 15: Scatter plots of response time in seconds (y-axis) and the contralateral VEP amplitude in microvolts (x-axis) in (a) channel P3 for the right trajectories, (b) channel P4 for the left trajectories. A line of best fit illustrates the correlation between the variables.

brain dynamics accompanying the acquisition of a moving target. First, we showed that MoBI is feasible for recording and analyzing both kinematic and EEG information during a simulated dynamic target acquisition task when conducted in fully immersive virtual reality. Second, VEPs observed in the EEG recordings after the target launch revealed that visual processing of the target occurred before the onset of eye, hand, and head movements. The mean amplitudes of the VEPs decreased over days, implying that changes in the brain processes might occur through training. Such changes in visual sensory processing have been observed with learning in other domains, including perceptual learning [12], visual search [1, 8], and reward learning [25]. Based on these, and other studies, it has been proposed that learning is accompanied by reorganizations at multiple stages of the neural hierarchy with dynamically interacting reorganizations at each stage. Moreover, the amplitudes of the contralateral VEP were also strongly correlated with accuracy and reaction times, which suggests that performance increased and reaction time decreased as the amplitude became more negative.

The overall aim of this study was to determine the changes in brain activity and body movements that accompany improvements

in performance during a dynamic task in a complex 3D environment. While the focus of this paper is on VEPs, additional brain processes might also provide valuable insight into the biological markers of visual-motor learning. For example, previous research on static marksmanship showed that the pre-shot routine to aim at a fixed target was characterized by an increase in EEG spectral power for expert marksmen when compared to novices, indicating that expert marksmen may have reduced cortical activation during the time period before the shot is taken [7, 13, 14]. Another brain response that may be of interest is the error-related negativity (ERN), which is known to occur in EEG recordings after a participant recognizes an error during a task. It has been shown that larger ERNs are elicited by unexpected negative outcomes than by expected negative outcomes, and could be associated with better negative reinforcement learning as participants learn from their mistakes and modify their behavior to improve performance [2, 22, 29]. Future work will include the exploration of EEG data before the target is launched and after the shot is taken to evaluate the preparatory brain processes and reinforcement learning mechanisms of ERN generation, respectively. Furthermore, future work will incorporate ecologically valid measures of learning to test expert marksmen with the eventual goal of closing the gap between the simulated task and real-world shooting in order to derive a closed-loop feedback approach that can alert individuals in real-time when shooting might be suboptimal.

## 5 CONCLUSION

Precise dynamic movements are critical for human performance, yet they are difficult to quantify and study, particularly at a neural level. The results presented in this study highlight the ability to utilize immersive VR to link kinematic measurements of eye, hand, and head movements with EEG during natural interactions with a dynamic system. The full-body orienting task, a simulation of trap shooting, required participants to actively interact with their environment using fast, precise movements. A gradual decrease in reaction and shot response times, along with decreases in the VEP amplitudes, accompanied a steady improvement in performance over the course of three days. Moreover, correlations between VEP amplitudes and shooting performance suggest that more robust visual processing may lead to enhanced shooting performance. Taken as a whole, this protocol demonstrates the ability to quantify the neurophysiological substrates of learning and superior performance, while also providing an empirical platform for the continued development of mobile brain-body imaging for applied uses.

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