Electrical Muscle Stimulation-Based Approach for Enhancing Hand-eye Coordination Training

Shuo Zhou
Kyoto Sangyo University
Kyoto, Japan
zhoushuo3@acm.org

Norihisa Segawa
Kyoto Sangyo University
Kyoto, Japan
sega@acm.org

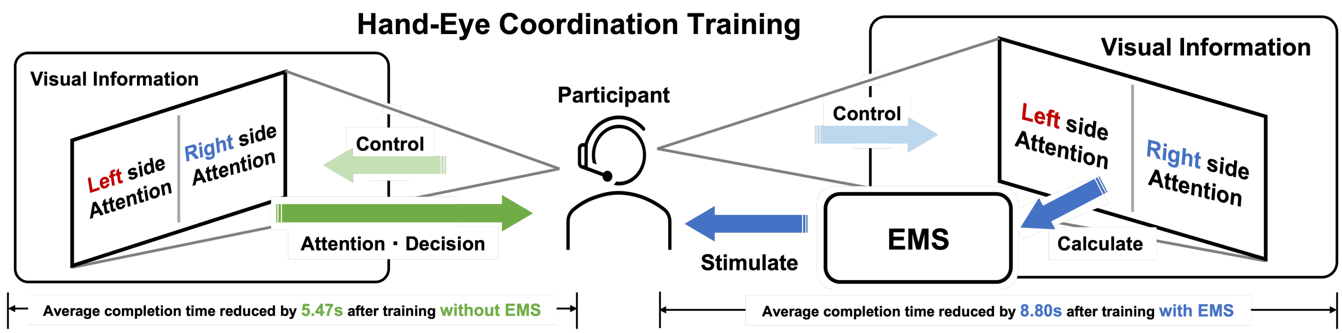

Figure 1: To facilitate hand coordination training, this study developed a customized training system based on EMS. Participants can switch their attention with the help of EMS to improve the efficiency of hand-eye coordination training.

ABSTRACT

Hand-eye coordination refers to the harmonization between visual information and hand movements. In this coordination, the information perceived by the eyes is used to guide the movements of the hands. When faced with an unfamiliar activity, it is challenging to develop coordination between the hands in a short period. This study proposes a method for hand coordination training using Electrical Muscle Stimulation (EMS). By employing EMS, it is possible to enhance attention distribution during bilateral hand movements and improve hand-eye coordination, potentially enabling individuals to train hand coordination skills in a shorter period. Ten participants performed a series of experiments with and without EMS. The results showed that the use of EMS rapidly improved participants' hand-eye coordination skills during a customized training program.

CCS CONCEPTS

• **Human-centered computing** → **Usability testing**; **User studies**.

KEYWORDS

Hand-eye Coordination, Attention, Electrical muscle stimulation, Training, Motion Perception, Sensorimotor, Hand Control, EMS

CHI EA '24, May 11–16, 2024, Honolulu, HI, USA

ACM ISBN 979-8-4007-0331-7/24/05
https://doi.org/10.1145/3613905.3650939

ACM Reference Format:
Shuo Zhou and Norihisa Segawa. 2024. Electrical Muscle Stimulation-Based Approach for Enhancing Hand-eye Coordination Training. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '24), May 11–16, 2024, Honolulu, HI, USA.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3613905.3650939

1 INTRODUCTION

Precise coordination between the hands is crucial for complex tasks such as playing musical instruments, playing games, or performing surgery, where the hands operate at different frequencies, amplitudes, directions, and forces [22]. This specific coordination, which relies on hand-eye coordination, integrates visual information to guide hand movements [11]. When tasks require both hands, attention isn't fixed on one hand but is distributed according to the demands of the task. Appropriate allocation of attention improves hand-eye coordination and supports complex bilateral movements [5]. As skills develop, individuals may rely less on vision and more on tactile feedback for precision tasks. However, this level of coordination typically depends on extensive, repetitive training. When people are faced with an unfamiliar sport, it is difficult to develop coordination between the hands in a short period. Hand-eye coordination plays a very important role in the early stages of training for these hand-coordination exercises. Through hand-eye coordination training, people can visually acquire information that can be used to modify and guide the coordination of the hands, thus mastering unskilled movements in a continuous process of modification [24]. Previously, hand-eye coordination training has been performed by touching a physical object or a 2D screen [8]. Wang et al. proposed a learnable action space, the Hand-Eye Action Network (HAN), which learns coordinated hand-eye movements from human remote control demonstrations [31]. There have also been several virtual reality-based studies of hand-eye coordination [18][23]. Batmaz et al. compared hand-eye coordination training in three approaches: augmented reality, virtual reality, and traditional physical touch [4]. However, there are no studies on hand-eye coordination training using electrical muscle stimulation.

Electrical muscle stimulation (EMS) is a technique that uses tiny electrical currents to stimulate and control muscle activity. Previous research suggests the potential of EMS to train human motor perception [33]. The mechanism of hand-eye coordination closely mirrors that of motion perception, with both relying fundamentally on sensory input to control the body. Drawing on this parallel, this study presents a method of training hand-eye coordination using EMS (Fig. 1). By using EMS, it's possible to improve the distribution of attention during hand activities and improve hand-eye coordination. This approach may allow for more efficient training of hand coordination skills in a shorter period.

2 RELATED WORK

Our approach is primarily based on the human learning process of hand-eye coordination. To explain our training method, we examine several key aspects of the principles of hand-eye coordination, the learning process, and the use of electrical muscle stimulation.

2.1 Hand-Eye Coordination

Hand-eye coordination is commonly defined as the control of hand movements using visual feedback. During movement, our eyes direct our attention to stimuli and help the brain to understand the spatial position of the body. By allocating attention appropriately, we can support bilateral hand movements with visual information received through the eyes, thereby distributing tasks efficiently. Research by Michel et al. shows that the human central nervous system can plan tasks involving hand movements based on visual feedback [6]. Roland and colleagues investigated the coordination between vision and touch in object manipulation by analyzing fingertip movements [11]. These studies suggest that proper allocation of attention is crucial for mastering hand-eye coordination in activities that require its use.

2.2 The learning process of hand-eye coordination

Training is the act of accumulating experience through practice to achieve a certain goal. Lachman [16] defined this process as one in which learning is a relatively stable modification of the stimulus-response relationship as a result of functional environmental interactions through the senses. Krakauer and Mazzoni [14] showed that human senses can be trained and that through learning, we can reduce the false predictions of our senses. The human primary motor cortex (M1) displays mirror activity in response to movement observation, is capable of forming motor memories, and is involved in motor learning [27]. We can train the movement by repeating the same process, and when the training is over, an after-effect is created, which retains the effect of our training [32].

Human learning of motor skills relies on the motion perception system. When attempting to learn new movements, we first gather information through senses such as vision and hearing to make judgments and decisions. We then adjust our limb movements and control intensity based on predictions made from this information [32]. Based on this motion perception system, when faced with unfamiliar motor tasks, we can gradually master them through repeated practice and feedback. The principles of hand-eye coordination are similar to those of motor perception, as both are controlled by sensory information. Research by Sailer and others shows that learning hand-eye coordination also involves using visual information, correcting decisions through feedback from hand movements, and improving control of hand activities through repeated practice [24].

2.3 Electrical muscle stimulation (EMS)

EMS is a method of driving a limb by stimulating muscle contractions using tiny electrical currents. Compared to the traditional actuation of robot arms [25] or exoskeletons [29], EMS devices tend to be more convenient to wear and smaller and easier to use. At first, EMS was commonly used as a treatment for the rehabilitation of patients with motor disabilities or to support patients with physical deficits [10]. With the expansion of EMS-related research, recent studies focused on the use of EMS for interaction and expansion of body functions. Takahashi et al. [28] achieved more flexible finger movements through EMS by configuring electrodes on the hand. Nishida et al. [20] demonstrated that EMS could enable people to have faster reaction times by driving muscles. Kasahara et al. [13] used EMS to drive the hand and developed an EMS-based system based to improve the reaction speed. When the EMS device was removed after training, the effect of the training was maintained. Therefore, EMS can be used as a training tool for improving physical performance.

Zhou and Segawa explore the potential of using EMS in first-person shooter (FPS) game training, demonstrating the prospects of EMS in the field of motor perception training [33]. As mentioned in Section 2.2, we propose a new hypothesis given the similarity between motor perception and hand-eye coordination in learning mechanisms: EMS has the potential to play an important role in hand-eye coordination training.

3 SYSTEM COMPOSITION

To facilitate hand coordination training, this study developed a customized training system based on EMS. The system consists of three main components: the EMS device, the eye-tracking device, and the customized training program (Fig. 2). During training, the participant's visual field is divided into left and right areas. Each area is equipped with an input device that is independently controlled by the left and right hands. Once training begins, the participant must shift their attention between the left and right areas as needed and make correct inputs with both hands. During this process, the electrical stimulation device automatically calculates the optimal timing of stimulation and delivers appropriate stimulation to the participant's left and right hands to help them switch focus and make the correct input. The eye-tracking device records the participant's pupil movements during this process to analyze the distribution of attention. Through this system, participants can receive targeted training using EMS to improve attention allocation and hand-eye coordination skills.

Figure 2: System composition. (a) Arduino. (b) PETTOYA 554 relays. (c) Power supply (EV-804) and electrode configuration. (d) Eye tracking. (e) Typing game.

3.1 Configuration of EMS

Our EMS device consists of a set of power supplies, switch controls and electrodes. By wearing the EMS device, participants can use the EMS to receive cues during training to assist in the proper allocation of attention.

Power supply: We chose the EV-804 [17] from iStim as the power supply for our EMS device. The EV-804 is a two-channel muscle stimulation massager that provides a stable power output (max. 3.7V). As our system only requires a mild electrical stimulation of the participant's hand muscles to change attention, we used this existing massage device to minimize the strain of the EMS on the muscles, ensuring the effectiveness of the EMS device and the safety of the participant.

Switch: We used Arduino UNO [3] (Fig. 2(a))and PETTOYA 554 relays [30] (Fig. 2(b))as controllers to control the switch of the EMS device through a program written in Arduino, which allowed us to activate it when needed and output the required current as a cue to stimulate the participants' hand muscles. When the switch is turned on, the EMS device outputs a 50ms-100ms pulse to stimulate the hand muscles and then turns off automatically. Taking into account individual differences in participants' age and bodily functions, we adjusted the pulse length according to the actual situation to ensure that the point stimulation could effectively prompt participants to switch their attention without causing discomfort.

Electrodes: We refer to the study [33] where electrodes were placed on the finger deep flexors of the participant's arm, which allowed the device to effectively stimulate the participant's hand muscles when the EMS device was activated (Fig. 2(c)). With this configuration, the EMS device can ensure that the participant effectively switches attentional areas without interfering with the normal activity of the hand muscles.

3.2 Eye tracking

This study uses the webcam that comes with the computer (Macbook Pro M1) to track the user's gaze during the game. Using a program written in Python and OpenCV, the system can track the user's pupil movement in real time and use it to analyze the user's attentional allocation (Fig. 2(d)). When the participant's attention is focused on the center of the screen, the system displays "Center". When the participant's attention shifts to the left and right (left and right hand), the system displays "Left" and "Right" respectively. The system is programmed to calculate the time spent by the participant in shifting attention.

3.3 Customized training

To train hand-eye coordination, this study used a customized training program. During training, participants are required to allocate their attention between two visual fields on cue and to make correct inputs on controllers with their left and right hands to complete the training tasks successfully. To facilitate targeted training in attentional allocation, a custom training program was developed using Python. The training system consists of a monitor and two keyboards. The monitor is placed in the center of the participant's view, while the keyboards are placed in the left and right visual fields, respectively. When the training starts, the participant must press the letters on the keyboard in the correct visual field based on the letters and colors displayed on the monitor (Fig. 2(e)). If the letter is red, the participant must press on the left keyboard with the left hand; if the letter is blue, the participant must press on the right keyboard with the right hand. During training, EMS provides stimulation cues to the left and right hands based on the corresponding letters, thus encouraging the participant to shift focus between the visual fields. At the same time, an eye-tracking device records the participant's attention in real-time, which allows analysis of the training results.

4 EXPERIMENTATION OVERVIEW

As described in Section 2.1, the allocation of attention plays a crucial role in activities involving hand-eye coordination. In particular, when attempting to master untrained activities, the appropriate allocation of attention is often the key to ensuring proficient hand-eye coordination. In this study, we will use the training system described in Section 3.3 to support the hand-eye coordination training process. Using EMS devices worn on the hands of participants, we provide cues through electrical stimulation to optimize the allocation of attention during training. To validate the effectiveness and feasibility of the proposed training method, a series of experiments will be conducted.

Initially, when participants train while wearing EMS devices, the method of allocating attention will change from self-evaluation (based on the brain's analysis of visual information) to external cues. Theoretically, with EMS, this feedback is almost reflexive due to the direct muscular stimulation. A study [13] has shown that participants achieve faster reaction times when using EMS. However, given that reaction speed and attentional allocation are not entirely the same in our study, it is necessary to test whether participants' attentional allocation improves by using EMS before experimenting with the effectiveness of the training method.

Subsequently, a controlled experiment will be conducted to confirm the effectiveness of our proposed training method. Participants will perform hand-eye coordination training using the customized training program. In the experiment, participants will be divided into two groups: those training without EMS and those training with EMS. We will compare and evaluate the participants' pre- and post-training scores and analyze both groups to confirm that the EMS-based training approach proposed in this study improves the efficiency of hand-eye coordination training in the customized training program.

Permission to conduct the experiment was obtained from the local research ethics committee. All participants were fully informed of the experimental procedure and gave their full consent.

5 EXPERIMENT 1: IMPROVEMENTS IN ATTENTION ALLOCATION

In this study, participants used EMS to replace their own attentional allocation during training sessions. To ensure that the use of EMS did not adversely affect their attention allocation due to unfamiliarity with the system, it was necessary to conduct an experiment. In this experiment, we verified that the participants' attentional allocation was not negatively affected by the use of EMS. We also assessed the improvement in participants' attentional allocation when using EMS.

5.1 Experimental Approach

Considering the operation of hand-eye coordination, we conducted experiments using the training system built in Section 3.3. In the experiment, participants had to make decisions based on the text displayed on the screen and allocate their attention to the correct area. At the beginning of each test, participants' attention was first directed to the central area (screen). Then, when red letters appeared on the screen, participants had to shift their attention to the left visual field and enter the correct letters using the keyboard on the left. When blue letters appeared, they had to shift their attention to the right visual field and enter the correct letters using the right side keyboard. During this process, the system automatically analyzed the participants' gaze movements and calculated the time taken for the eyes to move from the central area to the left or right area (attention allocation) after the letters appeared.

Ten participants (19-30 years old, 9 males and 1 female) performed the tests. Each participant first performed 10 tests without the EMS and then another 10 tests with the EMS device.

5.2 Results

Ten participants completed the test with and without the EMS device. We recorded the time taken by the 10 participants to switch attention each time, and calculated the average time taken by the participants for each of the 10 attention-switching tests with and without the EMS device. The following is a comparison of the time taken to switch attention before and after using the EMS device, where a shorter time means a more rapid switch of attention (Fig. 3). It is observed that the speed of attentional switching increased for all 10 participants when using the EMS device.

The Wilcoxon signed-rank test was used to examine the two sets of data without and with the EMS device. The significance level was set at 0.1 % (a two-tailed test). According to the statistical analysis, the Wilcoxon statistic was 0.0 and, the p-value was 0.0020. Test results confirmed that at the 1 % level, participants switched attention significantly faster with the EMS device than without it. Therefore, the participants' attentional switching was not negatively affected and was even significantly improved when using the EMS device.

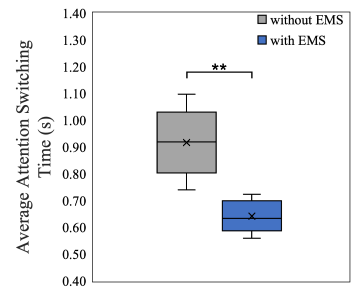

Figure 3: Attention switching test results. The average time of the participants without EMS was 0.92 s, and the average time with EMS was reduced to 0.64 s.

6 EXPERIMENT 2: HAND-EYE COORDINATION TRAINING

Our aim was to improve the efficiency of hand-eye coordination training by using EMS in a customized training setup and to explore the potential of using EMS in hand-eye coordination training. Therefore, we needed to conduct a controlled experiment to evaluate whether the EMS training method could improve participants' hand-eye coordination in a short time.

6.1 Experimental Approach

Similar to Experiment 1, this experiment was conducted using the training system constructed in Section 3.3. During the experiment, participants were required to complete the test as quickly as possible with 100 % accuracy. Participants had to enter the correct letters in the corresponding visual field areas based on the different colors of the displayed letters. Participants were required to make a total of 30 entries in each test. At the end of the test, the system calculated the participant's accuracy rate and the time taken to complete the test. If participants did not complete the test with 100 % accuracy (by entering the wrong letters or using the wrong keyboard), they were asked to repeat the test.

Ten participants (19-30 years old, 9 males and 1 female) performed the experiment. Each participant was first tested three times before the start of training. The 10 participants were then divided into two groups (5 in each group) and trained with and without the EMS for 10 training sessions (repeated runs). At the end of the training, each participant was tested again three times. The accuracy and time taken for each test was recorded for all participants. It is important to note that the five participants who trained with EMS only wore the EMS device during the 10 training sessions, and the rest of the procedure was exactly the same as for the five participants who did not use EMS. None of the participants had ever received similar hand-eye coordination training before the experiment.

6.2 Evaluation of effectiveness

Ten participants were trained with and without EMS. Before comparing the results of the two groups of participants, we needed to compare the time taken to pass the test before and after training separately for both groups to assess whether both training methods were effective. We recorded the time taken by each participant to pass the test before and after training, and calculated the average time taken before and after training for both groups of participants separately. The following is a comparison between the two groups of participants before and after training (Fig. 4). It can be seen that both groups showed an increase in the speed of passing the test after training.

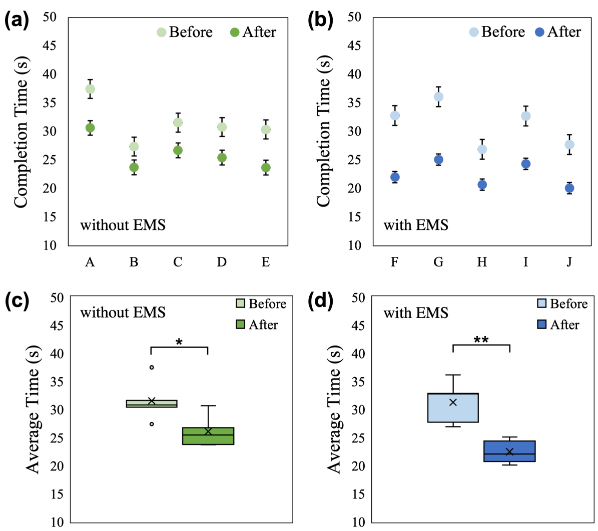

Figure 4: Comparison of completion times before and after training with and without EMS. (a) Comparison of completion times of five participants before and after training with EMS. (b) Comparison of completion times of five participants before and after training without EMS. (c) Average time change of participants trained without EMS. (d) Average time change of participants trained with EMS.

The Mann-Whitney u-test was used to examine the pre and post training data for the two groups of participants trained without and with EMS. We first analyzed the results of the group that did not train with EMS. According to the statistical analysis, the u-value was 23.0 and, the p-value was 0.0317. Subsequently, we also analyzed the results of the group that trained with EMS. According to the statistical analysis, the u-value was 25.0 and, the p-value was 0.0079. The results of the test confirmed that there was a significant difference between the pre- and post-training performance of the participants who trained without the EMS device at the 5 % level. And at the 1 % level, there was also a significant difference between the pre- and post-training performance of the participants who trained with the EMS device. Therefore, both participants with and without the EMS device had improved hand-eye coordination skills after training.

6.3 Comparison of the two methods

To verify that the training method with EMS proposed in this study is more efficient than the method without EMS (repetition only), we compared the change in average completion time after training between the two groups of participants. The average post-training time was 5.47 seconds shorter for the participants without EMS and 8.80 seconds shorter for the participants with EMS (Fig. 5).

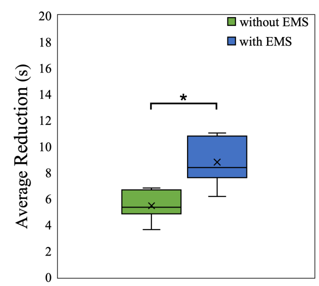

Figure 5: Comparison of training results between two groups of participants with and without EMS.

The mann-whitney u test was used to examine the two sets of data without and with the EMS device. According to the statistical analysis, the u-value was 2.0 and, the p-value was 0.0317. The test results confirmed that in a 10-participant experiment, the improvement in completion time after training was more significant for participants with the EMS device than for those without (at the 5 % level). Therefore, training with the EMS may have more potential for training efficiency than training without the EMS in customized hand-eye coordination training.

7 DISCUSSION

This study proposed a method of improving attention allocation using EMS to assist participants in hand-eye coordination training. Our study showed that the use of EMS in a customized training program can rapidly improve participants' hand-eye coordination skills. We believe that this method can be applied to some sports or eSports. Hand-eye coordination plays an important role in sports and eSports training [15][21][19]. Previous studies have shown that cumulative training loads over time can lead to an increased probability of injury and disease [2][12]. Improvements in hand-eye coordination may help to increase training efficiency and reduce training time in these sports.

Nevertheless, it is important to acknowledge certain limitations of our study: (1) Data were collected from only ten participants and we did not conduct a broader experiment. (2) The experiment was limited to customized training and did not include the reality of some sports or jobs. (3) The duration of the experiment was short and the long-term sustainability of the training effect was not assessed. (4) Attention allocation and time were just some of the parameters used to observe participants' hand-eye coordination.

8 CONCLUSION AND FUTURE WORK

In this study, we proposed a method of using EMS to help with hand-eye coordination training. Through a series of experiments, we confirmed that the use of EMS can help participants improve their results in a customized hand-eye coordination training program. In conclusion, this study represents an ongoing effort, and the effectiveness and generalizability of using EMS for hand-eye coordination training in reality remain topics for future investigation. However, our study introduces a novel approach to hand-eye coordination training using EMS. When future studies are completed, we believe that this method could be applied to sports and eSports. This study could serve as a reference for such investigations.

As for future work, we will conduct follow-up experiments to collect data from more participants to further validate the effectiveness and generalizability of hand-eye coordination training using EMS. In addition, we will further validate the effectiveness of the method in some real-life situations. Whether the training effect can be retained in the long term will also be investigated in the future long-term process.

ACKNOWLEDGMENTS

This work was supported by JSPS KAKENHI Grant Numbers 20K11780.

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