ARTICLE
Developing a New Experimental System for an Undergraduate Laboratory Exercise to Teach Theories of Visuomotor Learning

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Humans have a flexible motor ability to adapt their movements to changes in the internal/external environment. For example, using arm-reaching tasks, a number of studies experimentally showed that participants adapt to a novel visuomotor environment. These results helped develop computational models of motor learning implemented in the central nervous system. Despite the importance of such experimental paradigms for exploring the mechanisms of motor learning, because of the cost and preparation time, most students are unable to participate in such experiments.

Therefore, in the current study, to help students better understand motor learning theories, we developed a simple finger-reaching experimental system using commonly used laptop PC components with an open-source programming language (Processing Motor Learning Toolkit: PMLT). We found that compared to a commercially available robotic arm-reaching device, our PMLT accomplished similar learning goals (difference in the error reduction between the devices, *P* = 0.10). In addition, consistent with previous reports from visuomotor learning studies, the participants showed after-effects indicating an adaptation of the motor learning system. The results suggest that PMLT can serve as a new experimental system for an undergraduate laboratory exercise of motor learning theories with minimal time and cost for instructors.

Key words: reaching movement, visuomotor rotation, error-based learning, implicit learning mechanism, Processing

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INTRODUCTION

Without acquiring novel motor skills through experience (i.e., motor learning), living in ever-changing environments would be impossible. Conventionally, motor learning has been considered observable only through behavior and that we may only infer the internal process (Schmidt and Lee, 1998). Nevertheless, it is important to determine how learning can impact underlying mechanisms of motor behavior.

To uncover potential mechanisms, approaches based on computational neuroscience have been developed. For example, visually guided arm-reaching tasks have recently emerged as useful tools (Shadmehr and Wise, 2005). When investigating motor adaptation using reaching tasks, experimenters often artificially perturb the participants' movement and observe how performance gradually returns to the basal level. A typically used experimental paradigm to induce systematic errors during movement is visuomotor rotation that is designed to dissociate the existing mapping from visual information to motor commands in the brain (Krakauer et al., 1999; Krakauer et al., 2000; Mazzoni and Krakauer, 2006; Kasuga and Nozaki, 2011).

Experiments of visuomotor rotation require participants to move the handle of a two-link arm device hidden by an opaque shield in order to displace a cursor displayed on a computer monitor to a nearby target (Figure 1*A*). During this task, the spatial relationship between the hand and the cursor is modified, so that the cursor is rotated by a given angle around the starting position (Figure 1*B*). During training, participants compensate for the perturbation in a trial-by-trial error-based manner. In subsequent trials, after removing the perturbation, participants overcompensate even though they are aware of the removed rotation; this is known as an after-effect (Kagerer et al., 1997).
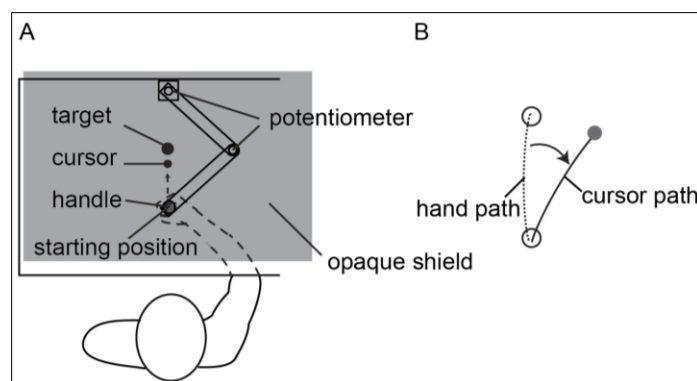

Figure 1. An example of a visuomotor rotation paradigm in computational neuroscience. *A:* Experimental setup. Participants sit in front of the horizontal plane to which the experimental device is connected. The device has a two-link bar to measure the handle position. The angular displacement of the bar is measured by potentiometers. The handle position is displayed on a computer monitor projected onto an opaque shield. *B:* Visuomotor rotation paradigm. If a participant moves their hand toward the target (dotted line), the cursor is displayed as being rotated by a given angle (e.g., 30º) around the starting position.

Because visuomotor rotation artificially intervenes on motor systems, theoretical lectures alone are insufficient to grasp such concepts. In addition, actually performing the experimental task themselves will allow for hands-on experience in implicit adaptation mechanisms. Unfortunately, the devices and software for arm-reaching

experiments are expensive, with long setup times and require a certain level of programming proficiency (e.g., Labview, Matlab, or C++). Therefore, in this study, we developed a simple finger-reaching experiment system composed of commonly used PC and open source programming language (Processing Motor Learning Toolkit: PMLT). The reason why we selected finger-reaching movements is that the movements do not take much space and the device for the movements is easy to transport. To perform arm-reaching movements as used in previous motor learning studies, we need relatively larger space and bigger devices. However, such solution for environmental constraints results in differences in the movement type (finger-reaching vs arm-reaching) and range of movement (5 cm vs 15cm) between other robotic systems for professional research use. In addition, there is also a difference in system accuracy. Therefore, it is not trivial that the finger-reaching motor learning task with laptop computer like PMLT can induce similar implicit adaptation to visuomotor rotation as traditionally used robotic devices. The best and the only way to evaluate the effectiveness of PMLT is to compare it with robotic arm-reaching device. Therefore, to ensure that our system is applicable for an undergraduate laboratory exercise, we evaluated whether PMLT can lead to a learning effect of visuomotor rotation equivalent to a robotic arm-reaching device. In addition, we verified whether the system could also induce similar implicit adaptation reported in previous studies using arm-reaching devices.

MATERIALS AND METHODS

Participants
This study was conducted according to the Declaration of Helsinki. The experimental procedures were approved by the ethical committees of the Faculty of Science and Technology, Keio University. Written informed consent was obtained from all participants prior to the experiments. Eight neurologically normal undergraduate students (three women and five men, aged 22–23 years) participated in the experiments.   All participants were right-handed [Laterality Quotient (Oldfield, 1971) = 92.7 ± 2.5; data values are expressed as means ± standard error (SE)], where on a scale of –100 to 100, –100 is completely left-handed and +100 is completely right-handed, as assessed by the Edinburgh Handedness Inventory. All participants were naïve to the purpose of the experiments. Individuals participated in two experiments (i.e., PMLT and robotic arm device) over two days. The order of the experiments was randomized for each participant.   The interval between experiments was four weeks.

Apparatus
1) PMLT
Hardware (Figure 2)
· Laptop computer
· USB Touchpad (SANWA SUPPLY, Japan)
· Blindfold plastic box
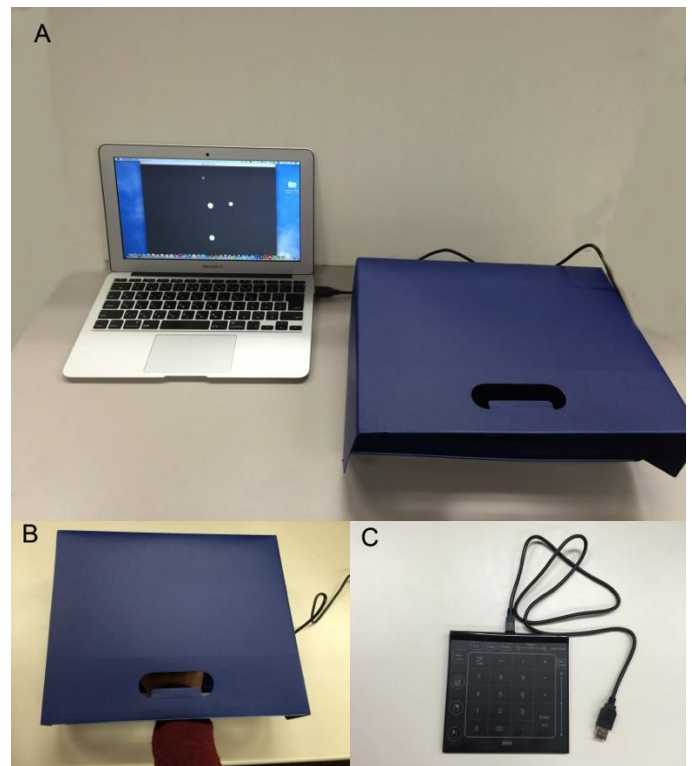Equipment cost was about $50 in total (excluding the PC).

Figure 2. Apparatus. *A:* Overall view.   *B:* Hand and blindfold plastic box. The hole on the upper surface was occluded during the experiment. *C:* USB touchpad inside the plastic box.

Software
The experimental task was designed using Processing 2.1. Processing is an open source programming language, development environment, and online community (http://processing.org/).   It can be downloaded for free, working on GNU/Linux, Mac OS X, and Windows. Processing has interactive programs with 2D, 3D graphics, or PDF output and OpenGL integration for accelerated 3D graphics. Processing provides over 100 libraries to extend the core software that was designed to facilitate the creation of sophisticated visual structures. These features are advantageous to undergraduate education in the following aspects: i) the language is free of charge, ii) it is available via the internet, iii) there are many instruction materials for undergraduates, and vi) the language is a runtime system, thus users do not need to install the programming environment (i.e., easily used on public PCs).

The experimental programs for the current laboratory exercise are comprised of two sketches for running visuomotor rotation experiments and of one sketch for behavioral data analyses. The programs and Processing execution files are available in http://www.brain.bio.keio.ac.jp/educationmaterials/.

VMrotation.pde and VMrotation_base.pde (Figure 3) are sketches for building a task display, manipulating a relationship between hand motion and cursor motion, recording fingertip positions and trial numbers, and saving the recorded data.

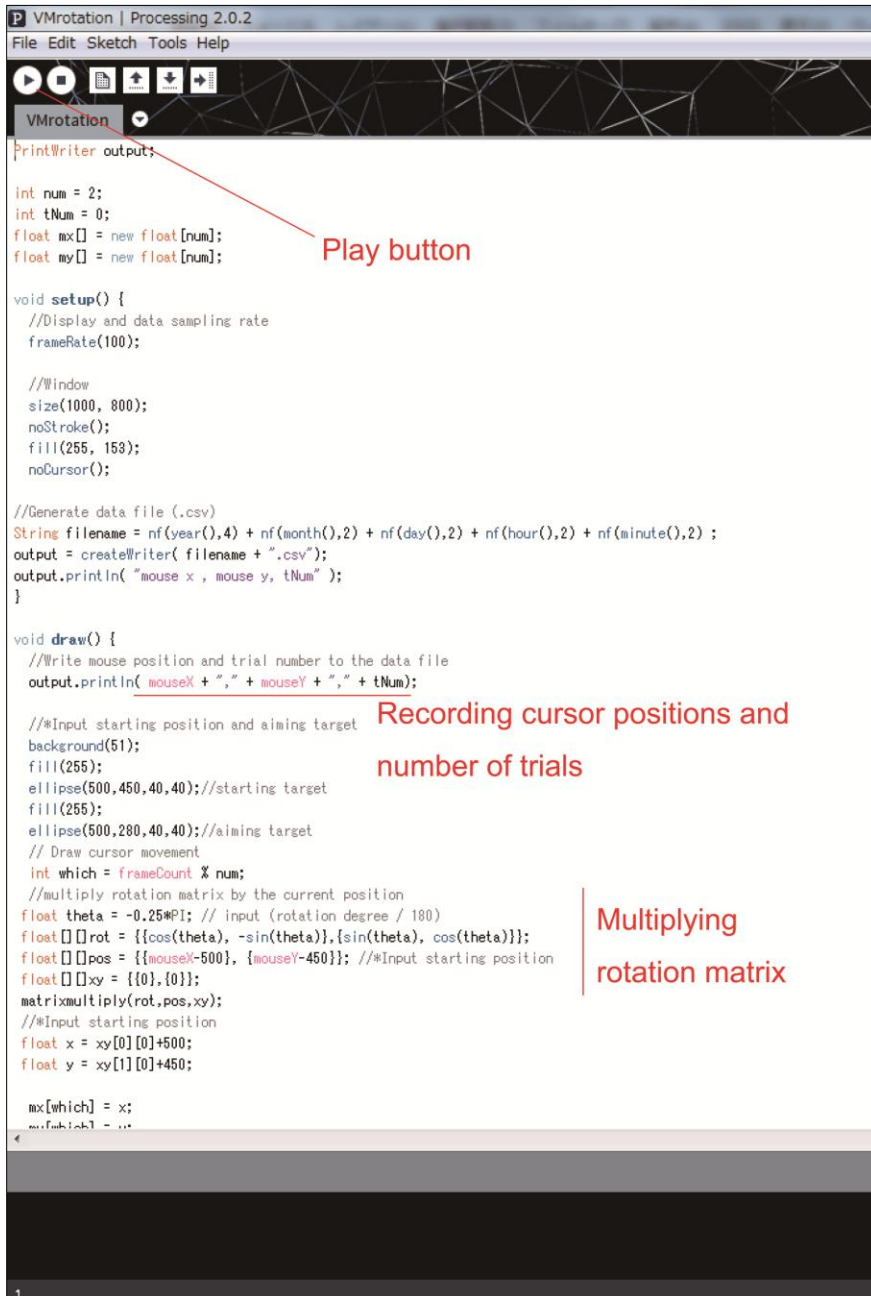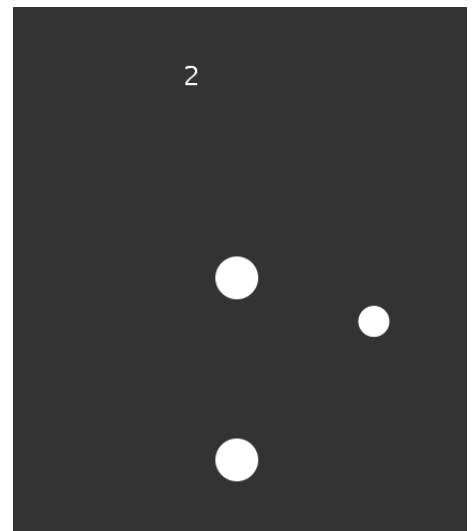When users run the sketches on Processing, a black

Figure 3. A sample image of the sketch. The experimental program starts when the upper-left "Play button" is clicked.

Figure 4. A sample image of the task window. Bottom-center circle, starting position; upper-center circle, target; left small circle, cursor; number, trial count.

rectangular window (1000 × 800 pixels) appears on the screen. There is a white circular starting position (40-pixel diameter), a white circular target (40 pixel diameter), and a white circular cursor (30 pixel diameter) on the workspace (Figure 4). Participants manipulate the cursor by moving their fingers on the touchpad and the blindfold plastic box occludes the participants' hand.

By editing the rotation matrix in the VMrotation.pde, we can apply an arbitrary amount of rotation in radian to the cursor on the computer screen. VMrotation_base.pde is a program for the baseline measurement of performances or trial practices that do not include visuomotor rotation.

Fingertip positions are sampled and recorded at 100 Hz. Pressing the "q" key while running VMrotation.pde or VMrotation_base.pde saves time-series data of the

positions in x- and y-coordinates during running of the program, and the number of trials in a CSV format.

CalcErrors_VMrot.pde and CalcErrors_base.pde are the sketches for quantifying adaptation of the motor learning system, visualizing errors, and saving the data and the figure. To use behavioral data obtained by VMrotation.pde and VMrotation_base.pde for data analysis, users must first move a CSV file of the data to the folder where the "CalcErrors_base/VMrot" file is located. If the read-out file name is appropriately specified in the program, a cursor error of each trial is calculated and plotted on a figure window (1000×500 pixels, Figure 5). By pressing the space key, the figure is saved in a PNG format. Pressing the "q" key saves the error data by trial in a CSV format.
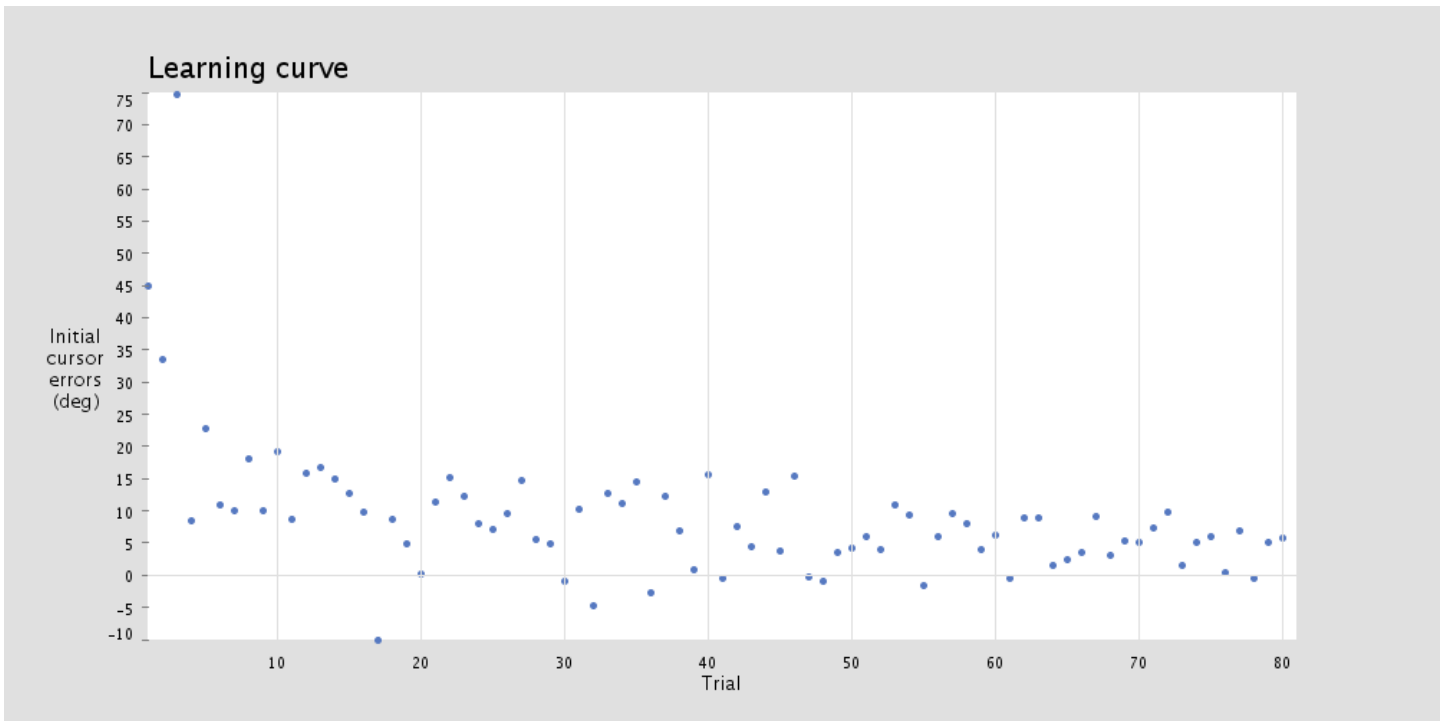
Figure 5. Example image of error-plots generated by "CalcErrors_VMrot." Blue dots indicate initial cursor errors across the trials in a representative participant.

2) Robotic Arm Device

The experiments were performed in a darkened room. The participants sat on a straight-backed chair while grasping the handle of a robotic manipulandum (Phantom Premium 1.5 HF, Geomagic, Morrisville, NC, USA; Figure 6) with their right hand. A virtual spring that was simulated by the Phantom device (1.0 N/mm) generated a virtual horizontal plane on which the handle could be moved. A projector was used to display the position of the handle (indicated by a 6-mm-diameter white circle cursor) on a horizontal screen (29 cm × 51 cm) that was placed approximately 20 cm above the virtual plane and about 10 cm below shoulder level. Thus, the screen board prevented the participants from directly seeing their arm and the handle. The participants moved the cursor by performing reaching movements from a starting position (10 mm diameter) toward a target position (10 mm diameter) displayed on the screen. The starting position was located approximately 25 cm in front of the body in the midsagittal plane, with the target located 10 cm away from the starting position. The position of the handle was converted by an analog-to-digital converter (sampling frequency, 500 Hz) and stored for offline analysis.

Procedure

The procedures were almost identical in experiments with PMLT and robotic arm device. The participants were instructed to move the cursor from the starting position to the target position by performing straight, fast, and single stroke movements. In PMLT, each trial began only after participants placed the cursor at the starting position.

Figure 6. Robotic arm device (Phantom Premium 1.5 HF, Geomagic, Morrisville, NC, USA).

In robotic arm device, the handle of the robotic manipulandum automatically moved the participants' hand to the starting position at the end of each trial.

The task consisted of two blocks: (1) the learning block to adapt to the visuomotor rotation, and (2) the washout block to investigate the after-effect of the adaptation. The learning block consisted of 80 trials and the washout block consisted of 20 trials. Before running the experiment, the participants familiarized themselves with the system by performing about 25 trials using VMrotation_base.pde. The last 10 trials of the practice were used to investigate each participant's baseline performance; this value was

subtracted from the data in other blocks for subsequent analyses. The 45° of visuomotor rotation was introduced without notice at the beginning of the learning block and removed at the beginning of the washout block.

Data analysis
Movement onset was defined as the time when the participants kept moving towards the target for 30 ms. Movement error was defined as the angle from a line connecting the starting position and the target to a line connecting the starting position and the cursor position 100 ms after movement onset. Counterclockwise (CCW) and clockwise (CW) directions were defined as positive and negative values of the direction, respectively.

Quantification of adaptation
To quantify the degree of adaptation, we compared the average movement error in the initial phase (trials 1–10) to the average movement error in the final phase (trials 71–80) of the learning block for both conditions. In addition, to investigate whether the implicit motor learning process adapted to the visuomotor rotation, we quantified the after-effect (i.e., errors in the opposite direction to the rotation observed after removing the rotation) by comparing the first trial of the washout block between the experiments, and the average movement error from trials 2–11 of the washout block between the experiments.

Survey
Following the experiments, an anonymous 7-item survey was distributed. The survey queried two basic domains: platform usability and perceptions regarding the role of the PMLT in motor learning education. The responses were rated using a 5-point Likert scale. Participants rated their agreement with the platform's ease of use, presentation of task and images, and statements regarding the use of PMLT as a method for motor learning education (1-strongly disagree, 5-strongly agree). Contents and procedures of the survey followed a previous study about a tool for undergraduate surgical education and assessment (Yang et al., 2013).

Statistics
Data values are expressed as means ± standard error calculated using data from all participants. A repeated measures two-way ANOVA (phase × experiment) was performed to detect learning effects and their differences between groups. A paired t-test was performed to detect differences in the aftereffect between the experiments.

RESULTS
Learning effects
A sudden increase in errors was observed in the first trial of the learning block in experiments with both systems (Figure 7). During the learning block, in both experiments the errors decreased from the initial (PMLT, $13.2 \pm 2.4°$; robotic arm device, $9.8 \pm 3.1°$) to the final phase (PMLT, $5.2 \pm 1.6°$; robotic arm device, $1.4 \pm 1.1°$). A repeated measures two-way ANOVA showed a significant main effect of block ($F_{1, 28} = 14.5$, $P < 0.01$; Figure 8A). No main

effect was detected between the systems ($F_{1, 28} = 2.83$, $P = 0.10$).

Aftereffects
In the initial phase of the washout block, a large increase in errors in the opposite direction to the rotation was observed in both systems (i.e., after-effects; Figure 7). The amplitude of the aftereffects in the first trial of the washout block was significantly larger for PMLT than robotic arm device (PMLT, $-24.7 \pm 4.0°$; robotic arm device, $-8.0 \pm 2.4°$; $t_7 = -3.1$, $P < 0.05$). There was no difference between the experiments when the average error from trials 2–11 of the washout block was compared (PMLT, $-3.8 \pm 1.1°$; robotic arm device, $-3.0 \pm 0.8°$; $t_7 = -0.62$, $P = 0.56$; Figure 8B).

Usability and Opinions Regarding the Platform
The survey response rate was 100% amongst participants. Participants reported that PMLT interface has good use of ease (median 4.0/5.0), good presentation of task (median 5.0/5.0), and good presentation of images (median 5.0/5.0). They also reported that PMLT enhanced understanding motor learning as an experience (median 3.5/5.0), was useful in understanding concepts of motor learning research (median 4.0/5.0), should supplement theoretical lectures (median 4.5/5.0), and reflected real experiments (median 4.0/5.0).

DISCUSSION
In this study, we sought to develop an experimental system suitable to teach undergraduate students about the human motor learning research through active participation. We therefore developed and tested the applicability of a novel finger-reaching experimental system. The system consisted of a PC, a USB touch pad and paper blindfold board, together with software programmed by free open source language. Together with lecture-based learning, we propose that our experimental system will enhance students' understanding of motor systems.

All participants successfully adapted to the visuomotor rotation both with PMLT and robotic device. That learning after-effects were similar in both experimental paradigms strongly implies an adaptation of the motor learning system. Our results indicate that PMLT can serve as an affordable alternative to robotic arm-reaching devices that are typically expensive and time-intensive, prohibiting their use in instructional laboratories for undergraduates.

Although a significant main effect of experiment was not detected by a repeated measures two-way ANOVA, we found differences in the amplitude of the initial errors between the experiments during the learning block (Figure 8A). We also found a difference between the experiments in errors in the first trial of the washout block. We assume that such differences resulted from the difference of effectors (i.e., finger or arm), or the difference of participants' postures during the trials between the experiments.

Neural correlates of visuomotor adaptation we observed in these experiments have been proposed both in humans and other animals. For example, many studies found that
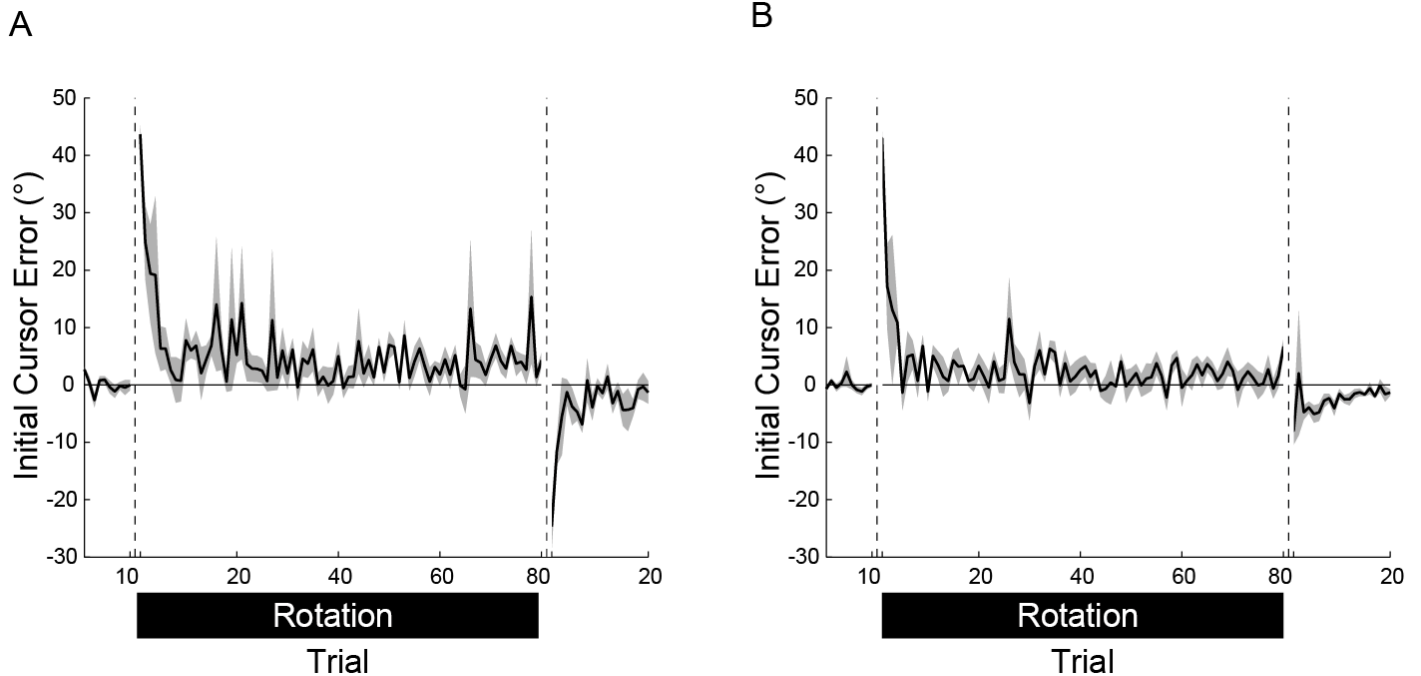
A

B

Figure 7. Changes in the averaged initial cursor errors in all blocks. Shaded colored regions represent the SE. In each panel, the first 10 trials indicate baseline performance, the next 80 trials indicate the learning block, and the last 20 trials indicated the washout block. *A:* Data from PMLT. *B:* Data from robotic arm device.
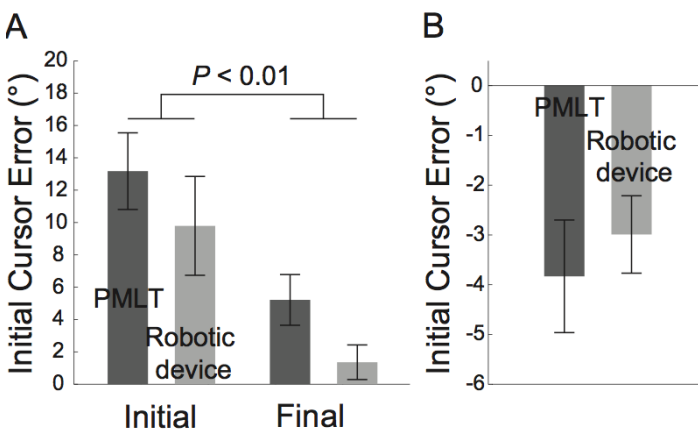
A

B

Figure 8. The averaged initial cursor errors from the learning block and the washout blocks. *A:* The errors in the initial and the final phase of the learning block. The dark gray bars indicate PMLT and the pale gray bars indicate robotic arm device. The error bars indicate SE across participants.

neurons in the primary motor cortex changed its activity after learning of visuomotor tasks (Wise et al., 1998; Paz, et al., 2003; Ganguly and Carmena, 2009; Chase et al., 2012). In addition, studies using functional magnetic imaging also suggest that many other areas in the brain such as dorsal premotor cortex, inferior parietal lobule, supplementary motor area, cingulate motor area (Grafton et al., 2008), parietal area 5 and cerebellum (Diedrichsen et al., 2005) contribute to visuomotor adaptation. These areas work as a motor learning system in a coordinated manner. Such system in the central nervous system automatically detects and computes movement-related

error signals (Diedrichsen et al., 2005), and generates a new motor command to achieve a desired movement (Grafton et al., 2008). Since a large part of these processes is implicit (Mazzoni and Krakauer, 2006) participants exhibit a substantial amount of aftereffects even after the removal of external perturbations, which takes some time to be washed out.

Our participants reported that PMLT had user-friendly interface, helped understanding motor learning research, and should be an addition to theoretical lectures. These reports suggest that development of portable experimental system for undergraduate motor learning education using finger-reaching movement is feasible. It would be possible to develop more specific assessment for the efficacy of PMLT in neuroscience education in the future.

By modifying the programs, we can design more arbitrary tasks. For example, we can also apply visuomotor rotation either gradually to investigate an implicit mechanism of the motor learning process (Kagerer et al., 1997; Kasuga and Nozaki, 2011; Hirashima and Nozaki, 2012) or intermittently to investigate trial-by-trial adaptation for different sizes of errors (Wei and Körding, 2009; Honda et al., 2012; Kasuga et al., 2013). The Processing website provides a huge number of open source libraries for customizing programs, enabling both instructors and students to program experimental setups as needed.

Some limitations of PMLT that instructors should bear in mind include:

1) The poor time resolution of the visual presentation and the data recording compared to commercial devices.

2) Tasks are limited to finger-reaching. Because using different effectors may impact visuomotor learning differently, then results from finger-reaching and arm-reaching experiments may not be directly comparable.

In conclusion, despite some limitations PMLT successfully replicated the learning effect of visuomotor rotation that was obtained in the experiment performed by the robotic arm device. Thus, it can serve as a good experimental system for an undergraduate laboratory exercise of motor learning theories with minimal time and cost for instructors.

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