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Andrei Nakagawa
Universidade Federal de Uberlândia (UFU)

Alcimar Barbosa Soares
Universidade Federal de Uberlândia (UFU)

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A FRAMEWORK FOR VISUOMOTOR ADAPTATION STUDIES

A. Nakagawa-Silva*, E. B. Gouveia*, A. B. Soares*
* Biomedical Engineering Lab, Federal University of Uberlândia, Uberlândia, Brazil
e-mail: andrei.ufu@gmail.com

Abstract: *Adaptation is a remarkable feature of the human sensorimotor system. It provides the flexibility that is needed to control movements in face of uncertainty and changes in our own bodies or in the environment. Adaptation calibrates an internal forward model that makes predictions of the outcome of movements, granting efficient feedforward control. The principles of sensorimotor adaptation can be applied to design novel rehabilitation therapies to enhance recovery. However, there is still a considerable gap into how using this paradigm efficiently for rehabilitation. In this paper we propose a software framework for visuomotor adaptation studies as a necessary step to create the various experimental setups. An experiment implementing a standard protocol in the literature was successfully performed to validate the system. Data analysis showed results comparable with other reports in the literature. The system can be easily adapted to support almost any reach-based protocol.*
Keywords: *visuomotor adaptation, motor learning, rehabilitation therapies*

Introduction

The nervous system faces a great challenge while controlling our movements. There are many muscles that can be activated differently to achieve the same goal (redundancy); our muscles fatigue, altering their properties and our sensors are noisy and slow, providing a delayed feedback [1]. Still, we are capable of performing incredible actions that the designers of current humanoid robots can only dream of. The ability of the nervous system to continuously adapt to different factors such as uncertainties or environment changes is one of the essential elements for effectively controlling our bodies, granting the flexibility required [1], [2].

Sensorimotor adaptation is an error-based paradigm that has been widely used for studying motor learning [3]–[5]. In visuomotor adaptation studies, subjects are asked to perform reaching movements to control a cursor on a screen. During the experiment, subjects experience a perturbation of the visual feedback where cursor movement is different from hand movement [6], [7]. Gradually, in a trial-by-trial basis, subjects learn how to counter the perturbation and improve their performance again. This process is termed adaptation and depends on the observed errors caused by the perturbation. After adaptation, when the perturbation is withdrawn, there are after-effects. Subjects do not immediately recover back to baseline performance, but have to de-adapt gradually [1].

Current theories propose that adaptation consists in reducing sensory prediction errors caused by the perturbations by updating an internal forward model that predicts the outcome of movements [8], [9]. The sensorimotor mapping of the task is adjusted iteratively and optimal performance can be achieved [10]. The cerebellum is considered to be the possible site of forward models [1]. Cerebellar patients could not adapt to perturbations caused by displacing prisms, for example [11]. Another study found that enhancement of cerebellar function with transcranial direct current stimulation (tDCS) actually resulted in faster adaptation [12]. Therefore, adaptation is not just a corrective process, but depends on the capacity of predicting the outcome of movements as well and the cerebellum seems to be crucial for this task [1], [13].

Current understanding of sensorimotor adaptation is being applied to design novel rehabilitation therapies. Stroke patients who suffer with hemineglect have been treated with visuomotor adaptation tasks using prism goggles with good results. The after-effects of the experiments caused subjects to reach towards their neglected side [14]. Additionally, [15] demonstrated that adaptation to a split-belt-treadmill restored walking symmetry during gait in stroke subjects, although they were rapidly washed-out [15]. In [16], Bastian suggests that: a) adaptation in rehabilitation can serve to verify whether subjects can perform movements with a more normal pattern; b) enhancing movement error during the therapy might force the nervous system to adapt and correct it, triggering a recovery process.

However, the study of sensorimotor adaptation requires carefully designed systems in order to capture the necessary elements that would allow reaching proper conclusions about the underlying processes. Therefore, the objective of this paper is to present the development of a software framework to be used for visuomotor adaptation experiments. A controlled experiment based on an established protocol was designed and executed to validate the proposed system.

Materials and Methods

Framework - The software in which the visuomotor adaptation experiments are performed was developed in C++ using Qt 5.7 Open-Source edition and is available online (*github.com/andreinakagawa*).

The software tracks reaching movements from an origin to a single target. The direction of the movement can be configured to be vertical or horizontal and the distance between them is also configurable. The objective of the task is to bring the displayed cursor from the origin to the target. The experiment protocol can be adjusted by configuring the number of trials and setting which ones will be perturbed trials.

The cursor is controlled according to mouse position. Thus, any device that behaves like a mouse can be used in the adaptation experiments, e.g. digitizing tables or joysticks. A dedicated thread reads the current mouse position and updates the cursor position on the screen while saving it to a file.

Visuomotor adaptation experiments consists on applying a perturbation to the cursor, usually rotating it by a given number of degrees. Perturbation is applied by: 1) translating the mouse position to the origin, 2) rotating the cursor localization using a rotation matrix (Equation 1) and 3) translating it back from the origin.

$$\begin{bmatrix} x_r \\ y_r \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} x_c \\ y_c \end{bmatrix} \qquad (1)$$

Where θ is the perturbation angle in radians. x_c and y_c corresponds to mouse position in x and y, respectively. x_r and y_r corresponds to cursor position in x and y, respectively.

Experiment details – An experiment was performed to validate the system by reproducing the classic results reported in studies of visuomotor adaptation [6]. This research has been approved by the Ethics Committee of the Federal University of Uberlândia.

Subjects - Three participants (1 man, 2 women; aged 19-22) were enlisted to validate the proposed system. All the participants were right-handed and naïve to the task. Subjects provided a formal written consent before participating.

Apparatus - Subjects sat facing a computer screen and controlled the cursor by moving a mouse across the table surface with their right hand.

Protocol - The protocol consisted of 40 baseline trials (without perturbation) followed by 80 trials with perturbation (cursor rotated) and 40 washout trials (no perturbation). Perturbation was set to 40° counterclockwise. Subjects also had a two-minute familiarization block before the beginning of the experiment.

A trial started when the cursor was placed in the origin (blue circle) and finished when it hit the target (red circle). Subjects should move the cursor from the origin to the target and could correct their trajectory whenever necessary during the trial.

When the target was hit, there was a 1.5 seconds delay during which subjects were instructed to return to the origin. During this period, there is no visual feedback of the cursor to avoid increased learning of the task.

Data analysis - The scripts for analyzing the experimental data were developed in Python 2.7 using NumPy, SciPy and Matplotlib libraries. We adopted the procedure presented by [6] to analyze the experimental data. Mouse trajectories were pre-processed by applying a third order low-pass Butterworth filter with a 10 Hz cut-off frequency.

For each movement, we determined the peak velocity and the instant in time when it happened. Then, we take the position of the cursor at this point in time and determine the directional error as the angle difference between this point and the straight line traced between the origin to the target (Equation 2).

$$Error = \left(\arctan\left(\frac{dx}{dy}\right)\right) * \frac{180}{\pi} \qquad (2)$$

Where dx and dy are the difference between cursor position and the origin in x and y, respectively.

For every trial, we estimate the directional error and plot it as a function of trial number. Group data were obtained by averaging the individual directional errors. The obtained curves were passed to a curve fit algorithm using single exponentials for the adaptation and washout trials (Equations 3 and 4, respectively) as proposed in the literature [17].

$$adaptation_{fit} = a - be^{-cx} \qquad (3)$$

$$washout_{fit} = a + be^{-cx} \qquad (4)$$

Results

Software - Figures 1 and 2 present the experiment window of the developed application. The blue circle is the origin, the red circle is the target and the green circle is the controlled cursor. Figure 2 illustrates an adaptation trial where the yellow circle indicates an actual position of the mouse and the green circle the position of the controlled cursor on the screen. In other words, in this perturbed trial, a straight reach from origin to target led to a deviated trajectory (40° counterclockwise). During the course of the many adaptation trials, subjects gradually learn to perform a reach to the right, to compensate the deviation to the left, so that the cursor moves straight again.

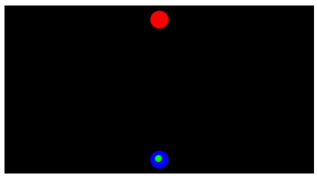

Figure 1: Experiment window. The objective of the task is to bring the cursor (in green) from the origin (in blue) to the target (in red).

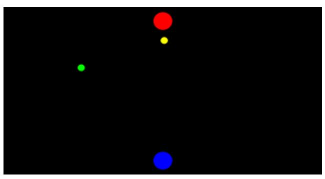

Figure 2: Early adaptation trial. Due to the perturbation, a straight reach (in yellow) deviates cursor trajectory with a specified angle (in green).

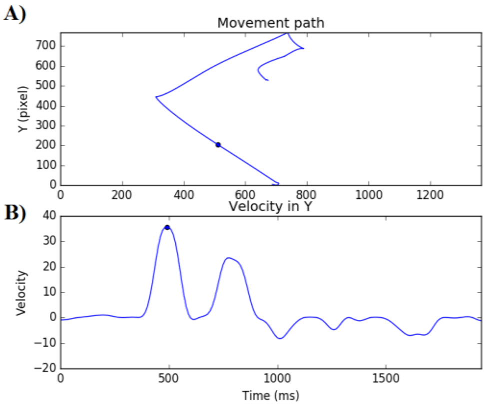

Figure 3: Adaptation trial. A) Movement trajectory in pixels. The trajectory is not a straight line since cursor rotation must be compensated to correct the movement midflight and bring the cursor back to target. B) Movement velocity. The online corrections on the trajectory create the various observed peaks. The greatest peak (blue marker) is used to compute the directional error according to Equation 2.

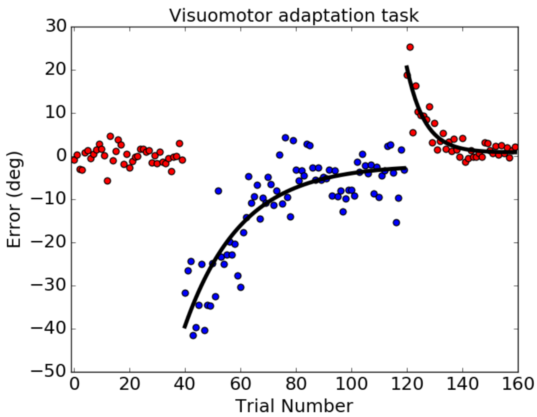

Figure 4: Learning curve during visuomotor adaptation tasks for group data. Baseline movements were straight and errors were close to zero (Trials 1-40). During adaptation (in blue, trials 41-120), directional errors decreased exponentially back to zero. During washout (in red, trials 121-160), expected after-effects were observed - the error reversed and then decreased exponentially back to zero.

Experiment results – Figure 3 illustrates the procedure to estimate directional errors. An adaptation trial was used to serve as example. During early adaptation, subjects make curved trajectories, correcting the direction back to the target later during movement, after the error in trajectory is captured by the nervous system (Figure 3, A). The velocity profile of movement changes from the usual single peak, bell-shaped curve to another with more peaks since movement corrections are necessary. From this curve, we take the greatest peak and the cursor position at that point in time (blue marker). Equation 2 is then used to calculate the directional error (Figure 3, B).

During baseline trials, subjects performed mostly straight movements with directional error close to zero. When the cursor was rotated during adaptation trials, the first movements showed directional errors close to the expected value of -40° (The negative sign comes from the counterclockwise direction). Figure 4 presents the learning curves obtained for each group data.

Discussion

This paper presented the development of a software framework for visuomotor adaptation experiments and an experiment was performed to validate the system. Data analysis showed that it was possible to observe the classic results of the visuomotor adaptation literature.

Any device that behaves like a mouse can be used to control the cursor in the designated interface and perform the sensorimotor tasks. The system can be easily adapted to support basically any reach-based protocol such as those described in [18] and [19].

The learning curves presented in Figure 4 are in accordance with results reported in other studies. The single exponential fit is a traditional approach that serves to approximate the learning function of the sensorimotor system during adaptation experiment. Although it has been suggested that double exponentials provide a better fit [6], for our experiment the single exponentials were a good fit (Figure 4). Subjects had incomplete adaptation, i.e. the directional error was never fully compensated back to zero [20]. This result is also in accordance with the literature, thus, validating the software, experiment and data analysis procedure.

Future works consists on creating a more sophisticated - Graphical User Interface (GUI) where users can specify all the details of the adaptation experiment. It is necessary to add the option for washout trials without visual feedback of the cursor and error-clamp trials. These last two are necessary for investigating savings and spontaneous recovery, for example.

Data analysis could also be enhanced by employing the two-state space model proposed by Smith et al. [21]. In this model, two processes run in parallel: one that learns rapidly but has poor retention and another one that learns slowly but has good retention. Although this model is outside the scope of this paper, but it will be implemented in the data analysis scripts.

Conclusion

We presented the development of a framework for visuomotor adaptation studies. The system was validated by reproducing standard protocols reported in the literature and data analysis showed compatible results. The system is available for download (github.com/andreinakagawa) by the researchers and can be easily adjusted to create various setups for visuomotor adaptation studies.

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