Interactive priming enhanced by negative damping aids learning of an object manipulation task.

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***Abstract*— We investigated how free interaction with an object influences the formation of motor planning. Subjects controlled a force-feedback planar manipulandum that presented simulated anisotropic inertial forces. As a performance evaluation, subjects made circular movements about a prescribed track. In order to investigate potential enhancement of motor planning, we introduced negative damping during an "interactive priming" phase prior to task performance. As a control, we presented a second subject group with normal interactive priming. Our results showed significantly greater reduction in maximum curvature error for the subject group that received enhanced priming (two-tailed T-test, p=1.86e-6) compared to the control group. Group-I demonstrated a 34.8% reduction in error while Group-II achieved 5.78% reduction. We also observed that the presentation of enhanced priming evidently caused a greater sensitivity to catch trials compared to the control. Group-I demonstrated a larger increase (92.0%) in maximum curvature error in catch-trials (with respect to baseline), compared to Group-II (50.8%) during early training (two-tailed T-test, p=1.9e-3). These results suggest that some forms of augmentation to task dynamics - leading to the exploration of a broader state space -can help the accelerate the learning of control strategies suitable for an unassisted environment. The finding is also consistent with the hypothesis that subjects can decompose the environment impedance into acceleration and velocity dependent elements.**

I. Introduction

While it is evident that humans exhibit skill and dexterity in object manipulation tasks in everyday life, it not clear what life experiences in particular best serve the learning of novel or challenging tasks, In order to learn a manipulation task, a plausible alternative to repeated practice is to perform free exploration or interaction with the environment. Certainly repeated practice of a prescribed movement, such as a reach-to-target action, allows effective learning through iterative corrections and tuning of a control strategy. Some researchers have even suggested that the motor skills learned through repeated practice can transfer to at least a local region of space[1]. Others have proposed that variable practice contributes to movement accuracy [2],[3]. The human motor system could learn more robust or general representations through exploratory movements, free of movement prescription, that visit a wider range of states.

It is not, however, immediately obvious what kind of training environment could encourage more effective exploration. Naive exploration of novel mechanical system may not lead to the best performance, since it is not known a priori what actions lead to the most revelatory information. Our previous work has suggested that human motor operators can rapidly identify at least simple dynamical properties such as resonant frequency ([4], and can improve performance by integrating visual and haptic information. Studies have suggested that motor adaptation can be influenced by added sensory channels [5],[6] and by visual error augmentation[7]. Perhaps such environments promote learning through more focused causal associations between motor actions and sensory consequences. The mechanics of a motor task, however, must to a large extent dictate the transparency of such associations. For example, Schaal[8] proposed that in the rhythmic control of a bouncing ball, the human motor system autonomously adjusts control towards a stable strategy. Sabes and Jordan[9] showed that individuals exploit the anisotropy of the arm to reduce the sensitivity to error in making obstacle avoidance maneuvers. In the above cases, a relatively large sensitivity to motor error can be attributed to properties of the task mechanics, and likely contributes to efficient strategy formation.

The purpose of this study was to explore potential means of enhancing free interaction to better serve the learning of novel task dynamics. We present an experiment that compares the effectiveness of free interaction with an object using both enhanced (including negative damping) and normal loading conditions. We hypothesized that the human motor system is capable of decoupling the contribution of forces from different mechanical properties, namely inertial versus viscous loading. Furthermore, we considered destabilizing viscous loading as a candidate for enhancement that could highlight sensorimotor experiences particularly relevant in the control of inertial dynamics. However, we also discuss the potential downside of enhancing the dynamics of an object with negative damping that may arise due to a failure in decoupling inertial and viscous elements.

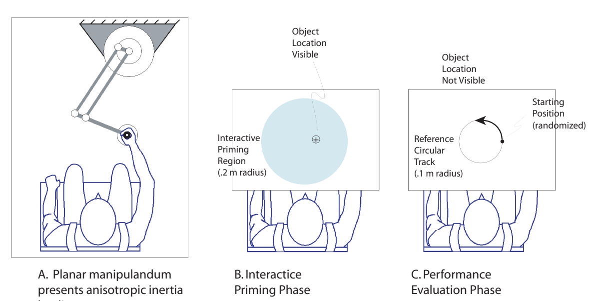

Fig. 1. (A) We simulated various anisotropic inertial loads with a force-feedback planar manipulandum. (B) Subjects were allowed to freely interact with each load in an "interactive priming" phase priming. (C) Following priming, subjects made circular movements with the manipulandum during an evaluation phase.

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II. METHODS

Apparatus and Implementation of Anisotropic Load: We asked subjects to control the movement of a two-degree of freedom planar force-feedback device (See Fig. 1) described elsewhere[10], programmed to present inertial and viscous anisotropic loads to the hand. We chose this dynamic environment and task in order to investigate how the human motor system copes with inertial anisotropy typical to human experience, yet nonetheless represents a novel and challenging task to learn. Using MATLAB XPC-Target (Natick, MA) a computer performed real-time differentiation and filtering (fourth order, low-pass cut-off at 11 Hz) of the robot joint-angle encoder data and calculated estimates of the velocity and acceleration of the handle end-point. Data were collected at 100 Hz. The basic rate of dynamics simulation was 2 kHz. We selected five orientations for the anisotropic loads: θ_M=0, 36, 72, 108, 144 degrees. End-point forces F_x(t) and F_y(t) approximating inertial and viscous loads were presented according to:

$$\begin{bmatrix} F_x(t) \\ F_y(t) \end{bmatrix} = R^T \begin{bmatrix} 0 & 0 \\ 0 & M_y \end{bmatrix} R \begin{bmatrix} \ddot{x}(t) \\ \ddot{y}(t) \end{bmatrix} + R^T \begin{bmatrix} 0 & 0 \\ 0 & B_y \end{bmatrix} \begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \end{bmatrix} R,$$

$$\text{where} \quad R = \begin{bmatrix} cos\theta_M & sin\theta_M \\ -sin\theta_M & cos\theta_M \end{bmatrix}$$

We chose a mass parameter M_y of 3 kg and a damping parameter B_y of either 0 or -5 N/s. With the rotation matrix R, various anisotropic loads were selected representing orientations of load.

A. Human Subjects

26 healthy individuals volunteered for this study, 13 in each subject group. All participants reported have normal or corrected to normal vision. Each individual provided informed consent in accordance with Northwestern University Institutional Review Board. Individuals were not paid for their participation. Two subjects reported being left-handed.Subjects performed the task with their dominant arm.

B. Description of Motor Task

Subjects were asked to perform free exploration movements and evaluation trials with the robotic manipulandum. During this ”interactive priming phase”, subjects were asked to manipulate the object at their discretion in the horizontal plane, with various directions, speeds, and positions within a .2 m radius circular region, centered within the workspace. Using an overhead projector, visual feedback of the handle-object position and the circular interaction region was presented on a tabletop covering the planar workspace. Within the priming region the damping term was set to -5 N/s for the ”enhanced priming” group and 0 for the ”normal priming” group. Negative damping tends to induce instability.

During the ”evaluation phase”, subjects were asked to perform circular movements (three complete counter-clockwise revolutions) with the end-point of the robotic manipulandum. The performance phase typically included the same inertial load (exceptions were the ”catch” trials) as that presented during the interactive priming phase. However, in all cases, the damping term (See Eq-1) was set to zero during performance. After each trial, feedback was also provided for a target speed (1 cycle per second). Visual feedback of a circular reference track (.1 m radius) was presented in the center in the workspace. For most trials, visual feedback of the handle-object position however was occluded to limit the amount of learning during evaluation. Random starting locations were indicated on the circular track at pi/8 intervals.

C. Experiment Conditions

Subjects were divided into experiment and control groups, which differed by the sequence of normal versus enhanced interactive priming. Both groups were presented with an initial baseline block of trials with primarily no load, followed by an ”early” and ”late” training block. The experiment group was presented with a trial block with enhanced interactive priming, followed by another block with normal interactive priming. The control group was also presented with the interactive priming blocks but in the reverse order. A brief break (3 minutes) was provided in between blocks.

Each experiment block consisted of 5 mini-blocks, each in turn associated with a different anisotropic load, an interactive priming phase, 10 regular and 2 ”catch” trials (unexpected changes in load). Catch trials during the main experiment blocks were trials in which the load was unexpectedly absent. We also included ”pre-priming” catch trials during the baseline block were trials in which the load was suddenly changed from none to either θ_m= 72 or 144 degrees (with respect to the horizontal). Presentation of the two unexpected load conditions allowed analysis of the change in performance before and after interactive priming. We presented a reduced set of load types for pre-priming trials to limit learning during the baseline phase.

In order to focus on the impact of interactive priming on learning, we also omitted visual feedback for the majority of performance trials. Visual feedback of the handle-object position was initially presented for all conditions in the baseline block until trial 40. Visual feedback was always available during interactive priming.

D. Data Analysis

We assessed the ability of subjects to maintain smooth circular movements while they manipulated various anisotropic inertial loads. Using the measured endpoint position data for each performance trial, we calculated the time-history of the instantaneous curvature κ, and the devised a performance metric describing the cumulative deviation of curvature:

$$\epsilon = \int_0^{4\pi} (\kappa(\theta) - \bar{\kappa}), \qquad (1)$$

where,

$$\kappa = \frac{\ddot{x}\ddot{y} - \dot{y}\dot{x}}{(\dot{x}^2 - \dot{y}^2)^{\frac{3}{2}}} \qquad (2)$$

We compared performance between the subjects groups in terms of the maximum curvature observed during each trial, using a two-way ANOVA, in which considered the main experiment factors of subject group (I or II), training block (early or late), load orientation (1-5), and trial sequence of non-catch post-priming trials (1-10). We then performed post-hoc t-tests between subject groups on the change in error pre- and post-priming for regular (two available loading conditions, see Methods) and catch trials (all five loading conditions). We present these results as percentage change from initial load exposure trials, and the catch trial results as a percentage change from initial baseline (no load) trials. These tests served as measures for how well subjects improved performance after interactive priming, and how sensitive subjects were to unexpected removal of loading. The threshold level of significance for both ANOVA and t-tests was set at α=0.05.

III. Results

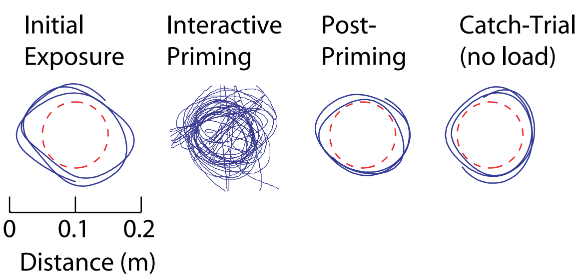

Fig. 2. Sample plots of handle motion (blue) from one typical subject in controlling an anisotropic inertia demonstrate how systematic errors with respect to the reference circular path (dashed) decrease following interactive priming. During the catch-trial, the systematic errors remain small but change in orientation.

Results from ANOVA suggest a strong influence from the experiment factors: subject group (p=7.0e-14), load type (p=1e-16), and trial sequence (p=3.3e-9). Interactions were significant only for the group-by-load effect (p=6.1e-15). Though we observed a trend of error reduction over trials for Group-II, the group-by-trial interactions was not found to be significant (p=0.071).

Our main experimental finding is that during early training Group-I (enhanced priming) demonstrated significantly larger reduction in error compared to Group-II (normal priming) following interactive priming (two-tailed T-test, p=1.86e-6). Each group on average exhibited a reduction in the maximum curvature error (see Fig. 3) in post-priming trials with respect to initial exposure trials. However, Group-I demonstrated a 34.8% reduction in error while Group-II achieved only a 5.78% reduction. We observed similar differences between groups in late training (two-tailed T-test, p=6.83e-7). Group-I demonstrated a 37.2% reduction in error while Group-II achieved an 11.1% reduction.

In addition, we found that Group-I demonstrated a larger increase in maximum curvature error in catch-trials (with respect to baseline), compared to Group-II during early training (two-tailed T-test, p=1.9e-3). Group-I showed a trend of increased error in catch-trials for both early (92.0%) and late (80.2%) training. Similarly, Group-II showed a trend of increased error in catch-trials for both early (50.8%) and late (60.0%) training. A similar difference between groups was found during late training, though the results were not significant (two-tailed T-test, p=0.179).

IV. Discussion

The results of this study provide support that, in an object manipulation task, the dynamics of the task environment can be enhanced during an interactive priming period to accelerate motor learning and improve performance during subsequent task performance. Analysis of the early training trial block showed that interactive priming enhanced with negative damping caused performance recovery to be significantly better compared to the control. Furthermore, the results of the late training trial block, suggest that even with normal interactive priming, subjects that had previously trained with enhanced priming successfully transfer their learned skills.

We also found evidence that enhanced interactive priming enabled better performance through improved task specificity. One plausible outcome of presenting a destabilizing environment is that subjects would increase their muscle co-activation. However, the analysis of the change in performance between catch-trials and baseline conditions during early training show increased error from both groups, suggesting that interactive priming enabled subjects to develop task specific strategies to cope with anisotropic inertial loading. Furthermore, we observed during the early training block significantly higher increase in sensitivity to catch trials from Group-I compared to Group-II, providing evidence that enhanced interactive priming actually increased the specificity of the control strategy.

We found evidence, however, that the introduction of enhanced interactive priming can lead worsening of performance if introduced later in training. Group-II exhibited increased error in transferring from normal to enhanced conditions, which suggests an interference effect of negative damping on performance when subjects were already accustomed to normal priming. In contrast, an analysis for late training suggested that for Group-I, the learning acquired from enhanced interactive priming transferred successfully to normal interactive priming. It is likely that subjects in Group-I were better prepared for the change in interactive priming, since they were exposed to both kinds of dynamics during the priming and performance phases of early training. In contrast, subjects in Group-I experienced only object dynamics without negative damping possibly leading to interference with prior, recent training. It is also plausible that the two priming conditions caused differential levels of fatigue between the subject groups. Further study is needed to determine in what situations augmented mechanics can interfere with prior learning.

The basis of this accelerated learning evidenced in this study could lie in the ability of the human motor system to transfer skills across tasks that differ both in kinematics and in mechanics. We found that even when task dynamics differ between the interactive priming and performance phases, subjects were able learn object-specific control strategies. These results suggest that the human motor system can in fact decouple the sensorimotor experiences associated with inertial versus viscous loading. The motion observed during free interaction (See Fig. 2) exhibits large differences with respect to the motion

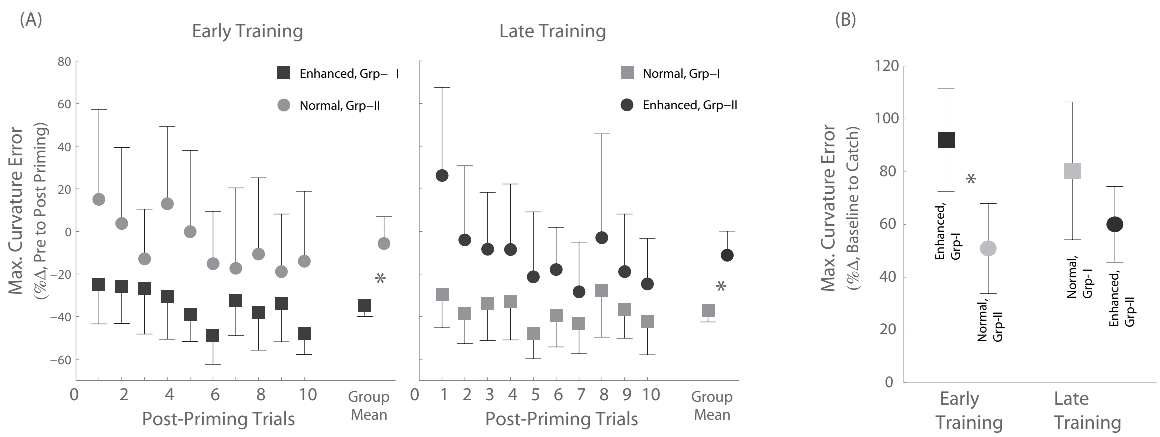

Fig. 3. (A) Following interactive priming in early training, enhancement with negative damping enabled Group-I to achieve a greater success in compensating for anisotropic loads (average error of two load conditions), compared to Group-II (two-tailed T-test, p=1.86e-6). In late training, Group-I maintained better performance (two-tailed T-test, p=6.83e-7) despite the change to normal priming. (B) Analysis of catch trials (five load conditions) suggests Group-I also exhibited greater increase in sensitivity (two-tailed T-test, p=1.9e-3) compared to Group-II during early training. Error bars represent 95% CI across all trials.

during performance. Yet for both subject groups, we observed that the performance in terms of the maximum curvature error reduced immediately following interactive priming. For the case of normal interactive priming, we reason that while the kinematics between stages differed, both exhibited similar force-motion relationships, which enabled the human motor system to learning an appropriate mapping between efferent commands and the desired performance. Furthermore, for the cases of enhanced interactive priming, subjects were evidently able to learn useful information though the mechanics between priming and performance stages differed. Note that by design, both stages included the same inertial loading, which must in part explain the successful strategy formation.

To explain how the presence of negative damping could improve motor learning despite its inconsistency with the target environment, we theorize firstly, that human motor system is capable of distinguishing whether interaction forces arise from inertial or viscous elements. Secondly, we reason that because negative damping is destabilizing, it would encourage subjects to explore at higher frequencies, consequently providing a richer experience of force-motion relationships associated with inertial dynamics. An alternative way to induce extended exploration would be to apply to the hand some time-dependent forcing function. However, earlier observations [11],[12] have shown that adaptation to time-dependent force is either impossible or harder than adaptation to state-dependent forces. Our priming paradigm uses a pattern of velocity- and acceleration-dependent forces. We can then speculate that through practice subjects develop a representation of the force field and that the simple suppression of the velocity dependent component does not abolish the representation of the acceleration dependent component.

The results of this study provide a potential framework for how to aid the learning of an object manipulation task through augmenting task mechanics. These findings could have implications to motor rehabilitation by providing a means to facilitate transfer between assisted motor training to non-assisted performance. Future work involves investigating how success in motor planning can be predicted from an analysis of movement during priming. In addition, we will investigate how motor learning through interactive priming differs from that achieved from repeated practice.

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