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Effect of Progressive Visual Error Amplification on Human Motor Adaptation

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***Abstract*—Amplification of error has been shown to be an effective technique in increasing the rate and extent of learning for motor tasks and has the potential to accelerate rehabilitation following motor impairment. However, current error amplification methods suffer from reduced effectiveness towards the end of training. In this paper, we propose a new approach, progressive error amplification, in which error gains increase as a trainee's performance improves. We tested this approach against conventional error augmentation in a controlled experiment wherein 30 subjects adapted to a visually distorted environment by performing target-hitting tasks under one of three conditions (control, constant error amplification, progressive error amplification). Our results showed that compared with repeated practice, error amplification does not accelerate learning or result in improved task performance with respect to trajectory error, although progressive error amplification does produce lower trajectory errors when training conditions are in effect. These results indicate a need for further tuning of error augmentation methods in order to determine their true potential as a training method.**

I. Introduction

In everyday life, humans easily adapt to new situations, using sensory information about themselves and their environment to adjust their movements and achieve their goals. It has been well established that error, the difference between the desired or expected outcome and the actual outcome, is a main driving force in this adaptation process [1]. Studies have shown greater adaptation for larger perceived errors, provided those perceived errors are not so large that the human begins to doubt the reliability of the feedback [2]. In light of these findings, error augmentation has gained attention as a promising method for training of motor tasks.

Exploration of the role of error augmentation on motor learning may have direct relevance to robotic rehabilitation protocols. Indeed, it has been shown that robotic training for rehabilitation after stroke, provided in a way that emulates concepts of motor-learning, leads to better outcomes in terms of movement coordination than does robotic-driven muscle strengthening [3], [4]. Studies further suggest a working model of recovery similar to implicit motor learning [5]. In this paper, we further explore the effects of visual error augmentation on motor learning in healthy individuals as a foundation for applying this technique in robotic rehabilitation.

The most popular type of error augmentation has been strict amplification, in which deviations from a preferred trajectory are multiplied by a constant value before being displayed to the trainee. Experiments on reaching tasks [6], [7], pinching tasks [8], and timing tasks [9] have all shown increased rate and extent of learning during training with error amplification. However, error amplification suffers from two main drawbacks. First, the amount by which error may be augmented is limited. Large error gains will cause the trainee to distrust and reject the feedback [1], [2]. Error gains that are too high may also lead to instability and inhibit learning [6]. Second, the method has decreasing effectiveness as training progresses. Improvements in trainee performance yield smaller errors and thus smaller error feedback, limiting the rate at which learning can proceed. Therefore, methods have been proposed to combat these deficiencies. For example, Wei et al. [6] determined that error offset leads to both increased rate and increased extent of learning over error amplification with a gain of 2 but warned of the dangers of overtraining. Subsequent experiments by Celik et al. [10] showed similar effects of error offset.

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We propose a new visual error augmentation method: progressive error amplification. Studies of adaptation to gradual compared with abrupt changes in environment indicate that participants exposed to gradual changes demonstrate more extensive adaptation [11] and that large changes in environmental conditions may be rendered unnoticeable to participants by introducing those changes in small increments [12]. We hypothesize that the same principle may be applied to overcome the limited effectiveness of error amplification due to discounting of feedback when large error gains are used. We expect that gradually increasing the error gain will allow gain values to increase above 2 without incurring the detrimental effects of introducing large gain values from the start. This training method also mitigates the second drawback of error amplification, that is, decreasing effectiveness with improved performance, by increasing gains and keeping perceived error levels high, without risking overtraining effects.

To test this progressive error amplification method, we asked 30 participants to complete target-hitting tasks under different error augmentation conditions. Section II details the experimental protocol, error amplification conditions, and data analysis methods used. Section III presents the performance of each group during both training with error augmentation and evaluations without. Finally, section IV discusses the results in relation to the relevant literature.

II. Methods

A. Task Description

The target-hitting task used in this experiment was similar that used by Celik et al. [10]. Participants sat in front of a computer monitor and controlled a pointer on the screen using

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Fig. 1. Setup used for the experiment. Participants were seated in front of a computer monitor and moved an Immersion IE2000 joystick with their dominant hand. A curtain obscured the joystick and the controlling hand from view. Note objects on the screen have been enlarged for greater visibility.

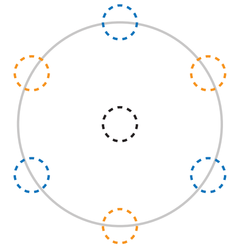

Fig. 2. Location of targets used in the experiment. Targets (dashed circles) were evenly spaced around the the center of the screen. The three targets indicated in orange were used during training and evaluation blocks. The three targets indicated in blue were used during the familiarization and generalization block. Reaching targets required $\pm 27^{\circ}$ rotation of the joystick.

a 2-DOF haptic joystick (Immersion, Inc., IE2000), as shown in Fig. 1. They were instructed to keep the pointer at the center of the screen until a circular target appeared. Participants then moved the pointer to the target as quickly as possible in a straight-line path, kept the pointer in the target for at least 0.25s to register a hit, and finally returned the pointer to the center of the screen. One out-and-back motion constituted one trial. Targets appeared in one of three locations (see Fig. 2) in pseudorandom order. A pause between trials of random length between 1s and 2s reduced the effects of anticipation.

To increase the level of difficulty of the task, a 45° counterclockwise rotational visual distortion was applied to the pointer position. During training, different error amplification gains were also applied to determine their effect on the amount of adaptation to the distortion. The position of the pointer was recorded at 100Hz for analysis.

B. Participants

Thirty healthy volunteers between the ages of 18 and 52 (mean: 22) successfully completed the experiment. Of these, eleven were male and four were left-handed. All performed the task using the dominant hand. No participants reported any significant vision or movement disorders, and all provided informed consent, as approved by the Institutional Review Boards of Rice University.

Participants were evenly and randomly assigned to one of three training groups: 1) no error augmentation, 2) constant error amplification, or 3) progressive error amplification. Further details on these training modes may be found in section II-D.

C. Experiment Protocol

The experimental design was block-based, presenting participants with sets of trials sharing the same environmental conditions. To begin a block, participants would press a button on the joystick. Trials would then follow automatically one after the other until the end of the block. Four types of blocks were present in this experiment. First, a 6-trial familiarization block allowed subjects to become familiar with the experimental setup and virtual environment without any visual distortion or error augmentation present. Evaluation blocks consisting of 7 trials measured performance in the presence of distortion but without error augmentation. Training blocks consisted of 18 trials with distortion and error augmentation both and provided additional feedback every 9 trials in the form of the participant's average trajectory to each target. Participants were allowed to look at these plots as long as desired and pressed a button on the joystick to continue the trial block. Finally, 12-trial generalization blocks with distortion but no error augmentation tested the extent of participants' adaptation to the environment by evaluating participants on targets in locations other than those used in evaluation and training. The same target locations were used for evaluation and training. A different set of target locations was used for the familiarization in order to make the form of the distortion in subsequent trials less obvious. The same targets were used during familiarization and generalization.

The experiment consisted of 19 trial blocks: a familiarization block, an initial evaluation block, 8 sets of alternating training and evaluation blocks, and a generalization block. Halfway through the experiment, participants took a mandatory 2-minute break to prevent fatigue, and short breaks between blocks were also allowed if desired. In total, participants performed 225 target-hitting motions over the course of about 20 minutes. A pilot study showed this number of trials was sufficient for participants to reach steady state performance.

Prior to beginning the experiment, participants were given a description of the task and of the experimental procedure. They were informed that visual distortion would be present and that during training blocks, additional visual feedback would be provided, but, in order to prevent them from intentionally adjusting their movements to the distortion, they were not given information about the specific form the distortion or feedback would take. Throughout the experiment, the hand on the joystick was obscured by a curtain so that visual feedback was limited to that from the monitor alone.

The experimental design used here differed from those commonly found in the literature in two ways. First, displays of average trajectory during training blocks provided participants with additional feedback on their movements. This summary information was presented to subjects so that they could see patterns in their movements or problem areas that they may not have noticed during individual trials. Second, the evaluation blocks used were relatively long. Differences in the training schemes between groups affect how trainees transition between training and evaluation blocks [10]. For us to obtain an accurate measure of progress independent of transition effects, participants made at least two movements to each of the targets during evaluation blocks, rather than the more common catch-trial approach.

D. Error Augmentation Conditions

Three modes of training were used in this experiment: 1) no error amplification (NA), 2) constant error amplification (CA), and 3) progressive error amplification (PA).

The NA group undergoing repeated practice with no error amplification served as a control. The other two groups experienced error amplification as described by Wei et al. [6]. Essentially, the deviation of the pointer position from the straight-line path was multiplied by a constant factor before displaying the pointer on the screen, resulting in movements perpendicular to the straight-line path being distorted.

The CA group experienced a gain of 2 throughout training. This gain value was chosen because it has been found to be the most effective for training in similar tasks [6], [10]. The PA group also began with an error gain of 2 so that it could take advantage of the accelerated learning achieved. However, training of this group differed in that the error gain increased over the course of the experiment based on performance during evaluation blocks. For each evaluation block, the mean trajectory error over all trials in the block was calculated and stored. During the next evaluation block, the mean trajectory error was calculated again. If the new value was lower than the old one, then the gain used during the next training block was increased by a factor of $\frac{TE_{old}}{TE_{new}}$ or 1.07, whichever was less. Error gains remained constant during individual training blocks. This scheme allows perceived error on the screen to remain relatively constant throughout training, even when the participant's performance improves. A cap of a 7% gain increase was chosen to prevent participants from noticing changes in gain from block to block and to ensure that the gain in the final block was less than the 3.1 calculated by Wei et al. [6] as the limit of stability.

E. Data Analysis

Because error augmentation trains primarily for straighter movements over other performance characteristics, trajectory error (TE) was selected as the sole measure of interest. Trajectory error is a measure of the difference between the participant's motion and the desired motion, in this case, the straight-line path. For each outward movement to a target, the mean absolute deviation of the subject's joystick position from a straight-line path was calculated and normalized over the distance to the target. The resulting value is independent of differences in speed and error gain value between participants.

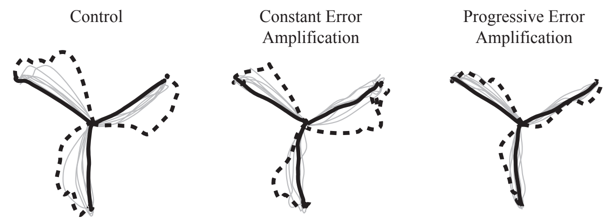

Fig. 3. Pointer trajectories of representative subjects in each of the three training groups. Dashed black lines show the average trajectories to each target during the initial evaluation. Gray lines show the progression of the participants' performance during intermediate evaluations. Solid black lines show performance in the final evaluation.

The TE values calculated in this experiment were right-skewed, so a logarithmic transform was applied before analysis. Normality of the resulting data was confirmed using a quantile-quantile plot. Effectiveness of the different modes of training was tested by conducting a repeated measures ANOVA with the main factor of condition (three: NA, CA, PA) and repeated factor of trial on each of the blocks individually. Alpha was set at 0.05.

III. Results

Plots of pointer trajectories for representative subjects in each group can be found in Fig. 3. Participants initially made curved movements when introduced to the rotational distortion (dashed black lines), but adapted over the course of the experiment (gray lines) and were able to produce straighter lines by the final evaluation (solid black lines).

An example of the increasing gain during training of the PA group can be found in Fig. 4. Whenever trajectory error during evaluation decreased, the gain was increased for the subsequent training block. The exact increase in gain was dependent on the percent decrease in trajectory error. Error gain values in the last training block ranged from 2.14 to 2.93 and averaged 2.69.

The average trajectory error over each block during evaluation and training are shown in Fig. 5 and Fig. 6 respectively. In all three groups, adaptation occurred, as evidenced by the decreasing trend in TE. Average values of TE were similar for all groups in both the familiarization and initial evaluation blocks, indicating that the groups were well balanced. In the final evaluation, the NA group performed with the lowest trajectory error, followed by the PA group and the CA group, though the difference in performance between groups was not significant. The same trend may be seen in the generalization block. In addition, NA group reached this higher level of performance faster than the other two groups, leveling off at TE values close to those achieved during familiarization starting from the second evaluation.

A comparison of the TE values during training and evaluation show that errors made during training for both error augmentation conditions were significantly lower than those

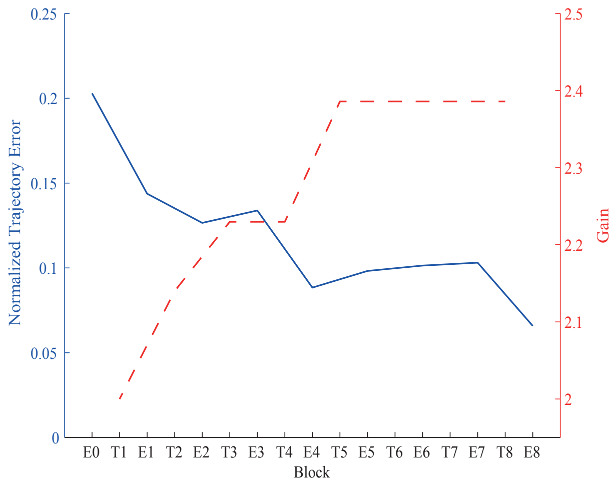

Fig. 4. Gain values of a PA subject during training, along with average trajectory error during the previous evaluation. Gain during training increases whenever performance improves (TE decreases) but remains constant when performance worsens.

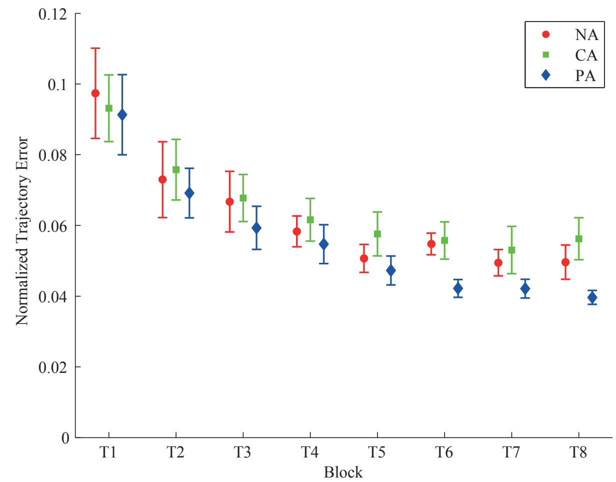

Fig. 6. Average trajectory error (TE) for each group during training blocks. Dots represent mean TE over subjects, and error bars represent standard error. Note how TE values for the control and constant error amplification groups tend to level off towards the second half of the experiment, while the TE values for the progressive error amplification group continues to decrease.

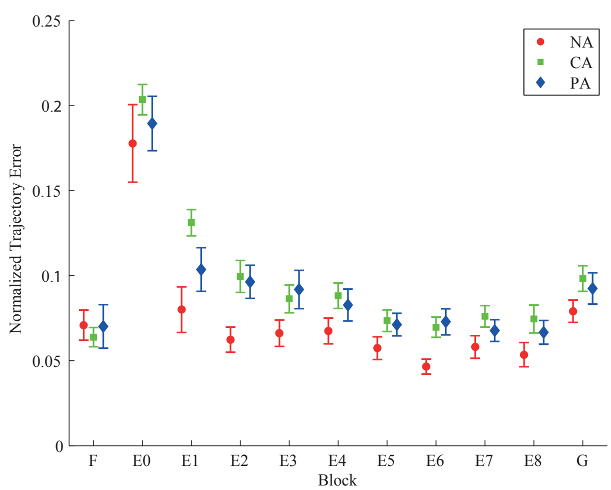

Fig. 5. Average trajectory error (TE) for each group during evaluation blocks. Dots represent mean TE over subjects, and error bars represent standard error. The control group adapts much faster than the other two groups, achieving TE values close to the those during familiarization by the second evaluation.

made during evaluation (CA: $F_{1,159} = 52.47$, $p < 0.001$; PA: $F_{1,159} = 74.18$, $p < 0.001$), while TE values did not differ significantly by block type for the control group. This indicates that error amplification did have an effect on trainee performance during the experiment. It is therefore of interest to see if similar trends in trajectory error can be found during training blocks as during evaluation blocks. During training blocks, the PA group performed with the lowest trajectory error, followed by the NA group and then the CA group. In addition, while the TE values for the NA and CA groups began to level off halfway through the experiment, TE values for the PA group continued to decrease. The variance in performance of the PA group also became smaller than that in the other two groups. In the final training block, the PA group achieved significantly lower TE than the CA group ($p = 0.009$).

IV. Discussion

From our results, error amplification does not appear to result in faster or more extensive learning than practice alone and may even have a detrimental effect on a trainee's ability to learn. While all three groups adapted to the visual distortion, the control group showed both the greatest rate and the greatest amount of adaptation in terms of trajectory error. This result is in opposition with previous studies [6], [7], [10] which showed both faster and more extensive learning with error amplification than without.

One possible reason for the observed lack of accelerated learning with error amplification is the dominance of visual feedback over proprioceptive feedback. Multiple experiments on the integration of visual and proprioceptive feedback have shown that vision dominates when the discrepancy between the two is small [13]–[15]. Therefore, real-time visual feedback of performance, as given in this experiment, while beneficial during training blocks, may actually be detrimental to long-term retention of a motor skill because it distracts participants from the proprioceptive information necessary for subsequent successful performance of the motion [16], [17]. Participants in all three groups indicated after the experiment that they were unaware of differences between training and evaluation blocks and that they took no notice of the block type when performing the task. It is probable that in this case, participants relied on the visual display of the pointer position to continuously update their movements rather than concentrating on learning the movements required to perform the task well. This strategy effectively nullified what benefit could be taken from error augmentation.

This explanation is supported by the results of Brewer et al. [8], whose experiment on coordinated pinching tasks demonstrated that error augmentation has the main effect of attracting the participant's attention away from secondary goals or additional sensory information. Further confirmation may be found in the different behaviors during evaluation and training blocks for different training conditions. TE values for training and evaluation trials for the groups experiencing error amplification were clearly different, while those for the control group receiving no error amplification showed no significant difference. These results may be expected. With the exception of the trajectory plots shown to participants at the middle and end of each training block, training for the NA group was the same as completing evaluation trials. Therefore few differences in performance between the evaluation and training trials should occur. Training with error augmentation, on the other hand, showed participants their pointer movements in greater resolution than in evaluation blocks, allowing them to make finer adjustments to position. Participants basing their movements off the displayed perceived error levels would naturally make larger errors during blocks where error amplification was not in effect. In future experiments, dependence on the display may be reduced by having participants perform in the absence of concurrent feedback of performance and providing them with summary information of their trajectories after each trial [16].

Alternatively, the comparatively long evaluation blocks used in this experiment may have had an effect on the results. Analysis of the TE trends within individual evaluation blocks clearly showed decreasing TE with trial. It is therefore probable that training occurred during the evaluation blocks. This, in addition to transition effects that would have been experienced by the error amplification groups but not by the control group, may have confounded the results. In future experiments, shorter or less frequent evaluations should be conducted to mitigate this effect.

Despite the absence of accelerated learning effects during evaluation, progressive error amplification does show promise for situations where a task may be performed under the training conditions. The progressive error amplification condition presents participants with increasing error gain based on their performance. During initial training blocks, groups training with error amplification performed no better than the control group. However, whereas with constant error gain, errors steadily became unnoticeable as participants' performance improved, training with progressive error amplification presented errors made in finer and finer resolution, allowing trainees to continue to improve their TE values beyond the point where constant error gain training methods lost their effectiveness. This finer resolution visible to participants training under progressive error augmentation also trained participants to perform more consistently, reducing the variance in TE between trials.

We have demonstrated a performance-based approach to error amplification as a training strategy and shown that training with error amplification does not necessarily result in greater accuracy of movement. It is possible that participants, because of the higher difficulty afforded by the error amplification, learned to accept larger perceived errors in favor of optimizing other task performance measures. This paper looks at the effects of error amplification on trajectory error alone. Further analysis of the data with respect to other commonly-used measures, such as hit time or smoothness, will allow us to determine under what conditions these error amplification training schemes should be used and for which measures they are effective.

V. Conclusion

In this paper, visual error amplification was evaluated as a training strategy. A new error augmentation strategy, progressive error amplification, was introduced and tested on a target-hitting task. Subjects adapted to a visually distorted environment by performing repeated movements under one of three conditions: no error augmentation, constant error amplification, and progressive error amplification. Contrary to previous studies, our results showed that constant error amplification produces no significant benefits over repeated practice in terms of minimizing trajectory error. Progressive error amplification produced the lowest error only when participants performed with the error amplification on. The results, suggesting that more work must be done in order to determine what factors make error amplification effective, have direct relevance to the development of effective protocols for robotic rehabilitation.

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