Nonlinear error augmentation applied to upper limb movements enhances motor learning*

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***Abstract*— We investigated adaptation to a nonlinear, power-based error-augmentation feedback to assess the hypothesis that it can promote effective motor learning. Two groups of healthy adults (experimental and control groups) participated in a study involving a planar reaching task. Participants' hand was occluded from view. The hand held the puck of a graphics tablet, which tracked its movement, represented by a round cursor moving in a display placed in front of the participant. Canonical Familiarization, Baseline, Adaptation, and Washout phases characterize the experiment. In the control group, all four phases involved a 1:1 mapping between hand and cursor position, whereas, in the experimental group, real trajectories were distorted by a nonlinear function according to a power-based error-augmentation approach, during the Adaptation phase. The experimental group showed learning increase and average error reduction. The proposed approach extends the error augmentation techniques proposed so far, and may be useful for inducing motor learning in teleoperation, sports, and rehabilitation contexts.**

I. Introduction

Movement errors play an important role in motor learning. The magnification of this error can stimulate the learning process, resulting in improved coordination and movement control [1], [2]. The error augmentation (EA) training is well known for its ability to improve motor error correction when applied to upper limb movements [3], [4], locomotion [5], and balance tasks [6]. EA is either purely haptic or visual perturbation. In the former case, it is applied through a robotic device that applies forces to the moving hand (e.g., in upper limb training), whereas in the latter case it distorts the visual feedback on the hand position through the cursor that maps the movement of the hand on the screen [4]. In this case, EA consists in a proportional displacement of the cursor with respect to a reference trajectory and results in an amplification of the motor error with respect to the requested trajectory. The rationale is that, by provoking movement errors, EA will provide enhanced sensory inputs and hence contribute to adaptation [7]. When participants perform movements that deviate from the intended path, the amplification of the error causes them to try to counteract the disturbance caused by EA, fostering their motor control.

At the same time, movement errors can also be induced by unexpected perturbations that disturb participants' training, for instance through nonlinear mismatches. The relationship between movement and the observed mismatch may not be easily understandable to the participant [8], but can be learned through experience, with prolonged training [5]. It is known that all the factors that contribute to increasing the variability of the movement create an excellent framework to enhance motor learning and encourage the exploration of errors [9], which is an important element to improve learning, especially during its early stages [10]. A perturbation governed by an unexpected law, not linearly proportional to the motor error relative to the ideal trajectory, can push participants out of their comfort zone, encouraging them to explore and adapt to new motor tasks.

In this work, we investigate whether a nonlinear EA might enhance motor learning in healthy adults. Deviations from the ideal, rectilinear trajectory were amplified with an EA approach implementing a power function, which amplifies larger errors in the hand trajectory while participants performed center-out reaching movements in the horizontal plane. Our results support the use of this nonlinear error augmentation technique to facilitate learning of motor tasks.

II. Materials and Methods

A. Participants

Thirty participants (18–35 years) were enrolled in this study. All of them reported having normal or corrected-to-normal vision, no history of neurological or upper limb motor disorders, and being either right-handed or ambidextrous. All participants were naïve to the purpose of the study and received written and verbal instructions before the start of the experiment. The research was approved by the Ethics Board of the University of Cagliari. Participants provided their signed informed consent, and were randomly and equally assigned to the experimental and control groups. Experimental tests were conducted at the Medical Devices and Signal Processing Lab of the University of Cagliari.

B. Apparatus

Participants were seated in front of a 60 Hz 40 inch screen connected to a Windows laptop, where visual stimuli were presented, as shown in Figure 1. During the experiment, they were asked to move the puck of a digitizer (CalComp, Inc, DrawingBoard VI, model DBVI 20 × 24 inches, sampling rate equal to 100 Hz) to perform a reaching task on its active area. Participants' hand was occluded from view by means of an opaque black cloth, to prevent them from receiving direct

*We acknowledge financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for tender No. 1409 published on 14.9.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU– Project Title "Advanced VISual feedback for neurorehabilitatION systems based on virtuAl RealitY" (VISIONARY) – CUP F53D23001600006

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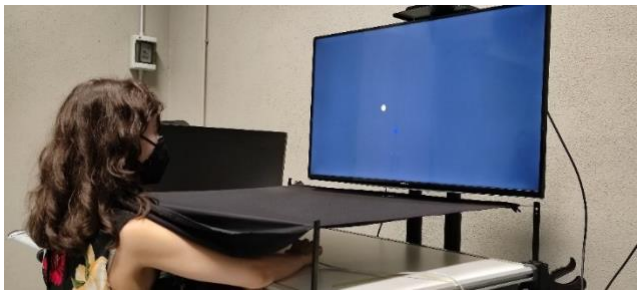

Figure 1. Experimental apparatus.

visual feedback from their hand. The 2D motor task was implemented in Unity 3D.

C. Motor task

Participants were asked to perform planar reaching movements from a starting point (white circular ring, diameter 2 cm) to the target point (white circle, diameter 2 cm). The hand position and movement were represented by a cursor (blue circle, diameter 1.6 cm) displayed on the screen.

At the beginning of each trial, the cursor must stay on the starting point for at least 2 s. Then, the starting point disappears, and the target is shown on the screen at a certain position for 1 s. When the participant completes the movement (i.e., when the cursor remains stationary for at least 1 s), the target disappears and the starting point reappears, which must then be reached by the participant. The cursor is not always visible during the movement. Near the target (approximately three-quarters of the way along the ideal trajectory connecting the starting point and the target) the cursor disappears, preventing participants from correcting the final position of the cursor relative the target. Visual feedback of the final hand position is briefly provided at the end of each trial through a color code, to encourage the exploration of the participants' motor strategy: the target becomes green if it was correctly reached (hit, i.e. a partial overlap between cursor and target is sufficient), otherwise orange (near hit - no more than 1.0 cm away from the target) or red (not hit, otherwise).

D. Perturbed visual feedback

When visual perturbation is disabled, the ratio between the hand position on the active area of the digitizer and the cursor position on the screen is 1:1. When visual feedback distortion is applied, non-linear scaling is introduced to create a mismatch.

For the purposes of this study, a purely visual feedback distortion was designed, characterized by an EA through a power function (EAPOW), applied to cursor position errors relative to the ideal trajectory, exclusively along the direction orthogonal to it. By ideal trajectory it is meant the imaginary straight line connecting the starting point to the target. The choice of the power function applied to EA aims to vary the distortion effect based on the size of the error, amplifying larger errors more than smaller ones. In fact, it is a nonlinear variant of the well-known EA paradigm [4], in which deviations from the ideal, straight-line trajectory were magnified by a linear gain factor. The EAPOW perturbation was defined as follows:

$$hp_y = (A\,|\Delta h_y|)^E \cdot sign(\Delta h_y) + (A\,|\Delta h_y\,|) \cdot sign(\Delta h_y) \qquad (1)$$

where hp_y is the y-coordinate of the perturbed position of the hand, Δh_y is the (orthogonal) position error relative to the ideal trajectory, E is the exponent of the applied power ($E>0$), and A is the gain ($A>1$). A simulation of the perturbed trajectory is shown in Figure 2 (in blue, with E=2 and A=1). Note that, in order to simplify the calculations, the error Δh_y with respect to the ideal trajectory (see Figure 2, the green line) was calculated by rotating the real trajectory of the hand (in red) with respect to the positive x-axis, and therefore the error Δh_y corresponds to the y-coordinate of this rotated trajectory (in magenta). The origin of the reference system is positioned on the starting point of the virtual scenario. The perturbation is parameterized by the exponent E, which defines the nonlinear behavior, and the gain A, which modulates the effect of the exponent. Both parameters are dimensionless and can be modified to obtain the desired effect. The first term of (1) has the role of amplifying the error in a nonlinear way; the second term, instead, prevents the perturbation from becoming assistive for displacements lower than a certain threshold (A must be >1). Nonlinear EA has the advantage of selectively amplifying larger errors over smaller ones.

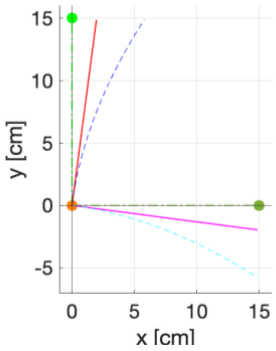

Figure 2 - EAPOW simulation with quadratic trend (E = 2, A = 1). The hand performs a rightward trajectory (red) with respect to the ideal one (light green). In this simulation the target (green circle) is placed at 90°. The perturbed trajectory is a dashed blue line. To simplify the calculations, all graphic elements are calculated by rotating the real trajectory of the hand with respect to the positive x-axis (in magenta), so that the target is placed in the x-axis (dark green) and the perturbed trajectory is in cyan.

E. Experimental protocol

The protocol consisted of four sessions in total:

1. Familiarization: no perturbation of the visual feedback was applied. The target was displayed in one of two possible directions (60, 120 deg) and at two different distances (10 and 20 cm) from the starting point, one at a time. Participants were asked to perform five repetitions for each target configuration, resulting in a total of 20 trials.

2. Baseline: no perturbation of the visual feedback was applied. The target was displayed in one of three possible directions (45, 90, 135 deg), with a single distance (15 cm) from the starting point, 15 times for each configuration (for a total of 45 trials).

3. Adaptation: perturbation of the visual feedback was applied (for the experimental group only). The target was presented in one of three possible directions (45, 90, 135 degrees), with a single distance (15 m) from the starting point, 60 times for each repetition (a total of 180 trials). The control

group had the same task, but no perturbation of the visual feedback was applied.

4. Washout: same as Baseline.

The total duration of the experiment was approximately one hour. The parameters of target direction and target distance from the starting point were uniformly distributed across the trials and set in a pseudo-random order, so that the same parameter value was never repeated for more than two consecutive trials.

F. Data analysis

Hand trajectories were preprocessed with a Savitsky-Golay filter (order 4, derivative order 0, window length 41 samples). The trajectory error was calculated as the maximum perpendicular distance between the actual hand trajectory and the straight line connecting the starting point and the target. Baseline conditions for reaching in the horizontal plane (without EA) typically approximate a straight line [11], [12], whereas adaptation to a visual feedback perturbation typically exhibit an exponential trend over trials. For this reason, the time series of the trial-by-trial error for the Adaptation session was fitted using nonlinear Nelder-Mead least-squares regression:

$$E_i = A\, e^{(-i/B)} + C \qquad (1)$$

where E_i was the trajectory error for the trial i within the Adaptation phase, A is the amount of learning (the change of the trajectory errors due to training), B is the time constant indicating the number of trials for the error to decrease up to 67% of the way to asymptote, and C is the asymptotic (steady-state) error value.

For all experimental conditions, we first assessed normality (Anderson-Darling test). If normality was not ruled out for trajectory errors, we ran a repeated measures 2-way ANOVA with time (baseline vs washout or initial adaptation vs late adaptation) and experimental condition (experimental and control groups) as within- and between-participant factors. Post-hoc analyses were conducted using pairwise t-test, with a Bonferroni-Holm correction.

Finally, pairwise t-test compared the amount and rate of learning (i.e. model parameters A and B respectively from the model fit to individual participant's data obtained in the Adaptation phase), and the amount of steady-state error (model parameter C during Adaptation).

III. Results

By comparing the average value of the trajectory error (i.e. the maximum perpendicular distance [cm]) among sessions (B: Baseline, iA: initial Adaptation - first 45 trials, lA: late Adaptation - last 45 trials, W: Washout) in both experimental and control groups, we found a significant decrease in the trajectory error in the experimental group only, as shown in Figure 3.

We tested for differences in trajectory error in Baseline and Washout sessions. The errors detected in both groups during Baseline (in which the visual perturbation is not active) are justified by the fact that the arm movement is completely occluded during the experiment and also the cursor is not always visible during the movement (see Methods). We observed a significant difference in trajectory error between

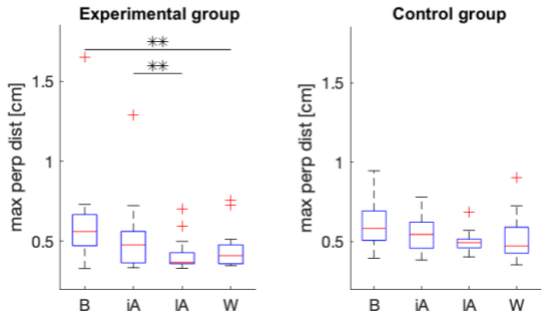

Figure 3 - Comparison of the average value of the trajectory error (i.e. the maximum perpendicular distance [cm]) across the sessions (B: Baseline, iA: initial Adaptation - first 45 trials, lA: late Adaptation - last 45 trials, W: Washout) in both experimental and control groups.

groups ($F(3,26) = 16.867$; $p=0.0012$). Post-hoc analyses (Bonferroni-Holm) revealed a significant decrease in the trajectory error during the Washout session with respect to the Baseline in the experimental group only ($p=0.0128$).

We tested for differences in trajectory error in initial and late Adaptation session. We observed a significant difference in trajectory error between groups ($F(3,26)= 9.233$; $p=0.0095$). Post-hoc analyses (Bonferroni-Holm) revealed a significant

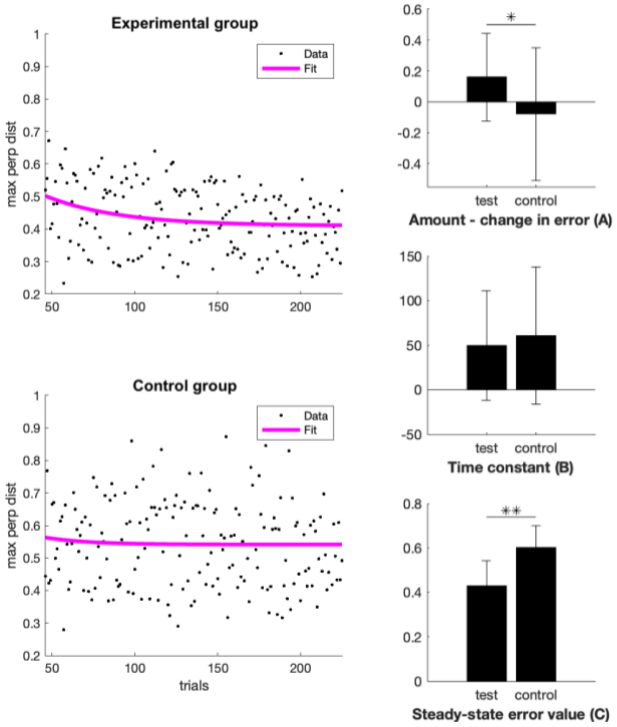

Figure 4 - Group results of the curve fitting for all subjects in the experimental and control groups, according to (1). On the left: representative trajectory errors and learning curves for typical subjects in each group during the Adaptation session (trials from 46 to 225), which was fit to exponential curves (magenta lines). On the right: the amount of learning (parameter A, top), time constant of error decay during learning (parameter B, middle) and steady state value (parameter C, bottom) are shown. Error bars indicate 95% confidence intervals. Horizontal lines indicate significant differences between groups. Single asterisks indicate a significant difference, double asterisks a highly significant difference.

decrease in the trajectory error during the late Adaptation session with respect to the initial Adaptation session in the experimental group only (p=0.0128).

Error augmentation significantly influenced the amount of learning (parameter A in (1); t-test, p=0.0251), and the asymptotic level of performance error (parameter C in (1); t-test, p=0.001) during the Adaptation session (trials from 46 to 225) in the experimental group only, as shown in Figure 4.

IV. Conclusion

This paper reports on a preliminary investigation to evaluate the effect of nonlinear error augmentation on motor learning in reaching tasks on the horizontal plane. The experimental group, which experienced this visual feedback during the Adaptation session, showed greater learning and lower steady-state error, indicating more effective learning compared to the control group, which also exhibited a higher (though not significant) time constant.

Although the manipulation of visual feedback is not new to the literature [13], [14], [15], this nonlinear form of visual feedback extends the capabilities of classical error augmentation to promote motor learning [4]. This is a form of implicit learning, which occurs unconsciously and automatically. This has interesting implications in neuromotor rehabilitation, as implicit learning may be more suited for post-stroke patients, since it minimizes the cognitive load. In addition, these patients often have a compromised nervous system, which makes them less sensitive to error evaluation. Accordingly, amplified errors may become more noticeable, increasing the likelihood of learning from them. Compared to classical (linear) EA which amplifies errors homogeneously with a constant gain, a nonlinear EA function can selectively amplify the larger errors, helping the patient to focus more on the larger errors at the beginning, gradually moving on to the smaller ones.

Power-based EA belongs to the class of training techniques that are thought to be effective in encouraging neuromotor rehabilitation in cases that require motor (re-)learning, such as in neurorehabilitation after stroke [16]. The reported results support and extend recent works showing that error-enhancing forces are more beneficial than error-reducing forces in restoring reaching performance after stroke [7]. Although not all types of augmented feedback have been shown to be therapeutically useful after stroke [17], the preliminary results presented here for healthy participants suggest that this training approach may be effective in facilitating motor learning in a variety of contexts, such as sports, remote-device use, and rehabilitation.

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