Accelerating Motor Adaptation by Virtual Reality Based Modulation of Error Memories

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Abstract—**When exposed to visual perturbations, the motor system rapidly learns to reduce errors through adaptation of future motor commands. However, in cerebellar and stroke patients with proprioceptive impairments, motor adaptation rates are significantly slower. A recent study suggests that adaptation rates may be modulated by the stability of perturbations and the history of errors. We hypothesize that reducing the visual magnitude of directional error in a reaching task should increase the speed of motor adaptation to a perturbation. We developed a method for the modulation of error magnitudes in virtual reality (VR), and we conducted two experiments exploring its effects on adaptation. 34 healthy subjects used a chair-mounted arm support to perform reaching movements towards a target while learning to compensate for visuomotor rotations. We observed that diminishing the visually perceived variability of visual directional error through VR accelerates adaptation. This effect showed persistence into trials when virtual error reduction was no longer present confirming the modulatory role of error memory. These findings support the hypothesis that the brain may keep a history of recent errors and differentially adjusts learning rates relative to the frequency of occurrence of errors. We predict that exposure to a distribution of visual motor errors with low variability and centered around task-relevant error values accelerates motor adaptation in patients with cerebellar degeneration.**

Keywords—*Motor adaptation, error feedback, memory of errors, rehabilitation.*

I. INTRODUCTION

The motor system has the capacity to adapt to sensory perturbations, which allows a reduction of error in subsequent movements. However, motor adaptations seem to be transient [1]. After learning to adjust to a specific perturbation, exposure to a set of error-clamp trials (without error feedback) will produce the progressive decay of adaptation. Previous studies have interpreted this de-adaptation as the result of a "forgetting" mechanism [2]. Others have proposed that a component of motor memory might be de-instantiated as soon as an individual detects a change in the task during error-clamp trials, thus producing partial de-adaptation or motor forgetting [3].

Slow and fast motor learning mechanisms have been suggested to play a role in motor adaptation and motor forgetting [4], [5]. The slow learning mechanism, probably controlled by primary motor areas, may be driven by reward and seems to be less susceptible to forgetting [2], [6], [7].

The fast-learning/fast-forgetting adaptation process may be insensitive to reward and has been attributed to cerebellar functions [6], [8]. For instance, complex spikes generated by the Purkinje neurons of the cerebellum occur early in a reaching task and appear to contribute to the encoding of the absolute direction and destination of an arm movement, thus computing the relative endpoint errors of the action [9]. We have shown in theoretical studies of the cerebellum that these errors are the result of a negative feedback loop that balances the relative contributions of predefined reactive and acquired adaptive motor control systems [10], [11]. The intermediate zone of the cerebellar hemisphere may play an important role in this feedback process, allowing the monitoring of prediction errors and optimizing future performance [12]. A subject who is missing this internal feedback process (e.g., cerebellar patients) would not be able to compensate for sensory feedback, thus resulting in dysmetric movements and slow motor adaptation [13], [14]. Consistent with this interpretation, Herzfeld and colleagues conduced a behavioral study with healthy subjects demonstrating that motor adaptation may be strongly driven by sensory feedback and that the brain may keep a history of visual errors to compensate for specific perturbations, instead of recalling the corresponding motor commands [15].

Following this line of research, we hypothesize that the gain of motor learning will correspond to the frequency at which errors occur. Therefore, by altering the distribution of visual error feedback in a virtual reality environment, it may be possible to influence the memory of errors and modulate learning/forgetting rates in a motor adaptation task. Identifying the mechanism to accelerate motor adaptation could be especially beneficial for patients affected by cerebellar ataxia and dysmetria. In this article, we present two experiments. Both of them follow a motor adaptation reaching paradigm using visuomotor rotations. In the first experiment, we explore the effect of task consistency on learning to adapt to visual perturbation. In the second experiment, we describe a methodology for the manipulation of feedback error magnitudes, and we investigate the effects on error sensitivity. Results from these experiments show that a memory of sensory errors may be altered by the manipulation of visual error variability, and that this memory subsequently regulates motor adaptation.
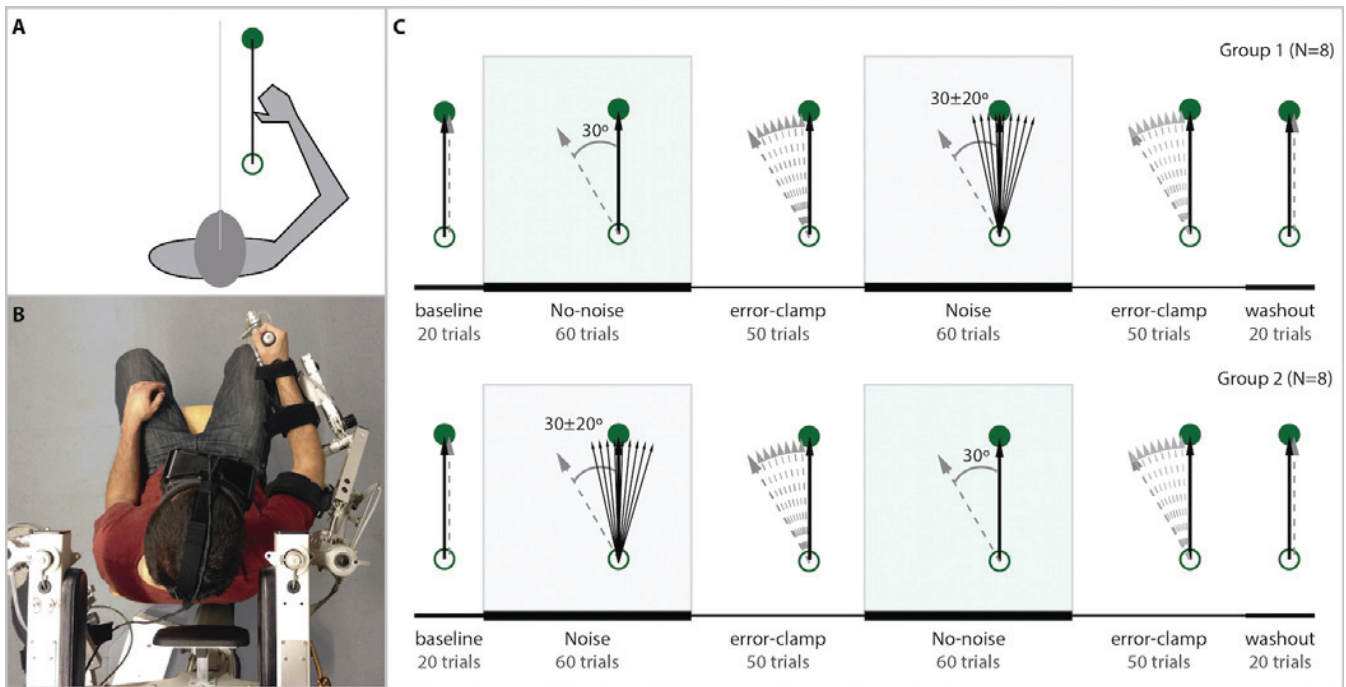
Fig. 1. Virtual reality reaching task with non-specific error feedback manipulation (Experiment 1): A. The user controls and observes the movements of a virtual limb. B. The participant's right arm was supported against gravity (between 45 and 75° abduction angle) using a light-weight, chair-mounted arm support (Armeo, Hocoma AG, Zurich, CH). The Head-Mounted Display (HMD; Oculus Rift DK2, Oculus VR, Invine, CA) occluded the vision of the real arm and provided the visual stimulation. C. Experimental Paradigm: Gray arrows indicate the direction of the executed movement, and black arrows indicate the direction of the visual movement. See text for further explanation.

II. METHODS

A. Equipment

In order to track the movements of the participant's right arm, we used the Armeo Spring (Hocoma AG, Zurich, CH), an exoskeleton for the upper extremities which provides anti-gravity support and allows for real-time recording of arm movements at shoulder and elbow joints. Prior to the experiment, the exoskeleton was adjusted according to the participant's body size and the length of the right arm. Subjects sat on a chair while wearing a virtual reality head-mounted display Oculus Rift DK2 (Oculus VR, Irvine, CA, US), which provides 360° head tracking and 3D stereoscopic vision with a resolution of 960x1080 pixels per eye and at 75Hz refresh rate (Fig. 1B).

B. Experimental Paradigm

1) Experiment 1. Non-specific error feedback manipulation: In this experiment we explored the effect of directional visuomotor noise on motor adaptation and de-adaptation. Sixteen right-handed subjects (age 23.29 ± 4.91, 9 females) with no motor or visual impairments participated in this experiment. All subjects gave informed consent and were randomly assigned to one of the two experimental groups (described below). Prior to the experiment, subjects were instructed to perform planar linear hand trajectories towards a target in VR while observing the movement of an avatar's arm (Fig. 1A). The participants were asked to reach the target being as fast and as accurate as possible. Hand movements in the virtual world were confined to the horizontal

plane. In the beginning of each trial, participants had to locate the virtual analog of their hand over a start button. After the subject had maintained the avatar's right hand over the start position during a variable time interval of 1 ± 0.5 ms, the start button disappeared, and a target (5 cm diameter) appeared 20 cm in front of the start position. We discouraged anticipatory initiation of arm movements by canceling a trial whenever the hand left the start button before target onset. Canceled trials were repeated, thus all subjects completed the same amount of valid trials. Trial time limits (1.75 s) were indicated by continuous changes in the color saturation of the target, which ranged from green to black. At the end of the trial the target and the virtual hand disappeared, and subjects had to return to the start position in the absence of visual feedback of the avatar's arm movements. When the hand was close enough to the start position, we showed the virtual arm again. This method prevented learning from return movements. Throughout the experiment, in addition to visual feedback of arm movements, subjects heard a pleasant tone if the virtual hand hit the target, and an unpleasant tone when they failed to hit it.

Subjects performed 320 reaches grouped into 6 blocks (Fig. 1C): 20 baseline trials, 60 trials with a fixed clockwise visuomotor rotation of 30° (no-noise condition), 50 error-clamp (EC) trials, 60 trials in which we introduced random uniform clockwise visuomotor rotations of $30 \pm 20°$ (noise condition), 50 error-clamp (EC) trials, and 20 washout trials. Group 2 experienced no-noise and noise conditions in reversed order. During EC trials the direction of the virtual hand was artificially clamped to the center of the
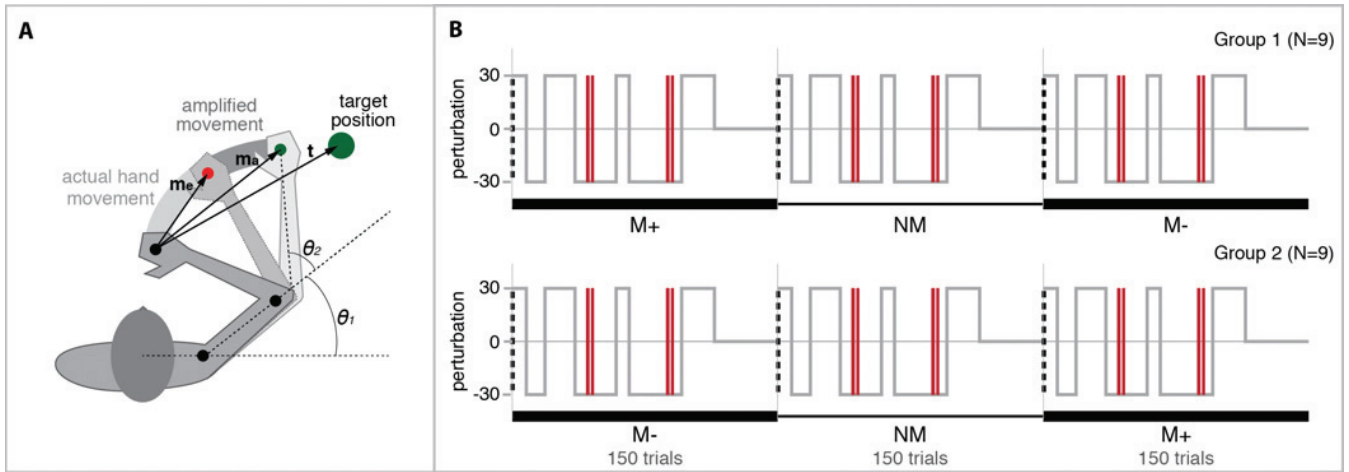
Fig. 2. Experiment 2: A. Methodology for the amplification of goal-oriented reaching movements in VR. The trajectory of the movement executed (light gray shadow) is amplified in accuracy (dark gray shadow) towards the target position, deriving from the start position and current position of the actual movement. The virtual arm is divided in two segments: the arm (l1) and forearm (l2). B. The experimental protocol is divided in three blocks, one per condition. During the positive mapping condition (M+) participants experienced reduced visual error magnitudes. During the neutral mapping condition (NM) visual error magnitudes were not altered. During the negative mapping condition (M-) participants experienced augmented visual error magnitudes. In addition, visuomotor rotation of the virtual trajectories changed direction with 0.1 probability. Red vertical lines indicate pairs of consecutive error-clamp trials. See text for further explanation.

target, and the extent of the virtual movement matched the actual movement executed. After the experiment, we briefly interviewed the participant to control for the unawareness of EC trials.

2) Experiment 2. Specific error feedback manipulation: In the second experiment, we studied whether manipulating the history of visual errors may modulate error sensitivity. Eighteen right-handed volunteers with no neurological impairments (age 29.77±5.90, 10 females) participated in a visuomotor rotation experiment. Subjects were instructed to perform the same reaching task described in experiment 1. However, in this experiment, participants performed 450 reaches grouped into 3 blocks. Each of these blocks corresponded to one of the three conditions characterized by positive (M+), neutral (NM), and negative (M-) visuomotor mapping (Fig 2A). Group 2 experienced these conditions in reversed order. In the M+ condition we diminished visual directional errors, therefore increasing the probability of exposure small error magnitudes. In the M- condition, we augmented visual directional errors, thus exposing the subject to larger and more variable errors. In the NM condition, we did not alter the magnitude of the error feedback.

In order to provide these different conditions, we modulated the visuomotor feedback by augmenting/reducing the accuracy of the movement of the virtual limb in a goal-oriented manner (Fig. 2B). At each frame, we projected the vector of the actual hand movement ($\mathbf{m_e}$) onto the target direction ($\mathbf{t}$), obtaining the vector $\mathbf{m_p}$. Finally we determined the amount of augmentation to be applied at the current time-frame by:

$$\mathbf{m_a} = \alpha \mathbf{m_p} + (1 - \alpha)\mathbf{m_e} \qquad (1)$$

$$\text{where } \alpha = \frac{|\mathbf{m_p}|}{|\mathbf{t}|} \cdot H$$

The constant help factor H was set to 0.8, 0, or -0.8 in the M+, NM, and M- condition respectively. After computing the movement amplification vector $\mathbf{m_a}$ and extracting its corresponding hand position, we recursively applied inverse kinematics technique (Cyclic Coordinate Descent) for estimating the angles of shoulder (θ_s) and elbow joints (θ_e) [16]. The length of the segments of the avatar's upper limbs were l1=0.29 cm, and l2=0.35 cm (Fig. 2B). Notice that l2 denotes the distance from elbow to fingers and therefore exceeds the length of the forearm.

We generated a sequence of visuomotor rotations of ±30°, where the direction of the visual perturbations changed with a probability of 0.1. This reaching paradigm allowed for measuring learning on a trial-by-trial basis, within a slowly switching environment [15]. In addition, every 15 trials we introduced a pair of error-clamp probe trials to estimate the adaptation decay ratio of each subject. Between blocks, participants were able to rest for 30 seconds. During these resting periods, the virtual limb was not shown. At the end of the experiment we briefly interviewed the participants to control for the unawareness of error-clamp trials.

C. Measurements and Data Analysis

We used the real hand position at target extent as a measure of hand direction. We estimated directional error (ϵ) at trial t by computing the angle between the ideal and the executed movement vectors. Thus, motor adaptation is given by:

$$x_t = |\epsilon_{t-1}| - |\epsilon_t| \qquad (2)$$

We estimated sensitivity to error for each subject taking into account consecutive trial pairs with equal visuomotor perturbation. Sensitivity to error was defined by the ratio of the executed error in previous trial that has been corrected
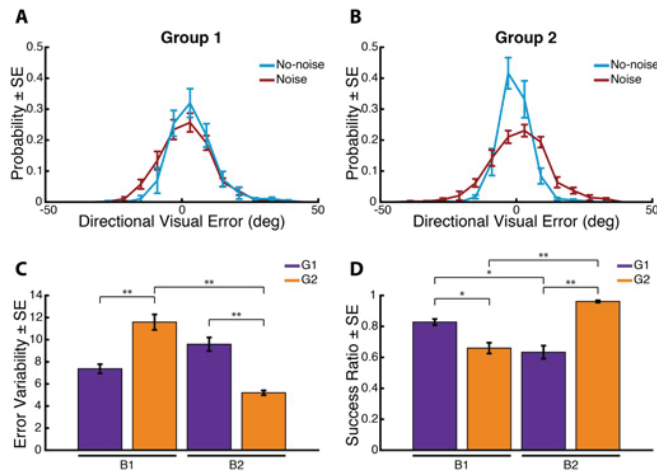
Fig. 3. Visual noise modulates motor performance. The distribution of visual errors (A-B), the variability of directional movements (C), and success ratios (D), during block 1 (B1) and block 2 (B2) for group 1 (G1) and group 2 (G2).
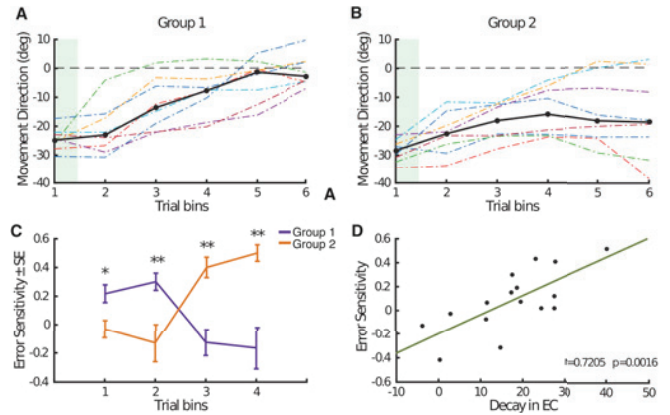

Fig. 4. Visual noise modulates motor adaptation. A-B. Averaged decay of motor adaptation during the first block of error-clamp trials for group 1 (G1) and group 2 (G2), binned by 10 trials. Green shaded areas indicate trial bins from the previous block. C. Mean error sensitivity during noise and no-noise blocks by group, binned by 30 trials. D. Correlation between error sensitivity and decay at the first EC block.

in the current trial divided by the magnitude of visual error v that was shown at the previous trial.

$$\eta = \frac{x_t - \alpha x_t}{|v_{t-1}|} \qquad (3)$$

where alpha refers to a decay ratio. Therefore, in order to compute the error sensitivity we first found the mean decay ratio of each participant and block:

$$\alpha = \frac{x_t}{x_{t-1}} \qquad (4)$$

Since we did not include interleaved error-clamp probe trials in Experiment 1, we excluded the decay term of Eq.3 for the estimation of error sensitivity in the first experiment data analysis.

For the statistical analysis we used Wilcoxon signed-rank test to quantify differences within-subjects across conditions, and the Wilcoxon rank-sum test to identify differences between groups. For multiple comparisons between conditions we performed a Kurskal-Wallis test.

III. RESULTS

A. Experiment 1: Visuomotor noise hampers adaptation and de-adaptation

The introduction of visual noise reduced the probability of experiencing small errors (Fig. 3A-B). This difference was more prominent for Group 2, indicating an order effect probably caused by learning. When we analyzed the performance, we detected that in the Noise condition the variability of the executed error increased ($p<0.01$) (Fig. 3C) and success ratios dropped significantly ($p<0.01$) (Fig. 3D). Again we noticed an order effect of learning, which magnified these differences in Group 2.

Analysis of decay in EC trials revealed differences between groups (Fig. 4A-B). After experiencing noise in visuomotor rotations decay of adaptation was attenuated

($p<0.05$). This difference disappeared in the second block of EC trials ($p>0.1$). Interestingly, sensitivity to error followed a similar trend. When compared to control (no-noise condition), noisy visuomotor rotations hampered adaptation by lowering sensitivity to error (Fig. 4C) ($p<0.01$). Notice that the modulation of error sensitivity in this experiment did not take into account decay rates due to limitations in the experimental design, which did not include interleaved pairs of error-clamp trials. In addition, we found that effects of noise on adaptation decay and error sensitivity during the first half of the experiment were significantly correlated ($r=0.72$, $p<0.01$, Pearson correlation coefficient), showing that those subjects who where more sensitive to error decayed faster in the absence of visual error, and participants with lower sensitivity to error exhibited higher retention of learned adaptation in the absence of visual error (Fig. 4D).

Overall, results of Experiment 1 revealed that noisy visual feedback of directional errors influenced adaptation and retention of motor adaptation in a reaching task. These results are consistent with previous experiments [15], [17]. However, visual noise not only generated an unstable environment but also altered the distribution of visual errors. In order to explore this ambiguity we designed a second experiment in which we exposed the subjects to a fixed paradigm of slowly switching visuomotor rotations (i.e., stable environment) while only modulating the magnitudes of the perceived errors.

B. Experiment 2: The distribution of perceived errors modulates adaptation

In order to validate the method used for altering the distribution of errors, we first computed within-subject normalized probabilities of exposure to directional errors. Figure 5A depicts the mean frequency of occurrence of specific directional errors for each condition. During the M+ condition, the probability of being exposed to small errors ($\pm20°$) increased, and the M- condition produced the opposite effect. Within-subject comparison of performance ratios
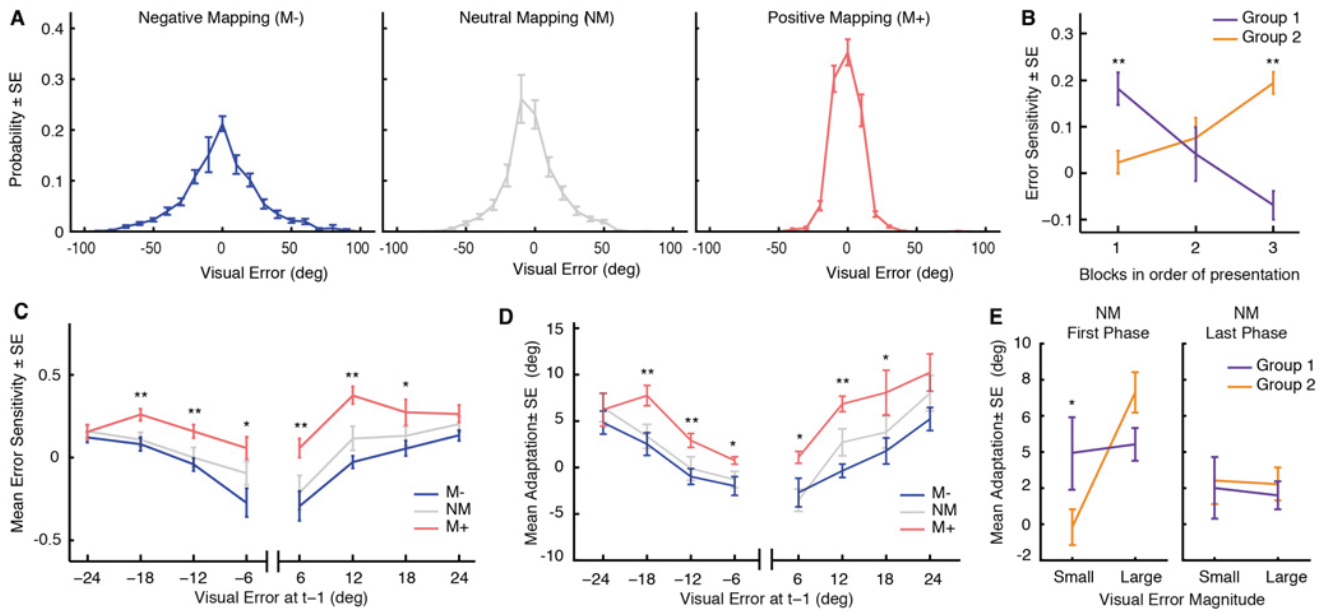
Fig. 5. History of errors modulates adaptation. A. Distribution of visual directional errors experienced by subjects across conditions. B. Mean error sensitivity for all subjects through blocks, in order of presentation for Group 1 and Group 2. C. Mean sensitivity to error for all subjects relative to the directional error observed at the preceding trial. D. Mean adaptation relative to the directional error observed at the preceding trial. D. Mean adaptation by group during the first and the second half of the NM block for small errors ($12 \pm 6°$) and large errors ($24 \pm 6°$).

in condition M+ and M- revealed significant differences for Group 2 (p<0.01), but not for Group 1 (p>0.25). As we observed in Experiment 1, this order effect may be derived from learning over the course of the experiment. Analysis of the variability of the executed directional movements indicated no differences across conditions, thus validating that although we altered the distribution of perceived visual errors, the distribution of executed motor commands remained similar (p>0.7).

We estimated the averaged sensitivity to error for each subject and each condition. Between-subjects analysis showed asymmetric patterns of error sensitivity changes across experimental blocks (Fig 5B). When frequently exposed to small visual errors (M+), subjects increased their mean sensitivity to error (p<0.01). These differences were also significant between groups (p<0.01) and conditions (p<0.01). Interestingly, this divergence was more prominent for those errors that had a greater change in probability across conditions (p<0.05) (Fig. 5C). In order to validate that these results were not an artifact of our methods, we performed a within-subjects analysis of adaptation (see Eq. 2). Notice that for this analysis we did not take into account the visual feedback and neither the decay factor α. We found significant differences in the mean adaptation across conditions (p<0.01), revealing faster adaptation to small error magnitudes during the M+ condition in comparison to the M- condition (p<0.05) (Fig. 5D). In order to explore the retention of this effect, we measured adaptation rates to small and large errors during the NM block. Surprisingly, the effect was still present during the first half of the NM block (p<0.05), when there was no manipulation of the visual feedback (Fig. 5E). These results suggest that there is an error memory that keeps track of the changes in error

magnitude that were induced though the visually perceived error. This memory persisted also when the visually perceived error was no longer present. These findings validate our method for speeding up adaptation though visuomotor manipulations in VR. In addition, they suggest that the brain may keep a history of sensory errors that determines how relevant is a specific error given how frequently it recently occurred [15]. The higher the frequency of occurrence of a specific error the more an individual may be willing to learn from it.

IV. DISCUSSION AND CONCLUSIONS

A. Recent history of visual errors regulates adaptation

In this study we explore a methodology for the modulation of learning from visual errors in a motor adaptation task. In Experiment 1 we showed that the persistence of visuomotor rotations regulate adaptation. In a highly consistent environment the sensitivity to error increased. Contrarily, in a highly inconsistent environment in which we randomly changed the direction and magnitude of visual perturbations, the sensitivity to error decreased. Decay of motor adaptation in the absence of error were attenuated in a noisy feedback context in comparison to a non-noisy feedback context. These results are consistent with previously reported data from healthy subjects [18], [15], [17]. However, we observed that the decay slowed down for all subjects during the second block of EC trials and the differences between-groups disappeared. This effect may be due to a higher contribution of the slow learning mechanism at asymptotic levels of learning [7].

In Experiment 2, we explored the mechanisms regulating the sensitivity to error. We developed a method for altering

the magnitude of directional errors during goal-oriented reaching while preserving the stability of the environment. Results showed that participants adjusted the sensitivity to errors depending on the frequency of exposure to specific error values. More interestingly, these adjustments were retained even when the visual feedback was accurate relative to the real motor error. These observations support the hypothesis that the motor system may have access to a memory of errors that determines the relevance of each specific error for the optimization of future performance. Thus, the gain of motor learning will be modulated by sensory errors relative to their frequency of occurrence. Our results show that this memory of sensory errors can be directly manipulated using VR, consequently boosting learning in a motor adaptation task.

Previous studies have suggested that a proportional augmentation of error can accelerate adaptation [19], [20]. However, many of these studies used externally applied forces to alter motor commands whereas we only manipulated visual feedback. Wei et al. compared the effects of different methods for the augmentation of visual error on motor adaptation in the absence of force field perturbations [20]. Results from this study showed that providing visual feedback of movement trajectories rotated by an additional (constant) offset angle produced an increase in adaptation rates. However, when visual errors were amplified with a gain of 3.1, adaptation rates dropped. Although they did not take visual error magnitudes into account for the quantification of learning, their main findings seem to be consistent with our results, thus suggesting that an effective method to accelerate adaptation may be to provide a distribution of visual errors with low variability and centered in task-relevant error values.

B. Implications for Rehabilitation

In a previous study, we showed that reducing visual error during motor training may be an effective strategy for counteracting learned non-use in chronic stroke patients [21]. Here we propose that this method for modulating goal-oriented reaching movements may be suitable to speed-up motor adaptation as well. Since we have shown this principle only in healthy subjects without visual or motor impairments, its actual efficacy for motor rehabilitation remains to be elucidated. For instance, patients with cerebellar ataxia show an impaired ability to correct for abrupt perturbations, however they show a lesser difficulty of learning to compensate for the same perturbations when they are introduced gradually [22]. This difference may be caused by the different distribution of visual errors between conditions. While for the abrupt perturbations the visual error may be more variable, in the gradual condition the patients were repetitively exposed to small errors with low variability, thus increasing sensitivity to task-relevant errors. The hypothesis of a memory of errors could also explain why hemiparetic stroke patients with impaired proprioception, who demonstrate greater final hand position variability, also show a decreased ability to adapt for perturbations [14]. Interestingly, in this type of patients, slow adaptation is also present when using the non-paretic limb to compensate

for a perturbation. If a memory of errors builds up from visual feedback, one could expect that this information is not lateralized and therefore generalizes to any effector. On these basis, we could speculate that bimanual training could speed-up motor adaptation in hemiparetic patients. Contrarily, unimanual training (e.g. constraint-induced movement therapy) would augment the variability of perceived visual errors and may decrease the sensitivity to error. Future work will address this issues and quantify the impact of this method as a novel rehabilitation paradigm for the treatment of patients with cerebellar dysfunction.

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