Haptically Enhanced Motor Variability Shows Contrary Effects on Transfer of Learning

MSc Thesis

W. Arink

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by

W. Arink

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Thesis committee:	Dr. ir. N. W. M. Beckers,	TU Delft, supervisor
	Dr. ing. L. Marchal-Crespo,	TU Delft, supervisor
	Prof. dr. ir. D. A. Abbink,	TU Delft, chair
	Dr. ir. A. Seth,	TU Delft, examiner

TU Delft

Preface

Dear reader, welcome to my master's thesis. This work concludes my masters of Mechanical Engineering, track BioMechanical Design, specialization Haptic Interfaces. This thesis additionally concludes more than 7 years of studying at the TU Delft. This report includes a scientific paper, in which I have condensed 8 months of work into 12 pages of text and figures. This paper is accompanied by several appendices that elaborate on the data or give additional information.

I have enjoyed working on this project a lot, thanks to many people. I first want to thank my supervisors Niek and Laura, who have supported me throughout this project. With your guidance I was able to find a topic that was really interesting to me. You really helped and motivated me to push this research to a higher level. You were also always very supportive in difficult times, which I appreciated a lot. Next, I want to thank David, first for being the chair of my thesis committee, but mostly for being an inspiration to dive into the field of human-robot interaction. You have helped me to find a way in combining my interest in human behaviour with mechanical engineering. I also want to thank Özhan, for all his help in setting up the pendulum game.

I would also like to thank some people on a personal note. First, I would like to thank my parents for their enthusiasm and support, it really gave me confidence during this project. Second, I want to thank Thomas for all our relaxing coffee breaks. It was nice to have a friend close by to ventilate difficulties of the thesis or just for an enjoyable distraction. I also like to thank my girlfriend Heleen for her unconditional support throughout this process. Her listening ear and motivational words kept me optimistic in going forward.

Last, I'd like to thank you, reader, for taking the time to read my work.

W. Arink
Delft, March 2022

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Scientific Paper

Haptically Enhanced Motor Variability Shows Contrary Effects on Transfer of Learning

Wouter Arink, Laura Marchal-Crespo, Niek Beckers

Abstract—**In order to improve skill acquisition and neurorehabilitation, we need to improve our understanding of human motor learning. It has been shown that innate variability of movements made by an individual when performing a motor task (motor variability) might enhance skill acquisition. Augmenting motor variability could therefore be a promising method to enhance learning. However, current methods that enhance motor variability show divergent results and need to be better understood.**

In a lab-based experiment with twenty healthy participants, we studied the effect of a new method that haptically increases participants' motor variability in learning a dynamic task, i.e., controlling a pendulum. This new method consisted of applying pseudo-random perturbation forces to the internal degree of freedom of the dynamic system (indirect haptic noise), instead of applying forces directly on the trainee's hands as previously studied. The main task consisted of swinging a virtual pendulum to hit incoming targets with the pendulum ball. To assess generalization of learning we used two transfer tasks, which consisted of altered target positions or altered task dynamics (i.e., a pendulum with shorter rod length). We evaluated the effect of the new method on learning by comparing performance gains after training to a control group who trained without perturbations. We found that the perturbations successfully increased participants' motor variability during training. Although we observed no learning benefits of training with this indirect haptic noise for the trained task compared to the control group, we observed divergent effects for transfer of learning. Participants that trained with indirect haptic noise seemed to benefit in transfer of learning to altered task dynamics but not in the task with altered target positions. Increasing motor variability by indirect haptic noise is promising for enhancing skill acquisition, specially in transfer of learning, and in tasks that incorporate complex dynamics. However, more research is needed to make indirect haptic noise a valuable tool for real life motor learning situations, e.g., in robotic neurorehabilitation.

I. Introduction

Motor learning is a process we all encounter throughout our lives. From learning how to walk as a baby, to practicing sports or music, it all (at least partly) consists of acquiring or improving certain motor skills. Skill can also be lost, e.g., after an acquired brain injury, which motivates researchers to continually try to optimise skill (re)acquisition, by challenging and investigating or even devising new theories on motor learning.

Motor variability, the variability in movements made by an individual when performing a motor task, plays an important role in motor learning, and has received renewed attention in the recent years. Motor variability arises from the redundancy of ways to perform a task, which can exist at different levels depending on the task to be learned, e.g., joint-space of the limbs, or the performed trajectory followed by the limb end-effector (e.g., the hand). Early theories considered motor variability to be a mere consequence of undesired noise from the peripheral [13, 32] or central nervous system [5]. However, experiments with songbirds suggested that motor variability might be actively regulated by the brain and facilitate learning [3, 18]. These studies investigated motor variability in songbirds using drugs [3] or by directly measuring cortical activity using electrodes implanted in the brain [18]. For obvious ethical reasons, such experiments are challenging to perform on humans. Therefore, motor variability in humans is often evaluated by certain behavioural metrics computed from, or which are a result of, their movements.

Wu et al. [36] showed that human participants' learning ability could be predicted from baseline motor variability, i.e., variability of movements before training. Since then, the role of motor variability in motor learning has been further reviewed (e.g., [6, 30]) and investigated in several different lab-based experiments [8, 11, 15–17, 20, 29, 33]. Besides Wu et al. [36], several other studies [8, 11, 29] found a benefit of increased baseline motor variability for motor learning. However, motor variability is usually measured in different ways and addressed using different terminology between studies, and those employ different tasks to be learned, making driving conclusions about its effect on motor learning challenging.

The rationale behind the potential benefit of motor variability on motor learning is still unclear. It might be the (action) exploration, an important aspect of reinforcement learning theory [34], what causes motor variability to be beneficial for motor learning [6, 29, 30, 36]. This is in line with the Schema theory [27, 28], which states that a wider spread of, for example, throwing distances in a throwing tasks, strengthen the recall and recognition of memories (Schemas) of a movement. It is, therefore, compelling to investigate if inducing motor variability during training could also benefit motor learning.

Several techniques to enhance motor variability during training have already been investigated, which showed divergent effects on motor learning. Inducing motor variability by changing obstacle locations [23] or adding intermediate targets [24] did not seem to be beneficial for learning. However, the use of haptic forces has shown more promising results. Several studies [2, 7, 14–17] have used haptic error amplification or haptic noise (i.e., random disturbance forces) during training to increase motor variability in order to promote learning. Except for Duarte and Reinkensmeyer [7], who did not find a clear benefit of haptic error amplification during training of a ballistic task (i.e., golf putting), the other studies did find a benefit of increasing motor variability by employing haptic noise or haptic error amplification, with haptic noise being superior in most cases [2, 14, 15].

Özen et al. [20] used a different haptic approach to promote motor variability, which seemed to enhance motor learning. The task consisted of hitting incoming targets with the mass of a virtual pendulum, whose dynamics were rendered by a haptic device. Participants controlled the pivot point of a virtual pendulum by moving the end-effector of the haptic device. Four different training strategies were compared. One training group experienced haptic assisting forces applied to the end-effector computed by a model predictive controller (MPC). These assisting forces allowed participants' to follow different end-effector trajectories to hit the targets, and thus, promoted their end-effector variability. Further, the MPC did not hamper the variability of the pendulum swing angle, when compared to participants in other training groups with more conventional robotic assistance (proportional-derivative control) or no assistance. Importantly, the MPC group did significantly reduce the power around the pendulum natural frequency after training, a metric suggested to be associated with learning of the task dynamics [12].

If not impeding motor variability in the experiment performed by Özen et al. [20] indeed enhanced learning, then increasing the motor variability might potentially further enhance motor learning. The dynamics of the pendulum task used by Özen et al. [20] offers the opportunity for implementing novel paradigms to enhance motor variability. Like many real-world tasks, e.g., carrying a coffee mug, the system to be controlled contains an internal degree of freedom –in the pendulum case, the swing angle. Potential benefits might arise when modulating this internal degree of freedom, e.g., by means of haptic noise.

First, because this internal degree of freedom is indirectly controlled by the participant, perturbation forces directly on the pendulum mass can not be directly counteracted by muscle co-contraction. Muscle co-contraction has been previously observed in conventional haptic noise and haptic error amplification studies (e.g., [15]) as a means to mitigate the perturbations effect on the movement. Brookes et al. [2] found that prompting participants to co-contract during training was detrimental for learning compared to participants that were not. By providing the haptic noise in the pendulum mass, participants are prompted to cope with the perturbations by actively moving the pendulum, instead of co-contracting the muscles, thereby possibly increasing the action exploration, which could further lead participants to better learn the task dynamics. Secondly, if participants do not co-contract their muscles during training, considerable energy might be saved, leading to longer training duration before muscle fatigue occurs. A third potential benefit of applying haptic noise to the internal degree of freedom, is that because the perturbations are not directly applied to the haptic interface (robot end-effector), participants might only perceive those indirectly (through the haptic rendering of the pendulum dynamics), and thus only slightly hampering the participants' experience of having control over the pendulum (i.e., participants' sense of agency [22]).

Other than agency, motivation is a psychological factor that has been shown to play an important role in motor learning. Wulf and Lewthwaite's OPTIMAL theory (Optimizing Performance Through Intrinsic Motivation and Attention for Learning) [38] has a focus on the psychological factors attention and motivation of participants, by stating that enhanced performance and skill learning can mostly be attributed to an increase in motivation and an external focus of attention. Indeed, the lack of benefit of error amplification in the work of Duarte and Reinkensmeyer [7] might be attributed to the low motivation reported by the participants during training, that was even visible during the retention trials without haptic forces. Thus, care should be put when designing haptic noise methods, so the motivation is not hampered.

Generalization of learning is important [28], because often in real life the primary goal is not merely improvement of the trained task, but a broader scope of tasks that for example vary in task dynamics (e.g., use of different clubs in golf) or target positions (e.g., different distances to put hole). Therefore, we assessed generalization of learning in two transfer tasks, which consisted of altered task dynamics (i.e., a pendulum with shorter length) or altered target positions.

In this study, we performed a lab-based experiment with twenty healthy participants in a between-participants design with two groups, to study the effect on learning of applying perturbation forces during training on the internal degree of freedom of the system to be controlled. We analyzed the variability of the internal degree of freedom of the system and two different metrics to evaluate motor variability, i.e., the end-effector and path variability. We hypothesize that haptic noise applied to the internal degree of freedom of the system to be controlled drives participants to increase their motor variability compared to participants in a control group who trained without force perturbations. We further examined if this increased motor variability during training indeed led to learning benefits for the trained task and two different transfer tasks using short-term and long-term retention tests. We also hypothesize that the indirect haptic noise would not reduce participants' sense of agency or motivation, which we analyzed with questionnaires.

II. Methods

A. Participants

Twenty participants (nine female, two left-handed, age range of 18-26 years with standard deviation of 2.5 years) provided informed consent to participate in the study. The experiment was approved by the Delft Ethics Committee (HREC, ID: 1906). All participants were students at Delft University of Technology, Netherlands, at the moment of the experiment; one participant already received their master degree. The participants had little or no experience in similar motor learning experiments or with interacting with robots. All participants received a compensation for their time in the form of a voucher.

B. Experiment Setup

The experiment was performed using a Delta.3 robot (Force Dimension, Switzerland) as a haptic interface. Participants sat in front of a monitor with the haptic device positioned on the side of their dominant hand next to the monitor, while resting their elbow on the table (see Fig. 1A). The robot motion control and task visualization, implemented in C++ and Unity (Unity Technologies, US) respectively, were obtained from Özen et al. [20] and were customized to fit the specific requirements of the current experiment.

Participants moved the virtual pendulum's pivot point on the screen by moving the end-effector of the haptic interface (see Fig. 1A). Shifting the end-effector by $1\,\mathrm{cm}$ resulted also in a $1\,\mathrm{cm}$ movement of the pivot point (one-to-one mapping). The workspace of the end-effector was constrained to move only in the vertical x-plane (see Fig. 1B). The haptic device allowed for rendering of the task dynamics, thereby making participants feel the dynamics of the pendulum while performing the task (see section II.C).

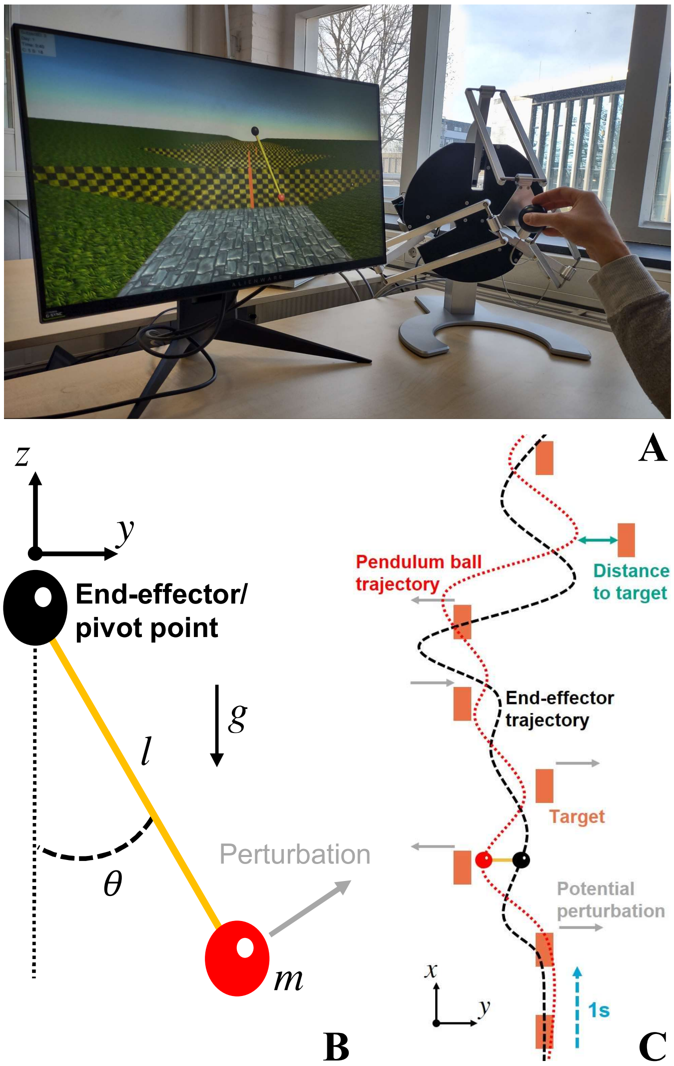

Fig. 1: **A**: Experiment setup. Participants sat in front of the monitor with the haptic device (Delta.3, Force Dimension, Switzerland) positioned next to the monitor, on the side of their dominant hand. **B**: Schematic representation of the front view (x-plane) of the pendulum. **C**: Schematic top view (z-plane) of a trial with exemplary trajectories of the ball (red dotted) and end-effector (black dashed). The gray arrows indicate the potential perturbation locations. Note that only two or three perturbations were applied during a trial and never after two consecutive targets.

C. Pendulum Dynamics

The pendulum dynamics were implemented and explained in detail by Özen et al. [19]. Here only a short description is provided for completeness. The position of the pendulum can be described by three variables: Two degrees of freedom (DoF) for the location of the pendulum pivot point (the y- and z-coordinate, see directions in Fig. 1B), as the pendulum was constrained to move in the x-plane. Additionally, the pendulum has one internal DoF describing the swing of the red ball with respect the pivot: angle θ. This swing angle is described in terms of the end-effector translation movements (y, z) by the equation of motion

$$\ddot{\theta} = -\frac{1}{l}((\ddot{z}+g)\sin\theta + \ddot{y}\cos\theta) - \frac{c}{ml^2}\dot{\theta}. \quad (1)$$

The length of the pendulum l was set to $0.05\,\mathrm{m}$, the gravitational acceleration g equal to 1/15 of earth gravity, damping coefficient c was set very low, equal to $3\times10^{-4}\,\mathrm{N\,s/rad}$ and mass m equal to $0.6\,\mathrm{kg}$. These settings were similar to the ones employed in the study by Özen et al. [20] and produced a realistic-moving but challenging-controllable pendulum.

Participants felt the dynamics of the pendulum through haptic forces rendered by the haptic device. These forces are described by the equation:

$$F_{rod} = m\left((\ddot{z}+g)\cos\theta - \ddot{y}\sin\theta + \dot{\theta}^2 l\right), \quad (2)$$

with the same variables as in Eq. (1).

D. Task Description

1) Task to be learned: The task to be learned was a target-hitting task. By moving the pivot point of the pendulum with the end-effector of the haptic device, participants indirectly controlled the red ball attached to the pendulum (see Fig. 1B) following equation 1. During the task, orange targets with different horizontal positions were coming towards the participants at a constant speed (see Fig. 1C). Participants were instructed to hit these incoming targets with the red ball as accurately as possible.

2) Target positions: A trial consisted of eight targets separated by $1\,\mathrm{s}$ each (see Fig. 1C). A period of $5\,\mathrm{s}$ without targets followed each trial after which the next trial started. Each trial started with two consecutive targets in the center of the workspace. As trials were separated by $5\,\mathrm{s}$ without targets, this prompted participants to bring the pendulum back to the center and reach a stable pendulum equilibrium, i.e., without swing, before the onset of each trial. We hereby attempted to start each trial with similar initial conditions.

The first two targets were followed by a relatively easy part with three targets varying by $30\,\mathrm{mm}$ from each other from left to right (y-direction). Targets 6, 7, and 8 were positioned to increase the task difficulty. The sixth target was positioned on the same location as the fifth target, which was challenging as the pendulum typically had considerable swing from trying to hit the previous targets. This was followed by a target which was positioned all the way on the other side at a horizontal distance of $60\,\mathrm{mm}$, followed by a last target positioned back to the center.

In order to make the task non-repetitive and thus engaging, for half of the trials the target locations were mirrored about the x-axis. The order of mirrored / non-mirrored trials was pseudo-randomized, with the same order for every participant.

3) Score: To enhance participants' motivation and provide visual feedback about their ongoing performance, after each target a score was visually provided on the virtual environment. This score was presented for $0.5\,\mathrm{s}$ in green if higher than zero and red if equal to zero. The score was based on the distance along the y-direction between the pendulum ball and the center of the target (see Fig. 1C) and calculated by Özen et al. [20]:

$$Score = 100 - 0.5 \cdot Distance, \tag{3}$$

with $Distance$ in mm. After each trial, the average score of that trial (all eight targets) was visually shown to the participants to further increase their motivation to keep training.

4) Transfer tasks: To determine how much of the learning during training generalizes to other similar tasks (i.e., the transfer of learning), we used two different transfer tasks.

The first transfer task consisted on hitting targets with the same pendulum that were located in different locations than those in the main task. This can be considered analogous to driving on a different track with the same race car. We tried to increase the difficulty of this transfer task by increasing the horizontal distance between the targets and the centerline from $30\,\mathrm{mm}$ to $35\,\mathrm{mm}$. We further changed the positioning of the targets such that it consisted of two times two consecutive targets on the same horizontal position, separated by a target all the way on the other side (at a distance of $70\,\mathrm{mm}$).

The second transfer task can be considered analogous to driving on the same track, but with a different car. For this transfer task the positioning of the targets was the same as in the main task, but we altered the pendulum dynamics by decreasing the length of the pendulum by $30\,\%$. Decreasing the length of the pendulum increases the natural frequency of the pendulum ($\omega_n = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$), which makes the pendulum swing faster. The pendulum length was not visually changed on the monitor, so participants could only notice the altered dynamics by perceiving differences in how the pendulum behaved.

E. Training Strategies

Next to a control group, that trained without any assistance or perturbation from the robot, there was an experimental group that experienced perturbation forces applied on the pendulum ball tangentially to its movement during training. Per trial, two or three perturbation forces were applied to the ball. The onset of the perturbation was always within $80\,\mathrm{ms}$ after crossing a target and lasted for $50\,\mathrm{ms}$ in order to minimize the effect on performance (i.e., participants had time to compensate for the perturbation before they crossed the next target). Because the aim of the perturbations was to increase motor variability, it would be undesirable if the participants learned how to anticipate the perturbations. Therefore, several components of the perturbations varied from trial to trial to prevent the anticipation of the perturbations. All the variations mentioned below were pseudo-randomized, such that every participant in this group trained with the same settings in the same order. The different combinations of settings appeared on mirrored and not-mirrored trials equally.

1) Force direction: The perturbations were always applied in opposite direction of the location of the next target. If a perturbation was applied after the fifth target, after which the next target was positioned on the same location (see Fig. 1C), the direction of the perturbation was towards the center. This direction was chosen because pilot experiments indicated that a perturbation outwards helped participants to hit the next target rather than driving them to explore, as the swing outwards would likely pass into a swing backwards before the sixth target was crossed. This made hitting the seventh target easier, as the applied perturbation helped with getting a swing in the correct direction. A perturbation towards the center likely had the opposite effect, therefore this direction was chosen.

2) Location: Participants experienced different combinations of perturbation locations during training. There were four combinations of perturbation locations, each consisting of two or three locations. Perturbations were never applied after two consecutive targets, to try to limit their effect on participants' sense of agency.

No perturbation was ever applied after the first target, as we did not want to interrupt participants in stabilizing the pendulum during the first two targets (see section II-D2). Also, few perturbations were applied after the sixth and none after the seventh target. Pilot experiments showed that applying perturbations at these locations were less desirable for two reasons. First, as hitting these targets was already relatively challenging, applying a perturbation before these targets would probably degrade performance and thereby motivation. Second, motor variability was already relatively high in this part of the trial.

3) Force magnitude: We also varied the magnitude of the perturbation forces. We reduced the mean magnitude of the perturbation forces across targets during a trial, as the difficulty within the course of a trial increased. The magnitudes of the perturbations after the second and third target varied from 1.1-$1.5\,\mathrm{N}$, after the fourth and fifth target from 1.0-$1.4\,\mathrm{N}$ and after the sixth target from 0.8-$0.9\,\mathrm{N}$.

4) Onset time: Last, we varied the onset time of the perturbation forces to further complicate anticipation of the perturbations. The onset time of the perturbations after the second to fifth target varied from 20-$80\,\mathrm{ms}$. The onset time of the perturbations after the sixth target varied between 20-$30\,\mathrm{ms}$. We kept this onset time relatively low to take the difficulty of the seventh target into account, i.e., to allow participants to recover from the perturbation and hit the last target.

F. Study Protocol

The experiment was designed in a between-participants fashion with two training groups within two days. Next to a control group (C) there was an experimental group (P) that trained with perturbations. A total of twenty participants (ten per group, five females and one left-handed in group C) performed the experiment. Fig. 2 shows the study protocol.

On the first day, participants first familiarized with the haptic device and pendulum dynamics with $40\,\mathrm{s}$ of moving the pendulum without targets. This was followed by four trials with targets located on the same positions as in the main task and trials two and four were mirrored (see section II-D2). When new to a task, novice learners typically show inconsistent movements and large performance variability as they try different strategies to perform the task [37]. This might contaminate results about learning differences. Baseline performance was therefore determined after this first familiarization phase in four trials that were the same as in the familiarization. Participants' subjective sense of agency and motivation was then obtained right after the first baseline through a questionnaire and next their baseline performance on the two transfer tasks was determined by four trials for each transfer task where again trials two and four were mirrored.

The baseline phase was then followed by the training phase in which participants performed three blocks of twenty trials each, between which they could rest. Each block was identical in terms of order of trials (mirrored or not-mirrored). The perturbation characteristics (i.e., force direction, location, magnitude and onset time) for group P was also identical between the three blocks. In each block, trials 3, 7, 13 and 17 were catch trials (i.e., no perturbations were applied), in order to evaluate the effect of the perturbation forces on participants' motor variability compared to trials where no perturbations were applied. After training, participants filled in the subjective sense of agency and motivation questionnaire.

To evaluate how much participants learned from training, participants performed short-term and long-term retention tests in the form of four trials of the main task and both transfer tasks. Short-term retention took place $15\,\mathrm{min}$ after training and long-term retention 1-3 days later. Participants filled in another subjective sense of agency and motivation questionnaire after the main task during long-term retention.

G. Data Processing

We used different metrics to evaluate motor variability and motor learning.

1) Motor variability metrics: To see if the perturbations affected the variability of the internal DoF of the pendulum, we analyzed participants' **swing variability** by taking the standard deviation of the pendulum angle θ for each trial.

We further focused the motor variability analysis on the point of human-robot interaction, i.e., the end-effector of the Delta.3 robot, because this is where participants' movements were recorded. Although the end-effector was constrained to move in a vertical plane, we focused our analysis only on the horizontal y-direction, because the target positions varied only along this direction.

In Fig. 3, the horizontal end-effector paths of representative trials of two participants, one per each training group, can be seen. As a first measure for the participants' motor variability, we took the standard deviation of the horizontal end-effector position of each trial. This **end-effector variability** quantifies how much of the workspace is explored during each trial. It should be noted, however, that the task already consists of inherent end-effector variability, since the targets have different horizontal positions. Also, this metric evaluates how variable a participant's movement is with respect to the workspace, but gives no information about how variable the participant's movements were from trial to trial. Therefore, to quantify how much participants explored from trial to trial over the entire training, we calculated the **path variability** of a trial by taking the standard deviation of the end-effector horizontal position around the participant's mean path. The participant's mean path was computed by taking the mean y-position of every time instant of a trial ($n = 8000$ data points per trial) over all sixty trials of the training block.

2) Performance metrics: As skill acquisition is not a straightforward concept and not directly measurable [28], we used three different metrics to evaluate motor learning.

First, the **trial score** was computed by taking the average score of the eight targets within a trial. The score per target was calculated using Eq. 3.

Next, we computed participants' **score variability** within a trial to evaluate how consistent they were at hitting all the targets. Performance variability is expected to be reduced with increased skill level [9, 20, 28].

We further evaluated if participants learned to control the pendulum dynamics by calculating how able they were at swinging the pendulum away from its natural frequency. The target positions do not follow a perfect periodic order, so in order to hit the targets accurately, participants need to make adjustments to the swing frequency and move away from its natural frequency. The **deviation from the pendulum natural frequency** was also found to correlate with performance in the study by Özen et al. [20].

To quantify this, we used a similar approach as Özen et al. [20] and Huang et al. [12]. For each trial we computed the power spectral density (PSD) of the swing angle θ and calculated the percentage of power at the pendulum natural frequency (ω_n=$0.57\,\mathrm{Hz}$). As the duration of each trial was $8\,\mathrm{s}$, the frequency resolution was $0.125\,\mathrm{Hz}$. We therefore selected the power at frequencies 0.5 and $0.625\,\mathrm{Hz}$ as the power at the natural frequency.

Data extracted from running the experiment (seven trials) with an MPC that applies forces to the end-effector (used in the study by Özen et al. [20]) to almost perfectly hit all targets, also suggested that in order to hit the targets accurately, the pendulum needs to shift away from its natural frequency, as with an average score of 96 over a maximum of 100, the average power around natural frequency was $56\,\%$.

For the second transfer task with different pendulum length, the natural frequency was ω_n=$0.69\,\mathrm{Hz}$. We then selected the power at 0.625 and $0.75\,\mathrm{Hz}$ as the power at natural frequency of the transfer task.

H. Psychological Factors

To see if the perturbations reduced participants feeling of having control over the movements of the pendulum, we assessed their **sense of agency** with three adapted questions from the questionnaire used by Piryankova et al. [22] (see Appendix A). Participants ranked the three questions on a seven-point scale from -3 to 3, with -3 corresponding to 'strongly disagree' and 3 to 'strongly agree'.

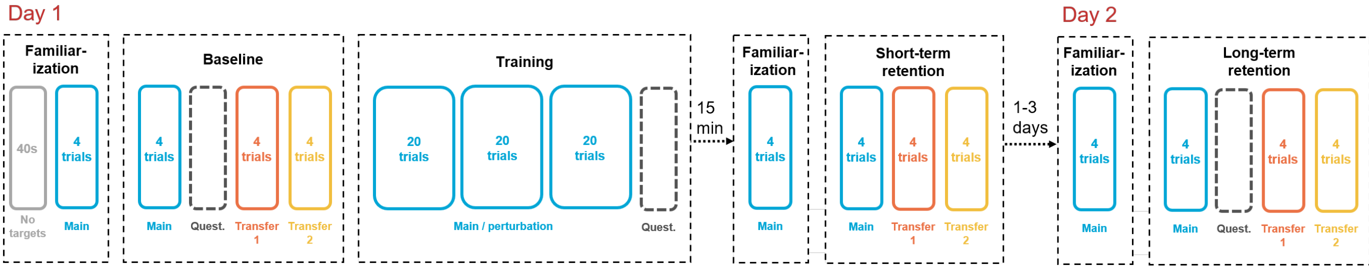

Fig. 2: Study Protocol. Participants were randomly allocated to either the control group or the experimental group that received perturbation forces during training.

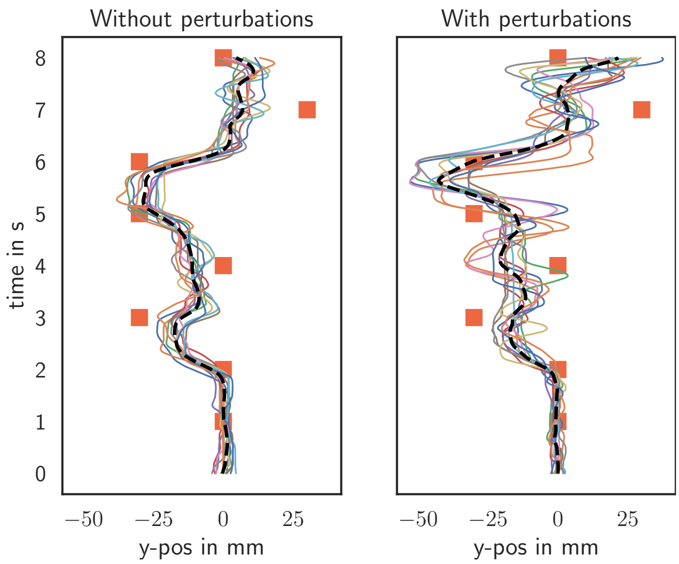

Fig. 3: Horizontal end-effector trajectories of twelve trials of a representative participant training without (left) or with (right) perturbation forces. The orange squares indicate the target locations. The dashed thick black trajectories are the mean of all twelve paths. The motor variability metrics extracted from this data were the **end-effector variability** – to evaluate how much of the workspace was 'explored' each trial– and the **path variability** – to account for the inherent variability of the task and to evaluate how much participants 'explored' from trial to trial.

Participants subjective motivation was evaluated using questions from the Intrinsic Motivation Inventory (IMI) Questionnaire [26]. During baseline, training and long-term retention (see Fig. 2), participants answered 12 questions on a scale from 1 to 7 related to their motivation, consisting of four subscales: *Interest/Enjoyment*, *Perceived Competence*, *Effort/Importance* and *Pressure/Tension*. Each subscale contained three questions (see Appendix A). The order of the questions was randomized but the same order was kept for each participant and at each questionnaire (i.e., at baseline, training and long-term retention).

I. Statistical Analysis

We performed a regression analysis on linear mixed effects (lme) models to evaluate the effect of the perturbations on motor variability and learning. The confidence intervals (CI) of the estimated coefficients were computed using bootstrapping and are reported in section III. We chose this method over more conventional methods of statistical inference for two reasons.

First, next to merely showing whether an effect was significant (if the CI of the coefficient does not include zero), coefficient estimations with CI give additional information about the size of an effect. Second, the method of bootstrapping is robust as it does not rely on assumptions like normality of the residuals or homogeneity of variance. Bootstrapping is a technique where samples are taken from the original data set (with replacement) to create new data sets, from which the estimates are calculated. By doing this many times, a robust estimation of the confidence intervals are obtained [35].

The `pymer4` package from R in python was used to conduct the statistical analysis. The models were fitted using a maximum likelihood estimation. The number of bootstrap intervals was set to ten thousand in order to ensure stable results.

1) Motor variability: To evaluate if the perturbation forces had the desired effect of increasing motor variability during training, we performed a regression analysis with the lme model:

$$DV_i = Group \times Catch + (1|Participant). \qquad (4)$$

Here, DV is the dependent variable and $i = 1, 2, 3$ is the index for the different motor variability metrics. $Group$ and $Catch$ are categorical independent variables with two levels. $Group$ refers to the two training groups (with or without perturbations) and $Catch$ refers to whether perturbations were applied in a trial ($Catch = 0$) or not ($Catch = 1$) (note that for group C no perturbation were applied in any of the trials). To account for dependency of the metrics on individual differences, $Participant$ was included as random factor.

All trials from the three training blocks were included, except for those with a path variability outside three standard deviations from a participants' mean path. This resulted in eight removed trials in both groups, where in both groups one participant had two trials removed and the rest maximum one.

2) Motor learning: To evaluate the effect of training on the performance change from baseline to short-term and long-term retention, the following lme model was employed:

$$DV_p = Group \times Time + (Time|Participant). \qquad (5)$$

The same model was used for the main task as well as both transfer tasks. Here, $p = 1, 2, 3$ refers to the different performance metrics and $Time$ is a categorical dependent variable with levels: baseline, short-term retention and long-term retention. This variable was also included as random slope to account for individual differences in learning ability. For every block, all four trials were used for the analysis.

Model (6) was also used with the motor variability metrics as dependent variable to check for baseline differences between the groups.

3) Psychological factors: To evaluate the effect of the perturbations on the psychological factors reported at the questionnaires, the following lme model was used for the regression analysis:

$$DV_{pf} = Group \times Time + (1|Participant). \qquad (6)$$

In this model, the dependent variables were the average scores per subscale from the IMI and agency questionnaires and $Time$ had factors baseline, training and long-term retention. The factor $Time$ was not included as random slope since there was only one data point per participant at each time instant.

To evaluate if there was in fact a relationship between the score and the deviation from the pendulum natural frequency, we computed the repeated-measures correlation [1] of these two variables. We used repeated-measures correlation to account for the fact that observations belong to different participants. The trials from all participants during baseline, training, short- and long-term retention were used for the computation of this correlation.

We further used Pearson's correlation metric to evaluate the relation between score improvement and participants' reported sense of agency. We used the changes in average scores from baseline to short-term retention and the changes in average sense of agency score from baseline to training for this computation. The 95% confidence interval of these correlations was again determined using bootstrapping with ten thousand samples.

III. Results

We found no significant differences between the groups for any of the motor variability or performance metrics in the main task baseline block.

There was a significant correlation between the score and the power at natural frequency in trials, $r = -0.21$ (95 % CI [-0.25, -0.16], see Appendix B.1). We also found a correlation between score improvement and changes in reported sense of agency, $r = 0.37$, although this did not reached significance (95 % CI [-0.15, 0.73], see Appendix B.2).

A. Motor Variability Metrics

Fig. 4 shows the average motor variability of the participants during training, divided by group and variability metric. For all three motor variability metrics, there was a significant effect of group, indicating that group P showed higher variability during training than the control group (see Table I). For the pendulum swing variability and horizontal end-effector variability, there was also a significant interaction between $Group$ and $Catch$, indicating that the perturbations significantly increased these two types of variability in perturbation trials compared to catch trials. The path variability did not show a significant interaction effect.

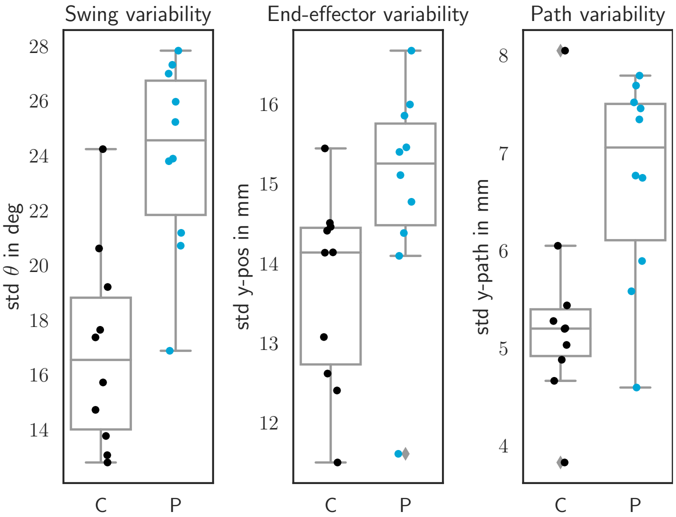

Fig. 4: Box plots of the average variabilities of the two groups during training. The difference between the groups was significant for all three metrics. The circles represent individual data.

TABLE I: Results from linear regression analysis of motor variability metrics during training. Significant effects are printed in bold.

	Swing variability		End-effector variability		Path variability	
Estimates	Coeff.	95% CI	Coeff.	95% CI	Coeff.	95% CI
Intercept	17.0	14.9, 19.2	13.7	12.9, 14.4	5.4	4.7, 6.0
Group P	**8.4**	**5.3, 11.4**	**1.5**	**0.4, 2.6**	**1.4**	**0.5, 2.3**
Catch	0.5	-1.5, 0.4	-0.02	-0.5, 0.4	-0.02	-0.4, 0.4
Group P x Catch	**-6.7**	**-8.1, -5.3**	**-1.1**	**-1.7, -0.5**	-0.1	-0.6, 0.4

B. Performance Metrics

Table II shows the regression coefficients with confidence intervals of the lme model (5). Fig. 5 shows the average scores and average power at natural frequency of the two groups in baseline, short-term and long-term retention of the main task, transfer task with altered target positions (Transfer 1) and transfer task with reduced pendulum length (Transfer 2).

1) Main task: Both groups increased their performance significantly from baseline to short-term and long-term retention for all three performance metrics, with the note that the reduction in power around the pendulum natural frequency from baseline to short-term retention was only trending towards significance (the 95% confidence interval barely included zero: [-13.9, 0.1]). There was, however, no significant interaction between $Time$ and $Group$ for both short-term and long-term retention for any of the performance metrics, suggesting there were no learning differences between the groups in the main task.

2) Transfer task 1: Similar results were found for the transfer task with altered target positions, except for the deviation from the pendulum natural frequency. For this performance metric, there was a significant interaction between $Group$ and $Time$ at both short-term and long-term retention. This interaction indicates that group C decreased the power around the pendulum natural frequency significantly more than group P.

3) Transfer task 2: Also for the transfer with reduced rod length, we found similar results as for the main task.

Again, only for the deviation from the pendulum natural frequency a significant interaction between $Group$ and $Time$ was found. However, in contrast to the first transfer task, in this transfer task group P decreased the power around the pendulum natural frequency significantly more than group C from baseline to short-term retention. This interaction, though, was not observed at long-term retention.

TABLE II: Results from linear regression analysis of performance metrics. Significant effects are printed in bold.

Main task	**Trial Score**		**Score variability**		**Power natural frequency**	
Estimates	Coeff.	95% CI	Coeff.	95% CI	Coeff.	95% CI
Intercept	71.2	67.8, 74.7	17.3	14.7, 19.8	61.8	57.4, 66.3
Group P	-2.2	-7.1, 2.7	-1.5	-5.0, 2.1	-0.4	-6.6, 5.8
STR	**8.8**	**6.1, 11.6**	**-9.1**	**-11.9, -6.3**	-6.7	-13.9, 0.1
LTR	**8.0**	**5.3, 10.6**	**-8.8**	**-11.3, -6.2**	**-11.8**	**-18.2, -5.3**
Group P x STR	-0.1	-3.9, 3.8	1.7	-2.2, 5.7	-0.1	-10.0, 9.7
Group P x LTR	0.1	-3.6, 3.9	1.5	-2.1, 5.1	5.1	-3.9, 14.1

Transfer 1 (altered targets)	**Trial score**		**Score variability**		**Power natural frequency**	
Estimates	Coeff.	95% CI	Coeff.	95% CI	Coeff.	95% CI
Intercept	66.4	63.7, 69.2	18.5	15.8, 21.1	60.8	53.4, 68.1
Group P	0.8	-3.1, 4.7	-0.3	-4.2, 3.4	0.26	-10.3, 10.6
STR	**8.6**	**6.2, 10.8**	**-6.6**	**-9.4, -3.9**	**-17.8**	**-25.1, -10.6**
LTR	**9.7**	**7.3, 12.0**	**-7.7**	**-10.2, -5.3**	**-14.8**	**-21.4, -8.2**
Group P x STR	-0.9	-4.1, 2.4	0.5	-3.4, 4.5	**12.3**	**2.0, 22.4**
Group P x LTR	-2.8	-6.2, 0.6	2.1	-1.4, 5.6	**11.0**	**1.7, 20.4**

Transfer 2 (reduced length)	**Trial score**		**Score variability**		**Power natural frequency**	
Estimates	Coeff.	95% CI	Coeff.	95% CI	Coeff.	95% CI
Intercept	75.2	72.8, 77.7	12.5	9.8, 15.1	52.7	47, 58.6
Group P	-2.3	-5.8, 1.2	2.3	-1.3, 6.1	6.6	-1.8, 14.8
STR	**3.1**	**1.0, 5.3**	**-4.3**	**-7.3, -1.3**	**-6.9**	**-13.6, -0.2**
LTR	**3.4**	**0.9, 5.8**	**-2.7**	**-5.2, -0.30**	**-12.9**	**-19.6, -6.1**
Group P x STR	-1.2	-4.3, 1.9	0.5	-3.8, 4.7	**-9.8**	**-19.1, -0.3**
Group P x LTR	-1.8	-3.8, 4.1	-0.3	-3.8, 3.1	-1.1	-10.8, 8.6

C. Psychological Factors

The statistical analysis did not reveal any significant differences between the groups in participants' reported sense of agency or motivation subscales (see Table III).

Participants' perceived sense of agency significantly increased from baseline to long-term retention. Furthermore, the interaction between $Group$ and $Time$ was trending towards significance from baseline to training, which indicated that participants' reported sense of agency might have decreased when training with perturbations compared to participants that trained without.

No significant interaction effects between $Group$ and $Time$ were found in any of the motivation subscales. There was also no significant effect of $Time$ for the subscales *Interest/Enjoyment* and *Effort/Importance*. Participants' reported *Perceived Competence*, on the other hand, significantly increased from baseline to training and long-term retention. Moreover, *Pressure/Tension* was trending towards a significant decline from baseline to training and significantly decreased from baseline to long-term retention.

IV. Discussion

We studied the effect on motor learning of a new method of haptically increasing participants' motor variability during training by applying pseudo-random perturbation forces to the internal degree of freedom of the system to be controlled (indirect haptic noise). These perturbation forces had the expected effect of increasing the movement variability of the internal degree of freedom and the end-effector and path variability. We observed no differences in reported motivation, but a reducing trend on perceived sense of agency for participants training with perturbations, although this trend did not persist on the long-term retention tests. The perturbation forces did not cause the expected effect of score improvement in the trained or transfer tasks from baseline to short-term and long-term retention compared to participants that trained without this indirect haptic noise. However, we did observe differences between groups in participants' ability to swing the pendulum away from the natural frequency, which is related to better performance. This suggests a benefit of training with indirect haptic noise for transfer of learning to altered task dynamics, but a disadvantage for transfer of learning to altered target positions.

The significant negative correlation between the score and the power at natural frequency suggests that learning this task is associated with being successful at moving the pendulum away from its natural swing frequency. These results are similar to the ones in Özen et al. [20] who used a similar task with a same natural frequency of the pendulum. The fact that this correlation was smaller than in the experiment by Özen et al. [20] ($r = -0.59$), might be explained by the fact that the positioning of the targets within a trial followed a more periodic order than in the trials of the study by Özen et al. [20]. Also, the trials in the current experiment were shorter, resulting in a lower frequency resolution, leading to a coarse-grained estimation of the true power at natural frequency.

A. Indirect Haptic Noise Increases Motor Variability

The statistical analysis showed that the perturbation forces on the ball had the desired effect of increasing motor variability. Next to the pendulum swing variability, both the end-effector and the path variability were significantly higher during training for participants that trained with perturbation forces compared to the control group. This shows that, next to applying haptic noise directly to a trainee's limbs [17, 25], applying it to the internal degree of freedom of the system to be controlled is also an adequate method for increasing their motor variability.

The fact that the interaction between $Group$ and $Catch$ was not significant for the path variability metric was expected due to the nature of this metric. This metric indicates per trial how much the path deviates from the participant's mean path. Their mean path is expected to be considerably influenced by the perturbations. Therefore, catch trials are also expected to differ more from a participant's mean path for participants training with perturbations compared to participants in the

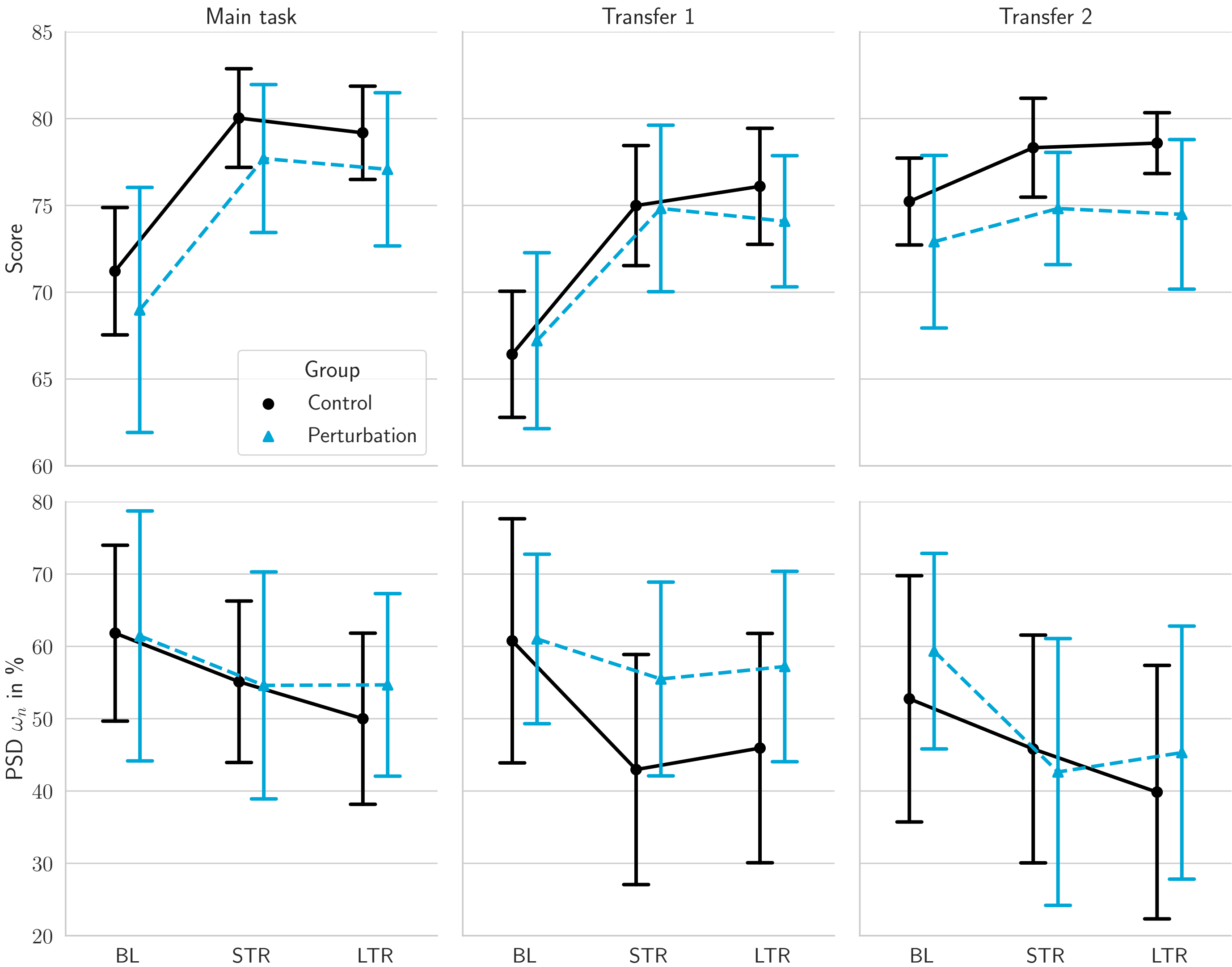

Fig. 5: Average score (top) and average power around the pendulum natural frequency (bottom) of the two groups in baseline (BL), short-term (STR) and long-term retention (LTR) of the main task, transfer task with altered target positions (Transfer 1) and transfer task with reduced pendulum length (Transfer 2). The control group is indicated by the solid black line and the perturbation group by the dashed blue line. The error bars represent one standard deviation from the mean. **Top:** Both groups increased their score significantly from baseline to short-term and long-term retention in all three tasks. We found no significant differences in score improvement between the groups. **Bottom:** The control group reduced the power around the pendulum natural frequency significantly more than the perturbation group in Transfer 1. This was the other way around in Transfer 2, although this effect faded at long-term retention.

TABLE III: Results from linear regression analysis of results from the questionnaires. Significant effects are printed in bold. We found no significant differences between the groups in any of the subscales. For sense of agency, the interaction between group and time was trending towards significance from baseline to training, indicating that the perturbations might have decreased participants sense of agency compared to participants that trained without perturbations.

Psychological factors	**Sense of Agency**		**Interest / Enjoyment**		**Perceived Competence**		**Effort / Importance**		**Pressure / Tension**	
Estimates	Coeff.	95% CI	Coeff.	95% CI	Coeff.	95% CI	Coeff.	95% CI	Coeff.	95% CI
Intercept	1.7	1.1, 2.3	5.7	5.0, 6.3	3.8	3.1, 4.5	5.4	4.6, 6.1	3.5	2.8, 4.3
Group P	-0.4	-1.1, 0.4	-0.3	-1.1, 0.5	-0.5	-1.5, 0.5	-0.03	-1.1, 1.1	-0.6	-1.7, 0.5
Training	0.3	-0.3, 0.8	-0.2	-0.6, 0.2	**1.8**	**1.1, 2.5**	0.2	-0.4, 0.7	-0.5	-1.1, 0.1
LTR	**0.6**	**0.03, 1.2**	-0.2	-0.6, 0.2	**1.5**	**0.8, 2.2**	-0.3	-0.8, 0.3	**-1.1**	**-1.8, -0.5**
Group P x Training	-0.7	-1.5, 0.1	0.03	-0.5, 0.6	-0.4	-1.3, 0.6	-0.6	-1.4, 0.2	0.3	-0.6, 1.2
Group P x LTR	0.3	-0.5, 1.1	0.0	-0.6, 0.6	0.3	-0.7, 1.2	-0.5	-1.3, 0.3	0.3	-0.6, 1.1

control group, which explains the non-significant interaction between *Group* and *Catch* for the path variability metric.

We focused only on the horizontal direction in the analysis of the variability of the end-effector and its path. It is possible that the perturbations also caused differences in motor variability in the vertical z-direction. We argue though, that this information is less important, because the target positions varied only in horizontal direction and the score was determined by only the horizontal distance to the target. Consider for analogy the findings by Wu et al. [36], who found a benefit for learning of only the task-relevant component of motor variability.

B. Indirect Haptic Noise Seems neither Beneficial nor Detrimental for Motor Learning of the Main Task.

We observed no differences between the training groups in learning of the main task (i.e., the task that was also trained). For all three performance metrics, no significant interaction between $Group$ and $Time$ was found, suggesting no benefits of increased motor variability due to the indirect haptic noise.

The lack of benefits of external perturbation forces to enhance motor variability may be explained by the extent they affect a learner's internal planning noise and execution noise. Planning noise, the component of motor variability that originates in the brain, where it might be compared with performance-related feedback (e.g., score), is thought to be beneficial for motor learning [6, 31, 33]. The brain has no direct way of assessing information about variability caused by execution noise, which originates in the peripheral nervous system [13, 32], and is therefore not thought to be beneficial for motor learning. Indeed, by fitting a state-space model to individual data, Van Der Vliet et al. [33] found that in their visuomotor adaptation task, planning noise correlated positively and execution noise negatively with adaptation rate.

This raises the question to what extent the perturbation forces affected planning noise and execution noise in the current experiment. Dhawale et al. [6] argue that task-relevant feedback about movements might restrict planning noise to increase because errors in the brain's internal model for generating movements (which might be the source of planning noise [31]) can be corrected. In the current task this task-relevant feedback was available as participants could see the movements of the pendulum. However, the perturbation forces directly altered the internal movement of the system to be controlled (i.e., the swing), which most likely influenced the task-relevant feedback used by the brain, and thereby maybe also the planning noise. The contribution of execution noise to the total motor variability is found to be substantially higher than that of planning noise [10, 33]. This could explain the lack of skill improvement due to increased planning noise, as the execution noise might counteract the benefit of increased planning noise for motor learning. It would be interesting to investigate to what extent and how the observed increase in end-effector and path variability altered the relative contributions of planning noise and execution noise to the total motor variability.

Moreover, it could be that the perturbations changed participants' coordination strategy. Pagano et al. [21] argue that in tasks with redundancy (i.e., tasks that include multiple solutions to solve them), introducing motor variability might affect the strategy by which participants try to solve the task (i.e., their coordination strategy). In the current task, the perturbations might have affected participants' strategy by which they move the pendulum in order to hit the targets with the ball. Maybe this strategy is less effective, or they switch strategy when no perturbations are applied (as in the retention tests), thereby not enhancing motor learning.

It should further be noticed that the training period was relatively short compared to real life learning of motor tasks. The training period consisted of sixty trials of merely eight seconds each. Also Marchal-Crespo et al. [17] argue that in their experiment the short training periods could have caused the lack of observed learning benefits for participants that trained with increased motor variability compared to the control group. Preferably, studying motor learning in lab-based experiments consists of much longer training periods, such as the extensive practice of six days in the study by Hasson et al. [10]. By doing this, learning differences might be found, which are not revealed in shorter training periods as is the case of the current experiment.

C. Indirect Haptic Noise Shows Contrary Effects on Transfer of Learning

We found a significant interaction between $Group$ and $Time$ in the power around natural frequency in the transfer task with altered target positions. This suggests that training with indirect haptic noise hampers generalization of learning to tasks that require a different path to be learned.

Importantly, this effect was found the other way around in the transfer task with altered task dynamics (higher pendulum natural swing frequency). As in the first transfer task, no interaction was found for the motor learning metrics *Trial Score* and *Score Variability*. However, opposite to the first transfer task, and as expected, participants training with the perturbations reduced the power around the pendulum natural frequency more from baseline to short-term retention than participants that trained without perturbation forces. Although this interaction was not significant at long-term retention, this suggests that indirect haptic noise enhances immediate generalization of learning to tasks with altered task dynamics. This is important, because dynamics in real life motor tasks change all the time. Consider carrying a coffee mug, where the dynamics of the slosh change every time you take a sip, or any outside sport, where weather conditions like wind influence how the system to be controlled (e.g., a volleyball) behaves considerably.

Maybe the benefit of indirect haptic noise in transfer with shorter pendulum length can be explained by participants being familiar with unexpected faster movements of the pendulum. Shortening the pendulum increased its natural frequency, which might be experienced similar to sudden increases of the pendulum angle due to the perturbation forces during training. This is in line with Henry's Specificity hypothesis, which states that transfer of skill is generally low because different motor tasks require a large number of different motor abilities, which are independent of each other [28]. Maybe the transfer task with increased natural frequency was more similar to training with indirect haptic noise than without, explaining the observed learning benefit in this transfer task. The transfer task with altered target positions might have more required motor abilities in common with training without indirect haptic noise, thereby explaining that participants in the control group better learned to decrease the power at natural frequency in this transfer task.

D. Indirect Haptic Noise Might Reduce Sense of Agency

The fact that the interaction between $Group$ and $Time$ was trending towards significance from baseline to training, indicates that the perturbations might have negatively affected participants' sense of agency over controlling the pendulum. Sense of agency is associated with skill learning, suggested by the correlation between the increase in participants' reported sense of agency and amount of learning observed in the experimental group in the study by Özen et al. [20] (r = 0.59, p = 0.07). Nevertheless, although we also found a correlation in the current experiment ($r = 0.37$), the $95\,\%$ bootstrapped confidence interval $[-0.15, 0.73]$ indicates that this correlation can not be considered significant.

The interaction effect did not remain during long-term retention, suggesting that the perturbations did not cause a lasting reduction in participants' sense of being in control over the pendulum compared to participants without perturbation forces. This could mean that perturbations applied to the internal degree of freedom of the system to be controlled can be used for training purposes in for example neurorehabilitation, without having a lasting effect on participants' feeling of having control over the system to be controlled.

It should be noted that one question might have been confusing for some participants, as we observed some contradictory answers compared to the other sense of agency questions. The question concerned is '*It seemed as if the pendulum was controlling me*', which, next to possibly led to interpretation differences, also required the opposite score for high perceived sense of agency compared to the other two questions (i.e., a score of 3 indicated low sense of agency whereas in the other questions this indicated high sense of agency). We suggest to avoid questions like this and emphasize the importance of clear formulation in questionnaires. Nevertheless, leaving this question out from the statistical analysis did not result in large differences compared to the results as presented in this study.

E. Indirect Haptic Noise Does Not Affect Motivation

According to Wulf and Lewthwaite [38], enhanced skill learning can be attributed to an increase in motivation. The results from the IMI Questionnaire, however, did not suggest that the perturbations forces reduced participants' motivation. It should be noted that participants' self reports on *Interest/Enjoyment* and *Effort/Importance* were already relatively high during baseline (average of 5.5 and 5.4 respectively on a scale from 1 to 7), which could make finding differences within and between groups harder (ceiling effect). Nevertheless, the results give no indication to suspect that participants' motivation was considerably affected by the perturbation forces.

F. Future Work

The perturbation forces seemed to enhance transfer of learning to different task dynamics. Therefore, studying the effect of increasing motor variability by indirect haptic noise on generalization of learning should be exploited in lab-based experiments. For example, different types of tasks could be used where transfer tasks with different altered dynamics can be used. Maybe we find more reasons to believe that indirect haptic noise is beneficial for learning of tasks that consists of changing dynamics, which could possibly be generalized to sports training and neurorehabilitation.

The question raised about how the increase in observed motor variability affected planning noise and execution noise, asks for more research into the topic. Fitting a model to the individual data to estimate the contributions of planning noise and execution noise like Van Der Vliet et al. [33] (and others [10]) did, is challenging because unlike in their tasks, performance in the current task is not determined by merely one executed movement angle. The current task is much more complex (multiple targets, internal degree of freedom, two movement directions, redundancy of possible paths) and does not seem suitable for such modeling. Simplifying the task to, for example only one target, might aid in this regard. It remains uncertain, however, how findings from highly-controlled simple tasks (like [10, 33]) generalize to more complex real-world motor learning as for example neurorehabilitation. Probably, a trade-off exists between generalizability of findings and confirmability of hypotheses regarding the complexity of motor tasks when studying motor learning in lab-based experiments.

Next to participants' motivation, their attention is also an important factor that influences learning according to Wulf and Lewthwaite [38]. Specifically, a more external focus of attention is desirable for enhanced performance and skill learning. Chua et al. [4] argued that the benefits of variability of practice could be explained by this theory. In the case of our experiment, it would be interesting to get insight into the focus of attention of the participants. Maybe the perturbation forces caused participants' attention to get more intrinsic, for example back on the ball of the pendulum instead of on the targets, which is a more external locus of attention. In future studies, it would be interesting to include questionnaires that contain questions about this, which could give insight in how indirect haptic noise or other interventions affect participants' focus of attention.

V. Conclusion

Perturbation forces applied to the internal degree of freedom of the system to be controlled increases motor variability. However, enhanced motor variability does not seem to enhance learning of the trained task, compared to training without perturbations. Yet, in the transfer task with different dynamics, the perturbation group showed higher deviations from the pendulum natural frequency during short-term retention, suggesting better control of the task dynamics. On the other hand, in the transfer task with altered target positions, the control group showed higher deviations from the pendulum natural frequency during short-term and long-term retention.

To the best of our knowledge, this study is the first to use haptic noise applied to the internal degree of freedom of the system to be controlled to increase motor variability. This indirect haptic noise indeed successfully enhanced motor variability, thereby possibly increasing exploration of the task dynamics.

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A
Sense of Agency and Motivation Questionnaire

On the next page you find the questionnaire that was filled in by the participants three times over the entire duration of the experiment (2 days). The questionnaire started with three questions about their perceived sense of agency, followed by twelve questions related to their motivation. The motivation questions consisted of 4 subscales: *Interest/Enjoyment*, *Perceived Competence*, *Effort/Importance* and *Pressure/Tension*. Each subscale contained three questions. The order of the motivation questions was randomized but the same order was kept for each participant and at each questionnaire (i.e., at baseline, training and long-term retention). For a better overview the questions are listed below, grouped by subscale.

Sense of agency:

- It seemed like I was in control of the pendulum.
- It seemed as if the pendulum was controlling me.
- It seemed like I was causing the movements of the pendulum.

Interest/Enjoyment:

- I thought this activity was quite enjoyable.
- The task was fun to do.
- I would describe this activity as very interesting.

Perceived Competence:

- I was pretty skilled at this activity.
- I am satisfied with my performance at this task.
- I think I am pretty good at this activity.

Effort/Importance:

- I tried very hard on this activity.
- I put a lot of effort into this.
- It was important to me to do well at this task.

Pressure/Tension:

- I felt pressured while doing these.
- I was anxious while working on this task.
- I felt very tense while doing this activity

Questionnaire

Participant ID: ……

1. It seemed like I was in control of the pendulum.

strongly disagree						strongly agree
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
O	O	O	O	O	O	O

2. It seemed as if the pendulum was controlling me.

strongly disagree						strongly agree
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
O	O	O	O	O	O	O

3. It seemed like I was causing the movements of the pendulum.

strongly disagree						strongly agree
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
O	O	O	O	O	O	O

4. I thought this activity was quite enjoyable.

not at all						very true
1	**2**	**3**	**4**	**5**	**6**	**7**
O	O	O	O	O	O	O

5. I tried very hard on this activity.

not at all						very true
1	**2**	**3**	**4**	**5**	**6**	**7**
O	O	O	O	O	O	O

6. I felt pressured while doing this task.

not at all						very true
1	**2**	**3**	**4**	**5**	**6**	**7**
O	O	O	O	O	O	O

7. I was pretty skilled at this activity.

not at all						very true
1	2	3	4	5	6	7
O	O	O	O	O	O	O

8. It was important to me to do well at this task.

not at all						very true
1	2	3	4	5	6	7
O	O	O	O	O	O	O

9. I was anxious while working on this task.

not at all						very true
1	2	3	4	5	6	7
O	O	O	O	O	O	O

10. The task was fun to do.

not at all						very true
1	2	3	4	5	6	7
O	O	O	O	O	O	O

11. I put a lot of effort into this.

not at all						very true
1	2	3	4	5	6	7
O	O	O	O	O	O	O

12. I am satisfied with my performance at this task.

not at all						very true
1	2	3	4	5	6	7
O	O	O	O	O	O	O

13. I would describe this activity as very interesting.

not at all						very true
1	2	3	4	5	6	7
O	O	O	O	O	O	O

14. I think I am pretty good at this activity.

not at all						very true
1	2	3	4	5	6	7
O	O	O	O	O	O	O

15. I felt very tense while doing this activity.

not at all						very true
1	2	3	4	5	6	7
O	O	O	O	O	O	O

B

Correlations

The figures on the next pages visualize the results from the correlation analyses.

B.1. Trial Score & Power at Natural Frequency

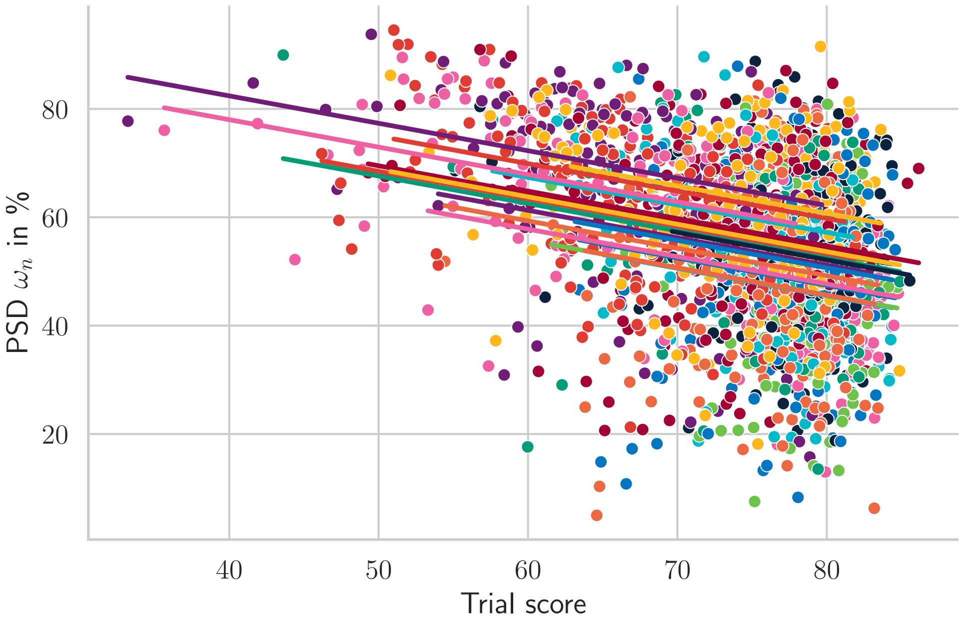

Figure B.1: Repeated-measures correlation between the trial score and power at natural frequency, $r = -0.21$. The different lines correspond to different participants.

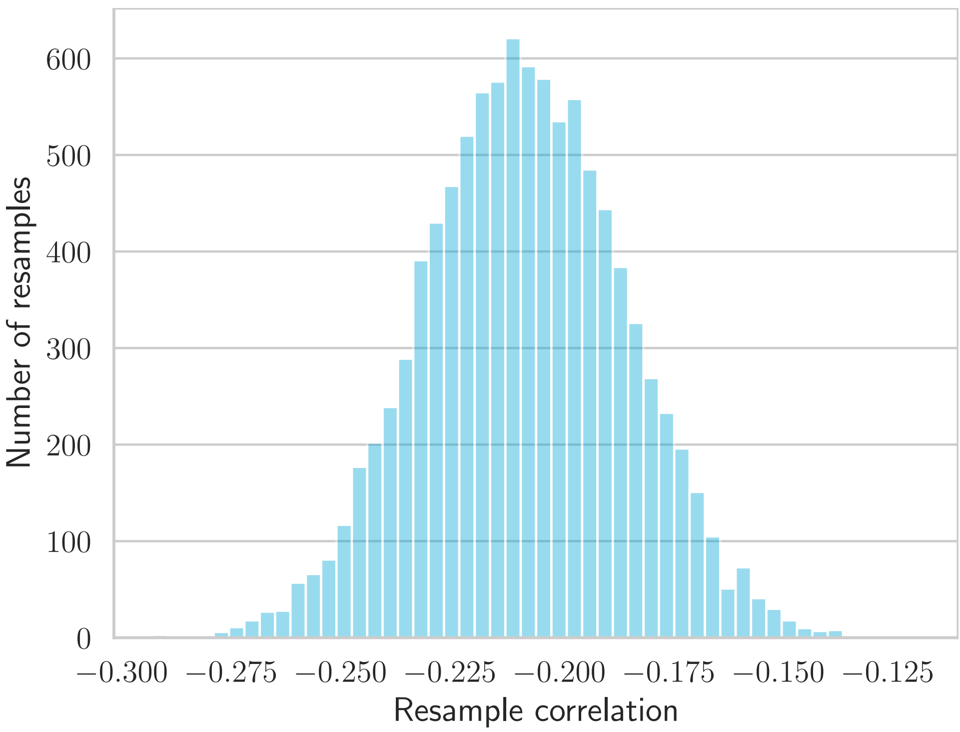

Figure B.2: Resample frequencies of the repeated measures correlation between trial score and power at natural frequency. Correlations from 10 000 resamples. The 2.5 and 97.5 percentiles are −0.25 and −0.16 respectively.

B.2. Trial Score & Sense of Agency

Figure B.3: Pearson correlation between the trial score improvement and changes in reported sense of agency, $r = 0.37$. The blue dots indicate the different participants.

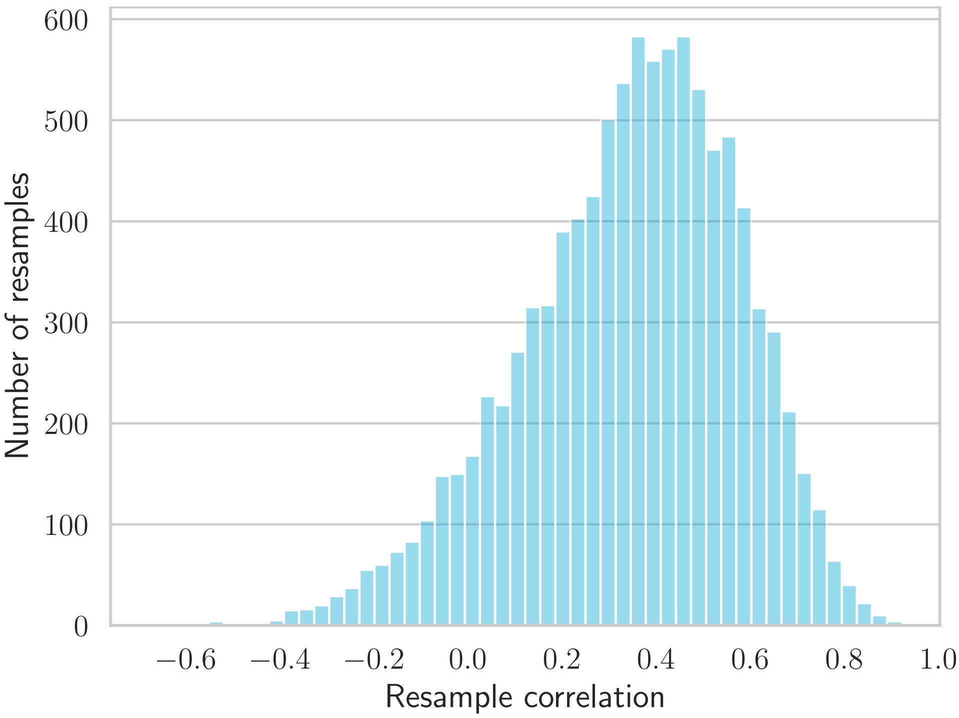

Figure B.4: Resample frequencies of the Pearson correlation between the trial score improvement and changes in reported sense of agency. Correlations from 10 000 resamples. The 2.5 and 97.5 percentiles are −0.15 and 0.73 respectively.

C

Psychological Factors

This appendix visualizes the results from the sense of agency and motivation questionnaires.

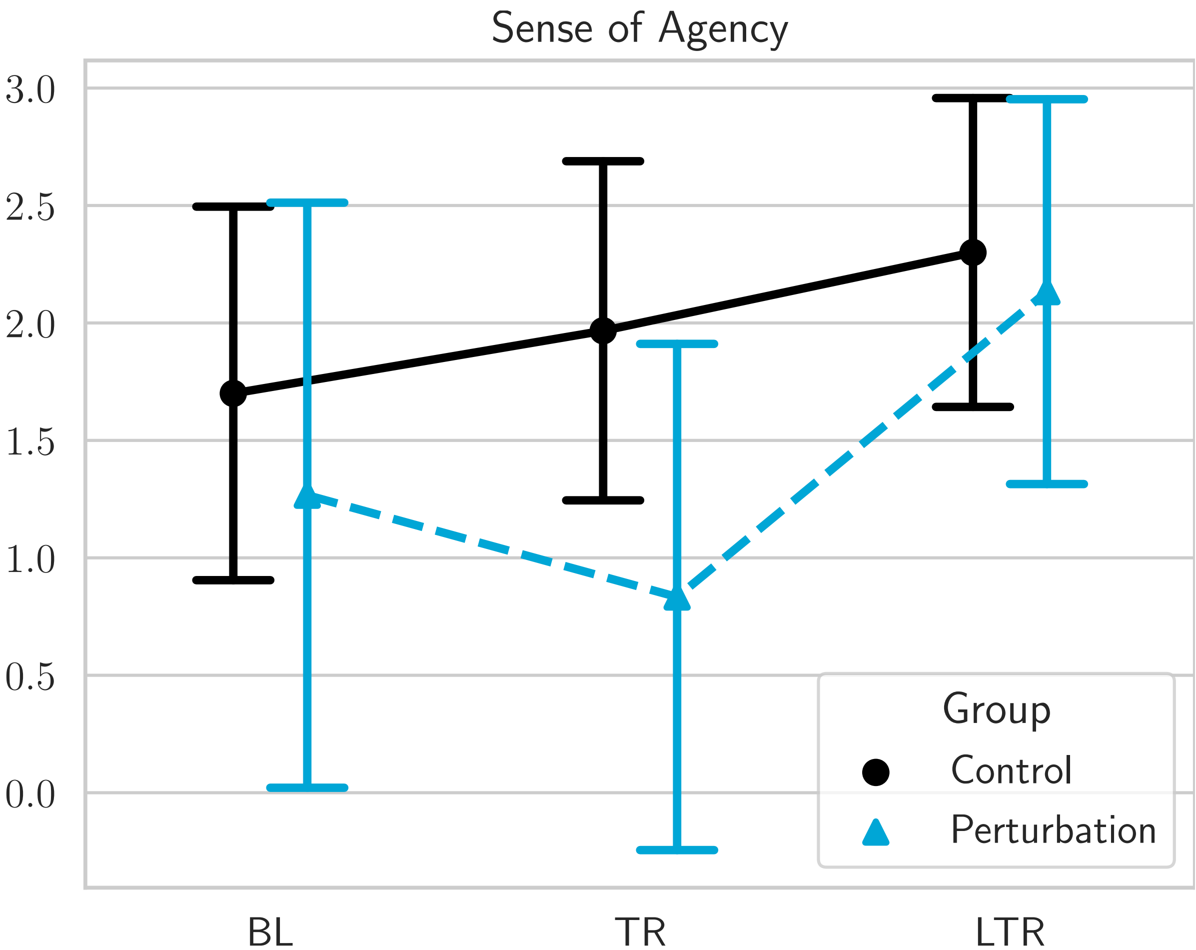

Figure C.1: Average of participants' reported sense of agency values (7-point scale from −3 to 3) of the two groups at baseline (BL), training (TR) and long-term retention (LTR). The error bars represent one standard deviation from the mean. The interaction between group and time was trending towards significance from baseline to training.

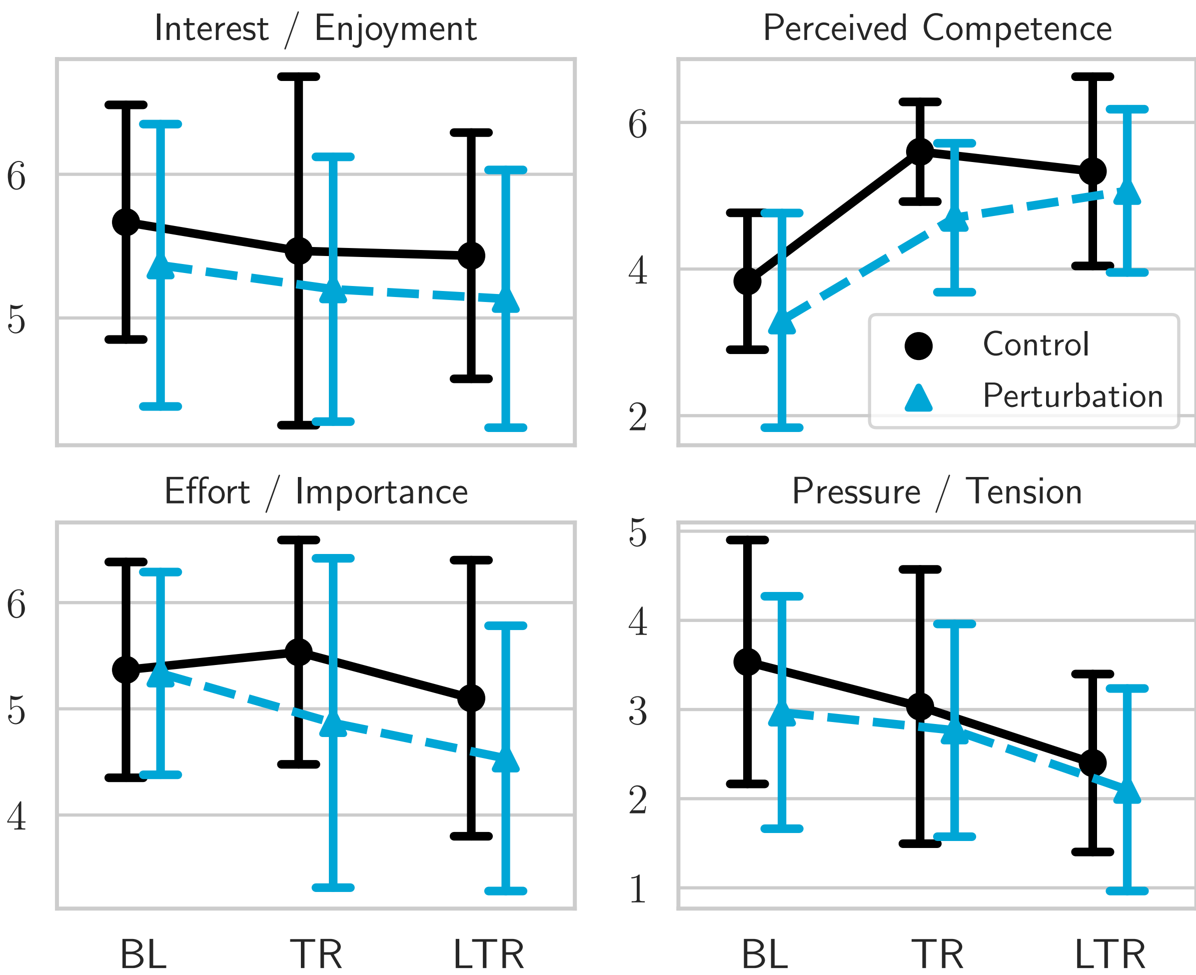

Figure C.2: Average of participants' reported motivation values (7-point scale from 1 to 7) of the two groups at baseline (BL), training (TR) and long-term retention (LTR) of the four subscales *Interest/Enjoyment*, *Perceived Competence*, *Effort/Importance* and *Pressure/Tension*. The error bars represent one standard deviation from the mean. Their was no significant interaction effect between group and time for any of the subscales.

D

Training Data

The figures below show the end-effector and pendulum swing angle data from participant 6 (control group) and 19 (perturbation group) from all 60 training trials.

D.1. End-effector Trajectories

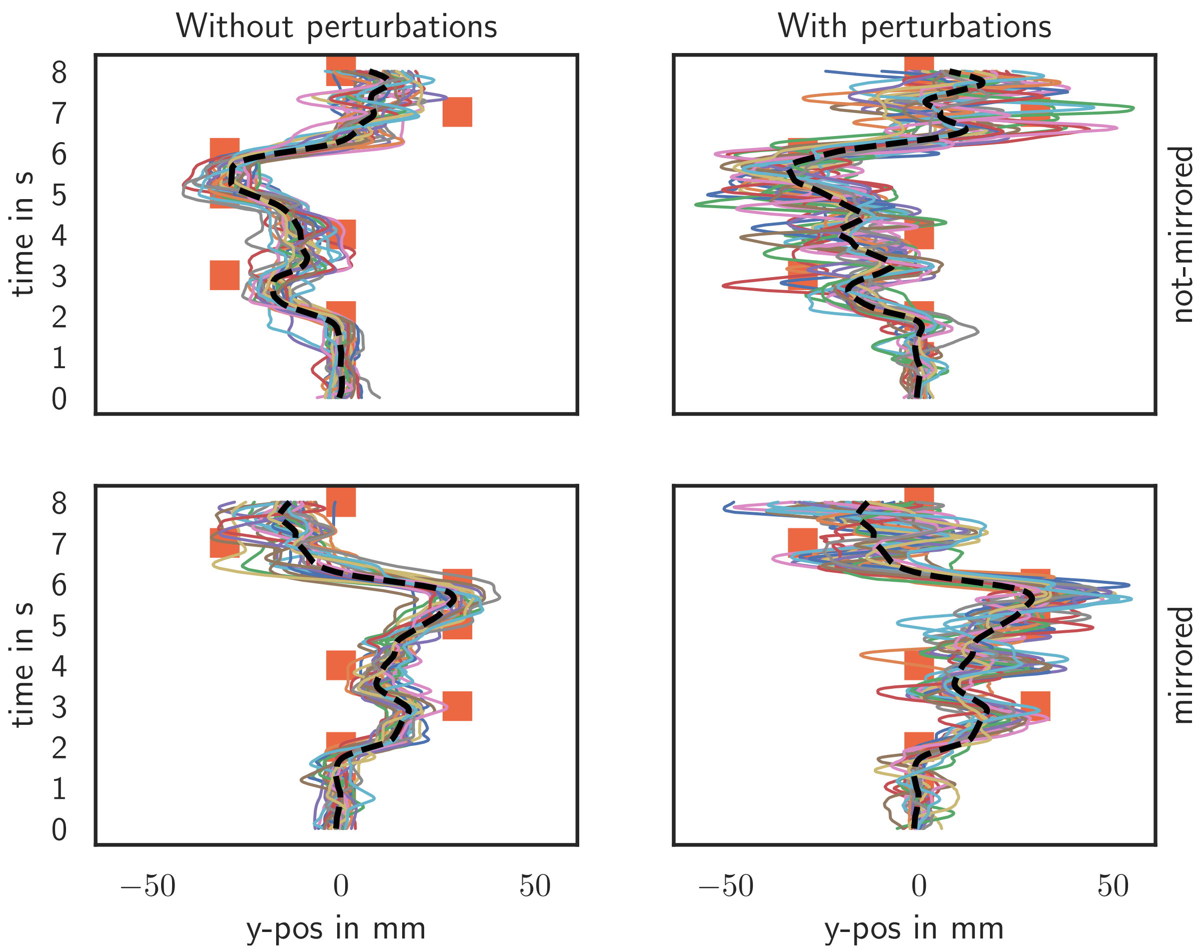

Figure D.1: Horizontal end-effector trajectories of the 60 training trials of a participant training without (left) or with (right) perturbation forces. The trials are further separated by not-mirrored (top) and mirrored (bottom) trials. The orange squares indicate the target locations. The dashed thick black trajectories are the mean of the 30 paths in that figure.

D.2. Pendulum Swing Angle

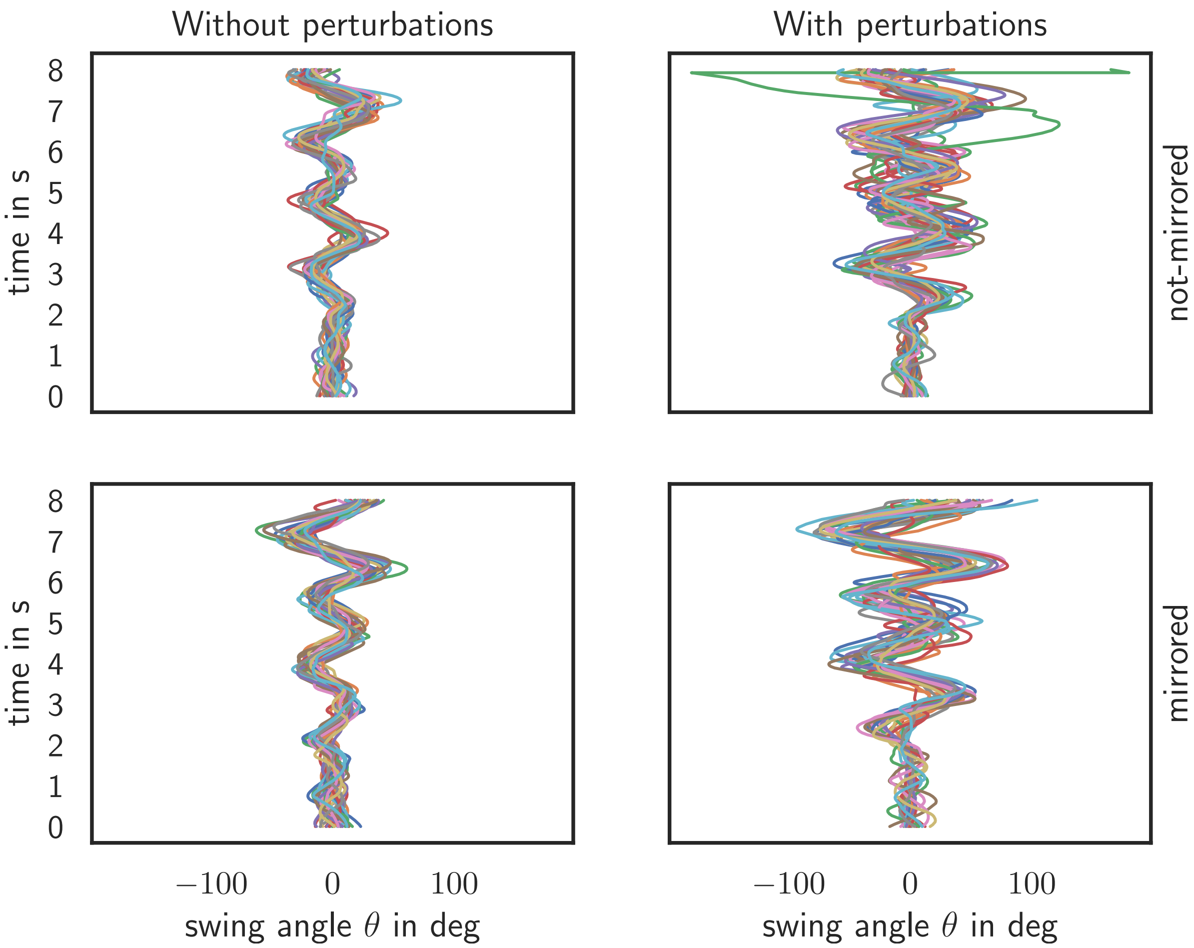

Figure D.2: Pendulum swing angle θ of the 60 training trials of a participant training without (left) or with (right) perturbation forces. The trials are further separated by not-mirrored (top) and mirrored (bottom) trials. The green line in the upper-right figure jumps from −180 deg to 180 deg, indicating that the pendulum flipped over its pivot point.

E
Score Variability

This appendix shows the average score variability of both groups, one of the three performance metrics used to evaluate motor learning.

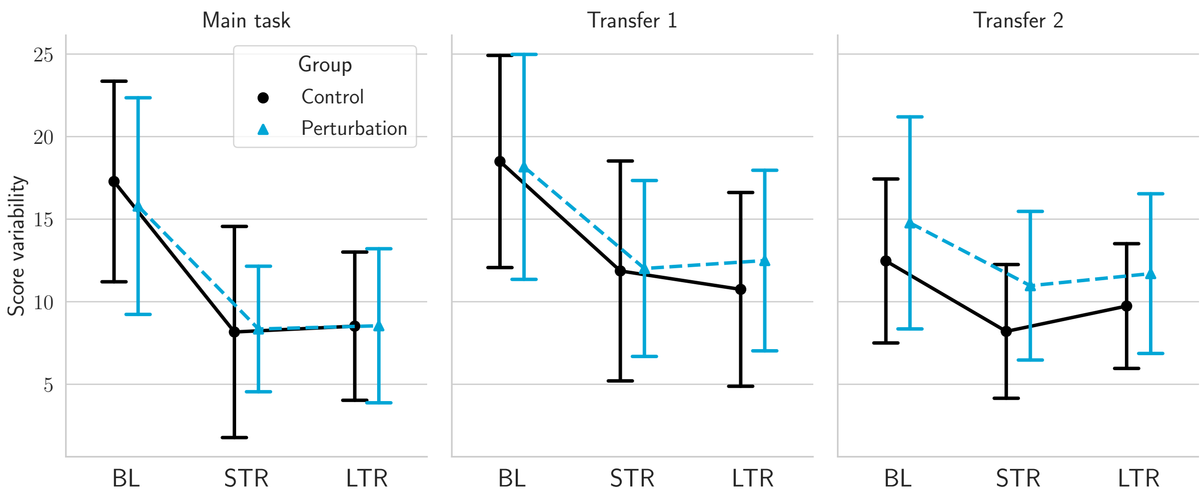

Figure E.1: Average score variabilities of the two groups in baseline (BL), short-term (STR) and long-term retention (LTR) of the main task, transfer task with altered target positions (Transfer 1) and transfer task with reduced pendulum length (Transfer 2). The control group is indicated by the solid black line and the perturbation group by the dashed blue line. The error bars represent one standard deviation from the mean. Both groups decreased their score variability significantly from baseline to short-term and long-term retention in all three tasks. We found no significant differences between the groups.

F

Transfer 1 Setup

The figure below shows the target positions of the first transfer task.

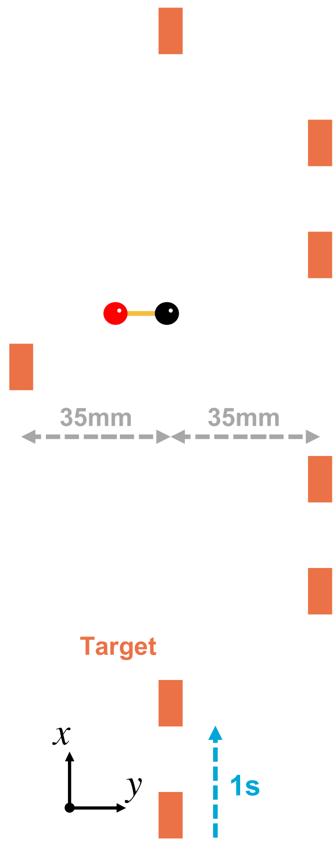

Figure F.1: Schematic top view (z-plane) of a trial in the transfer task with altered target positions. A trial consisted of eight targets separated by 1 s each. A period of 5 s without targets followed each trial after which the next trial started. Each trial started with two consecutive targets in the center of the workspace. As trials were separated by 5 s without targets, this prompted participants to bring the pendulum back to the center and reach a stable pendulum equilibrium, i.e., without swing, before the onset of each trial. We hereby attempted to start each trial with similar initial conditions (as in the main task). We tried to increase the difficulty of this transfer task by increasing the horizontal distance between the targets and the centerline from 30 mm to 35 mm. We further included two times two consecutive targets on the same horizontal position (difficult because of the swing of the pendulum), separated by a target all the way on the other side (at a distance of 70 mm).

G

Motor variability during Baseline and Retention

On the next page you find the different variability metrics of both groups during the baseline and retention blocks.

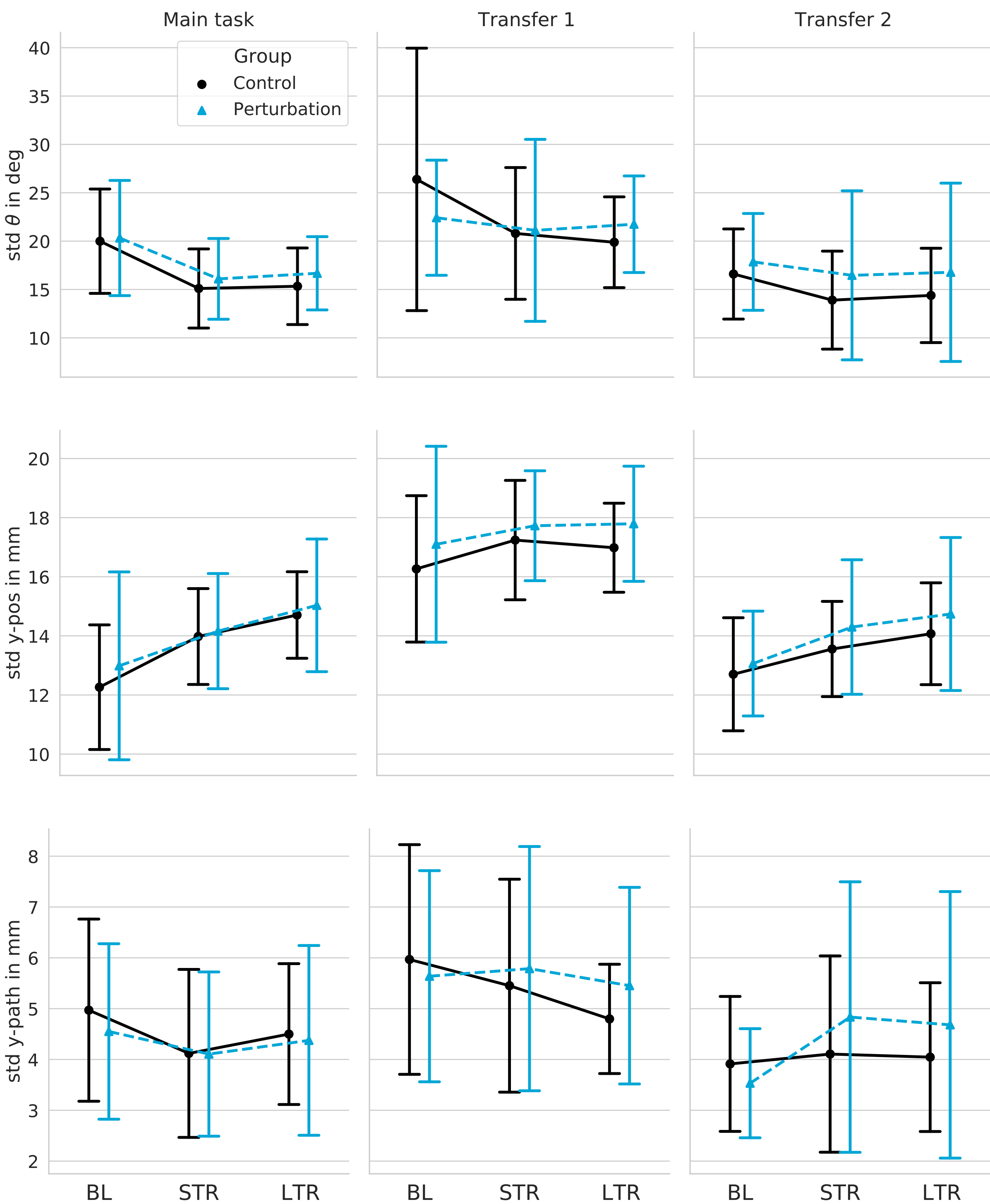

Figure G.1: Average swing (top), end-effector (middle) and path (bottom) variability of the two groups in baseline (BL), short-term (STR) and long-term retention (LTR) of the main task, transfer task with altered target positions (Transfer 1) and transfer task with reduced pendulum length (Transfer 2). The control group is indicated by the solid black line and the perturbation group by the dashed blue line. The error bars represent one standard deviation from the mean. There were no significant differences between the groups for any of variability metrics in the main task baseline block. All variability metrics were similar between the perturbation and control group, although higher for the perturbation group in all three tasks during short-term and long-term retention, except for the path variability in the main task.

H

Individual Data

The figures on the next pages show the individual data of the three performance metrics used to evaluate motor learning in the baseline and retention blocks, separated by task and group.

H.1. Score

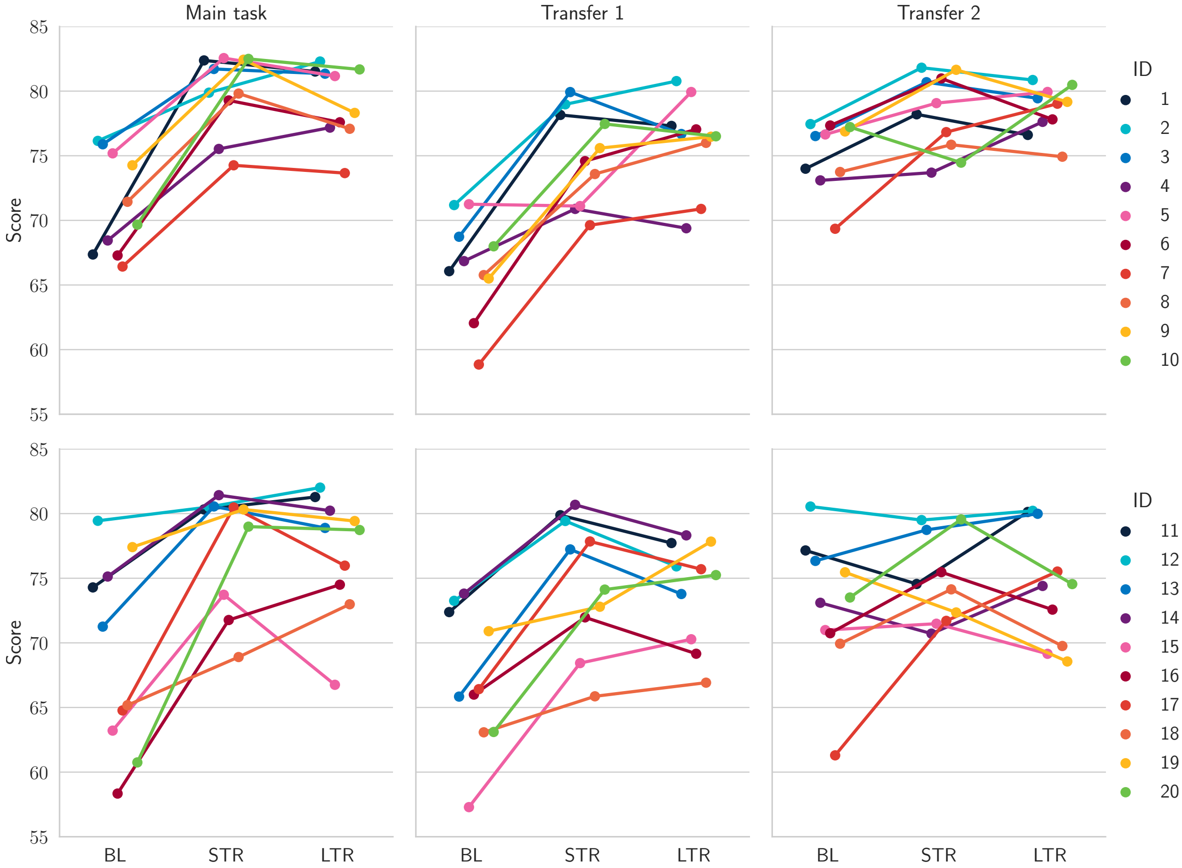

Figure H.1: Scores per participants in the control group (top) and the perturbation group (bottom) in baseline (BL), short-term (STR) and long-term retention (LTR) of the main task, transfer task with altered target positions (Transfer 1) and transfer task with reduced pendulum length (Transfer 2).

H.2. Power around Natural Frequency

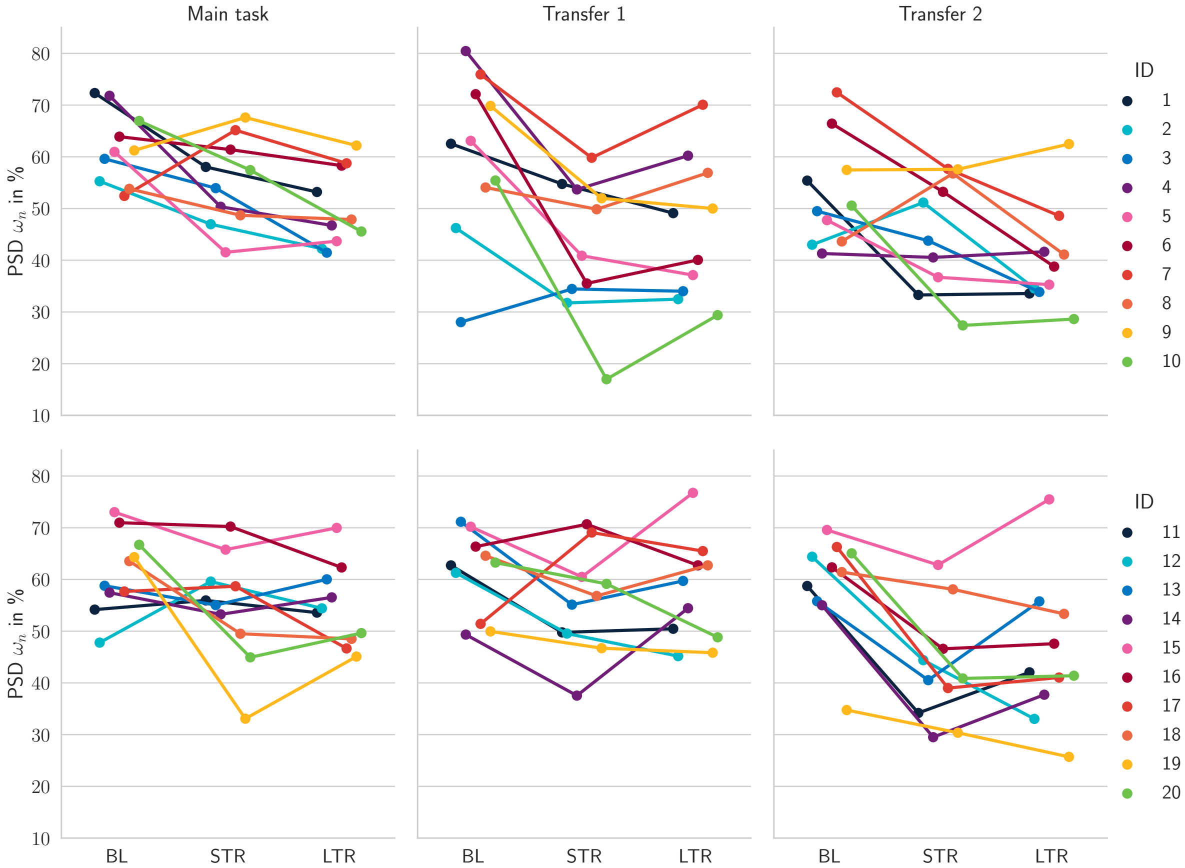

Figure H.2: Power around the pendulum natural frequency per participant in the control group (top) and the perturbation group (bottom) in baseline (BL), short-term (STR) and long-term retention (LTR) of the main task, transfer task with altered target positions (Transfer 1) and transfer task with reduced pendulum length (Transfer 2).

H.3. Score Variability

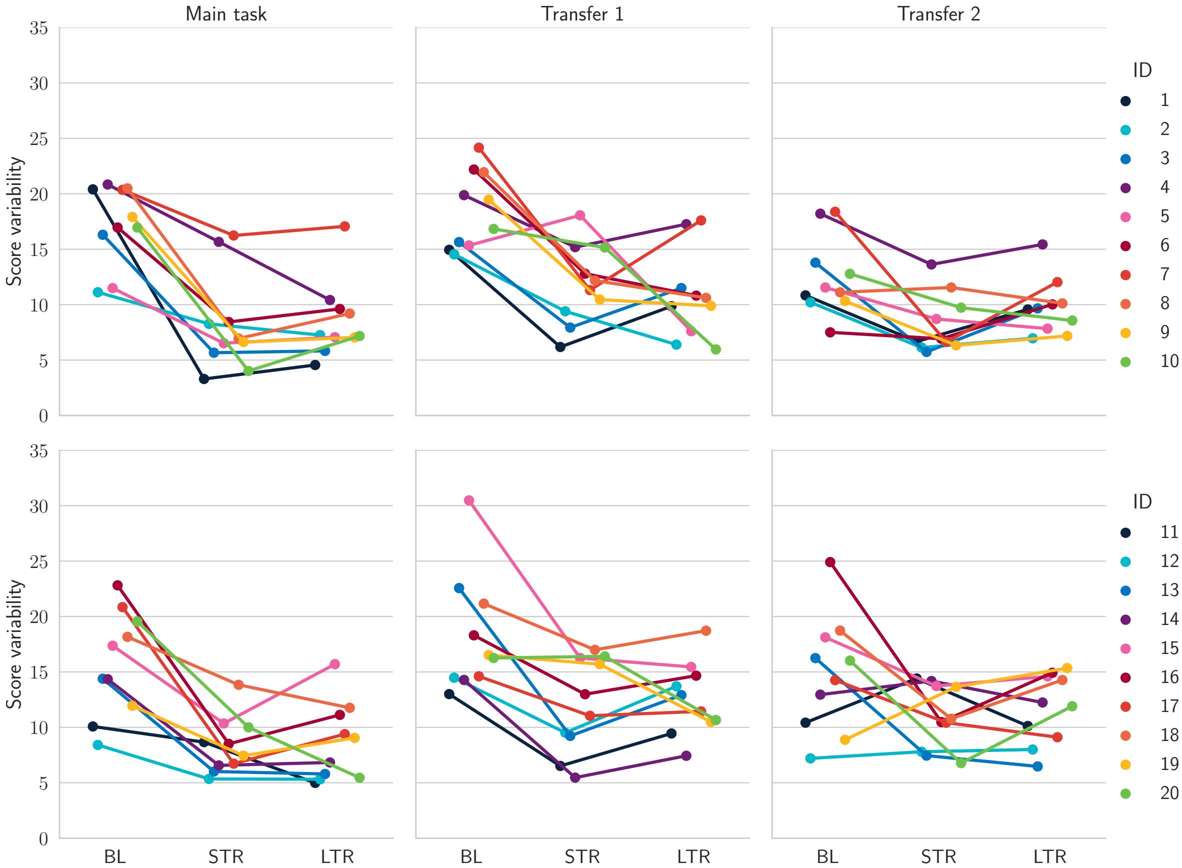

Figure H.3: Score variability per participants in the control group (top) and the perturbation group (bottom) in baseline (BL), short-term (STR) and long-term retention (LTR) of the main task, transfer task with altered target positions (Transfer 1) and transfer task with reduced pendulum length (Transfer 2).

I

Perturbations

This appendix shows and visualizes the protocol of the perturbation forces, i.e., how the perturbations locations, magnitudes and onset times were divided over a training block for participants in the perturbation group. Fig. I.1 also shows the order of mirrored and not-mirrored trials, which was the same for participants in the control group.

I.1. Protocol

Trial number	1	2	3	4	5	6	7	8	9	10	11	12	13	1	15	16	17	18	19	20
	A	B		C	H	D		E	F	G	F	E		B	C	H		D	A	G
Mirrored (y/n)	N	Y	N	Y	Y	N	N	N	Y	Y	N	Y	Y	N	N	N	Y	Y	Y	N
Perturbed locations	2, 4	2, 5	Catch	3, 5	2, 4, 6	2, 5	Catch	2, 4, 6	2, 4	3, 5	2, 4	2, 4, 6	Catch	2, 5	3, 5	2, 4, 6	Catch	2, 5	2, 4	3, 5
Magn 1st [N]	1.4	1.5		1.4	1.3	1.3		1.2	1.5	1.2	1.5	1.2		1.5	1.4	1.3		1.3	1.4	1.2
Magn 2nd [N]	1.2	1.4		1.3	1.1	1.1		1.2	1.3	1.4	1.3	1.2		1.4	1.3	1.1		1.1	1.2	1.4
Magn 3rd [N]					0.9			0.8				0.8				0.9				
Time onset 1st [s]	0.02	0.08		0.06	0.04	0.04		0.06	0.02	0.08	0.02	0.06		0.08	0.06	0.04		0.04	0.02	0.08
Time onset 2nd [s]	0.06	0.06		0.04	0.02	0.04		0.08	0.08	0.02	0.08	0.08		0.06	0.04	0.02		0.04	0.06	0.02
Time onset 3rd [s]					0.02			0.03				0.03				0.02				

Figure I.1: Protocol of training block for participants in the perturbation group. Columns with corresponding letters (second row) indicate the same perturbation characteristics (i.e., location, magnitude and onset time), but are either mirrored or not-mirrored.

I.2. Force Magnitude Distribution

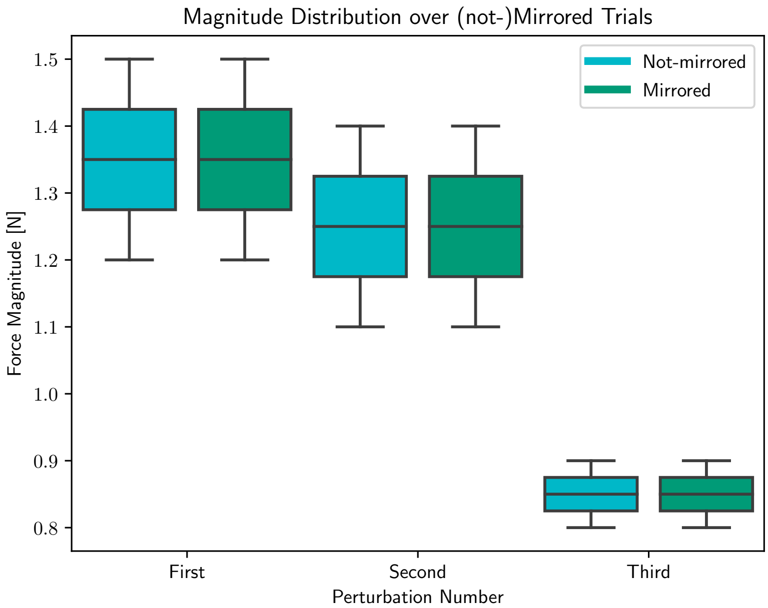

Figure I.2: Perturbation force magnitudes distribution of one training block of the first, second and third perturbation (within trials), divided over mirrored and not-mirrored trials. This figure shows that the magnitudes were distributed over mirrored and not-mirrored trials equally.

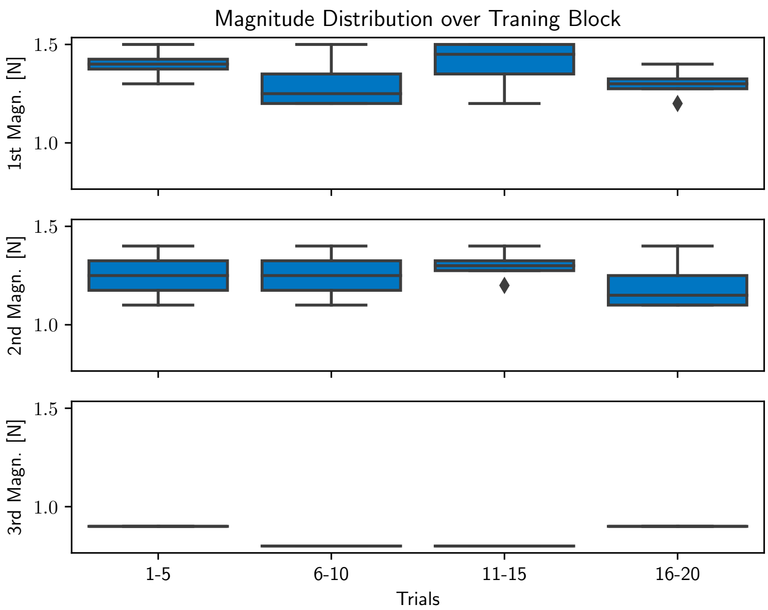

Figure I.3: Perturbation force magnitudes distribution of one training block of the first (top), second (middle) and third (bottom) perturbation (within trials), divided per five trials. This figure shows that the magnitudes were evenly distributed over the course of one block. A third perturbation in a trial occurred only once per five trials, hence the flatness of the box plots in the bottom figure.

J

Score Distribution

This appendix shows different figures to give insight into the score distribution between and within trials.

J.1. Mirrored versus Not-mirrored Trials

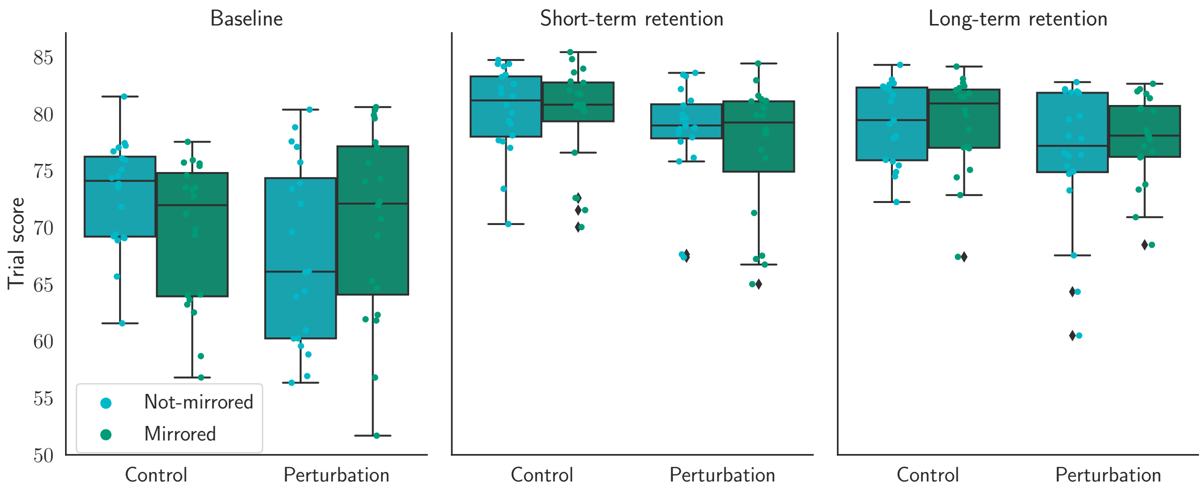

Figure J.1: Box plots of the scores of all trials of all participants during baseline, short-term retention and long-term retention, divided by group and mirrored and not-mirrored trials. This figure shows that the scores of mirrored and not-mirrored trials were similar. Note that the score variability during baseline was relatively high (see Appendix E), which explains that the trial scores of mirrored and not-mirrored trials were also less similar.

J.2. Target Scores

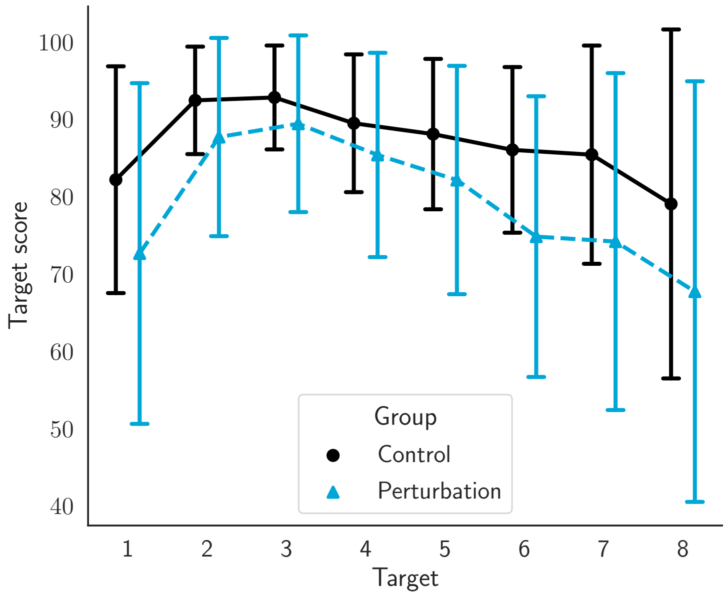

Figure J.2: Average scores per target of all trials during training, divided by group. The error bars represent one standard deviation from the mean. This figure shows that hitting the targets seems to become more challenging during the course of a trial (as intended). The mean scores per target were higher in the control group for all targets. Bringing the pendulum back to the center and reach a stable pendulum equilibrium, i.e., without swing, before the onset of each trial was challenging, suggested by the relatively low score of the first target.

J.3. Training Scores

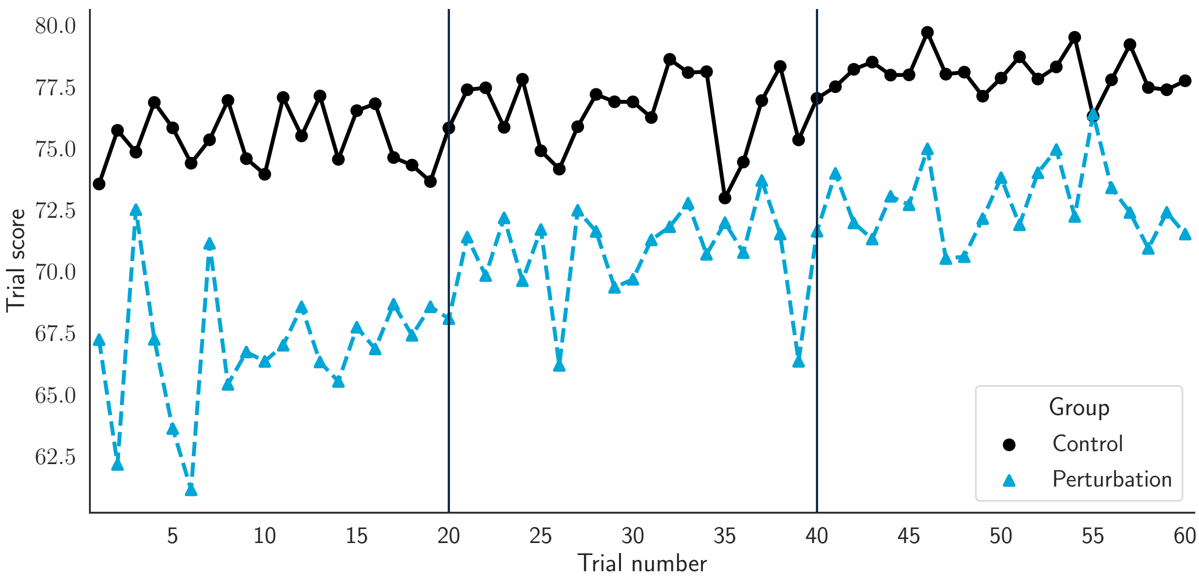

Figure J.3: Average scores of all trials during training, divided by group. The vertical lines separate the three different training blocks. It can be seen that the scores gradually increase for both groups. The perturbation forces seemed to degrade performance, as the control group scores generally higher, and the two peaks in the curve of the perturbation group at trials 3 and 7 were catch trials (i.e., without perturbations).

K

MPC pilot experiment

This appendix shows the results from a pilot experiment. We used the Model Predictive Controller (MPC) devised by Özen et al. [1] for a pilot experiment, in order to see if the pseudo-random perturbation forces applied to the pendulum ball had the desired effect of increasing motor variability. The MPC applies forces on the end-effector to almost perfectly hit the targets.

To see an effect of a certain intervention by running a pilot experiment, you either need many participants in a between-participants design, to account for individual differences, or use a repeated measures design, which has the drawback of order effects (and still multiple participants are needed). Performing a pilot experiment with the MPC solves this problem, as its performance is high and constant. Also, no order effects occur, as the MPC has no memory. The drawback is that it is not a human, so it remains a question if observed effects also will appear in humans.

We ran several trials with the MPC, with and without perturbation forces. The figures on the next page show the results.

K.1. Trajectories

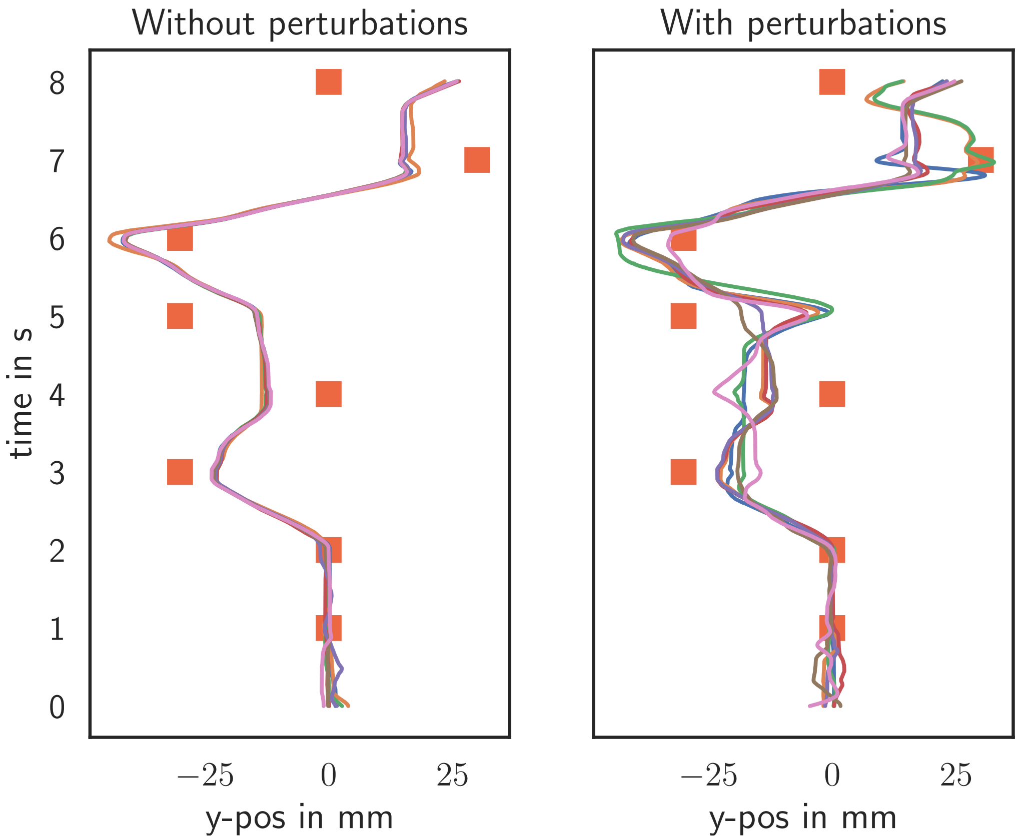

Figure K.1: Horizontal end-effector trajectories of the MPC devised by Özen et al. [1] of seven trial without (left) and with (right) perturbation forces applied to the pendulum ball. The perturbation forces made the MPC use different trajectories in order to hit the targets.

K.2. Variability Metrics

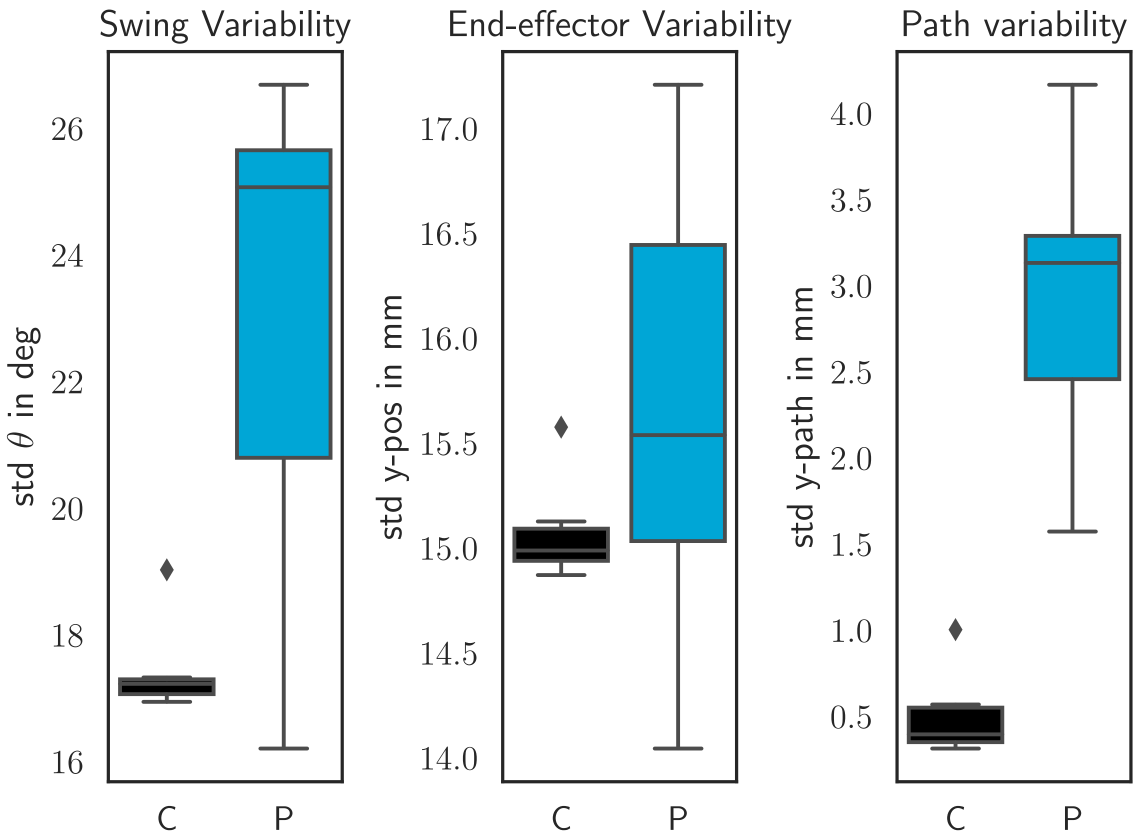

Figure K.2: Box plots of the variability metrics of seven trials of the MPC without (C) or with (P) perturbation forces applied to the pendulum ball. The perturbation forces increased the swing variability and forced the MPC to take different paths, thereby increasing the end-effector and path variability.

L

Participant Information Questionnaire

The next page shows the participant information questionnaire, filled in by the participants at the start of the experiment.

Participant information

Participant ID
Age
Gender
Handedness
Highest level of education
Have you ever performed a novel task during an experiment? If so, how often?
Have you ever performed a task with a robot? If so, how often?

How often do you play video games?

Per month:

0 times	1-3 times	4-6 times	7-9 times	>9 times	Prefer not to respond
O	O	O	O	O	O

How often have you played video games in the past?

Per month (for at least one year):

0 times	1-3 times	4-6 times	7-9 times	>9 times	Prefer not to respond
O	O	O	O	O	O

I am likely to trust a machine even when I have little knowledge about it.

Strongly disagree	Disagree a little	Neither agree nor disagree	Agree a little	Strongly agree	Prefer not to respond
O	O	O	O	O	O

M

Informed consent form

The next pages show the informed consent form that was signed by all participants. The experiment was approved by the Delft Ethics Committee (HREC, ID: 1906)

Informed Consent Form for a Motor Learning Experiment

Researchers:
Wouter Arink – MSc. student
E-mail: w.arink@student.tudelft.nl
Tel: +31 (0)6 30958345

Dr.ing. L. Marchal Crespo – Supervisor
E-mail: L.MarchalCrespo@tudelft.nl

Dr.ir. Niek Beckers – Supervisor
E-mail: N.W.M.Beckers@tudelft.nl

This document describes the purpose, procedures, benefits, risks and possible discomforts of a motor learning experiment. It also describes the right to withdraw from the study at any time in any case. Before agreeing to participate in this study, it is important that the information provided in this document is fully read and understood.

Location of the experiment
TU Delft, Faculty of Mechanical, Maritime and Materials Engineering (3mE)
Cognitive Robotics Lab (F-1-490)
Mekelweg 2, 2628CD Delft

Description of Experiment:
In this experiment you will be asked to perform a target hitting task. You will be asked to move the end-effector of a haptic device in order to move a virtual pendulum on a screen. The experiment will take approximately 60 minutes to complete. You will be asked to come back the next day to perform the experiment again, which will approximately take 10 minutes.

In order to participate in this research, it is necessary that you give your informed written consent. By signing this page you are indicating that you understand the nature of this research and your role in it and that you agree to participate in the research.

Task instructions: During the experiment you are asked to try to hit incoming targets on a screen as close as possible with a ball attached to a pendulum. You control this pendulum by moving the end-effector of a haptic device.

Confidentiality: The collected data in this experiment is kept confidential and will be used for research purposes only. The data will also be anonymised i.e. you will be identified by a subject number.

Right to refuse or withdraw: Your participation is strictly voluntary and you may withdraw from or stop this experiment at any time, without consequences.

Questions: If you have any questions regarding this experiment, feel free to contact W. Arink (contact details are provided at the top of this document).

Additional information regarding COVID-19: To prevent the spread of COVID-19 (in compliance with the university's policy), researchers and participants in the study:
- don't have any underlying ailments that could be seen as a risk factor for a COVID-19 infection
- don't have any complaints or symptoms that could be indicative of a COVID-19 infection
- have not been in contact with a COVID-19 patient at least 14 days before participation in the study
- take suitable protective measures if a minimum distance of 1.5 meters is not viable
- are enabled to travel outside of rush hours to and from the research location

Also, any objects or surfaces researchers and participants come into contact with will be disinfected prior and after use.

Please confirm the following points before signing:

- **I understand that I am participating in human factors research;**
- **I consent that the data gathered during the experiment may be used for a MSc thesis and possible future academic research and publications;**
- **I understand that my participation will be anonymous (that is, my name will not be linked with my data);**
- **I understand that I will be provided with an explanation of the research in which I participated and will be given the name and e-mail address of an individual(s) to contact if I have questions about the research;**
- **I understand that participation in research is not required, is voluntary, and that I may refuse to participate further without negative consequences;**
- **I adhere to the preventative measures with regards to COVID-19 as explained above.**

By signing this form, I am stating that I understand the above information and consent to participate in this study being conducted at TU Delft.

Name: ____ *Participant ID:* __________________

Signature: ___________________________________ *Today's Date:* _________________________

Bibliography

[1] Özhan Özen, Karin A. Buetler, and Laura Marchal-Crespo. Promoting Motor Variability During Robotic Assistance Enhances Motor Learning of Dynamic Tasks. *Frontiers in Neuroscience*, 14, February 2021. ISSN 1662-4548. doi: 10.3389/fnins.2020.600059. URL https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7884323/.