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Influence of haptic guidance in learning a novel visuomotor task

Edwin H. F. van Asseldonk\textsuperscript{a}, Martijn Wessels\textsuperscript{a}, Arno H. A. Stienen\textsuperscript{a,1}, Frans C. T. van der Helm\textsuperscript{a,b}, and Herman van der Kooij\textsuperscript{a,b}

\textsuperscript{a}Institute for Biomedical Technology (BMTI), Dept of Biomechanical Engineering, University of Twente, PO Box 217, 7500 AE, Enschede, The Netherlands

\textsuperscript{b}Biomechatronics & Bio-Robotics group, Dept. of Biomechanical Engineering, Fac. of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Mekelweg 2, 2628 CD, Delft, The Netherlands

\textsuperscript{1}Present address: Physical Therapy and Human Movement Sciences, Northwestern University 645 North Michigan Avenue Suite 1100 Chicago, Illinois 60611

E-mail address in same order as order of authors: e.h.f.vanasseldonk@utwente.nl, m.wessels@utwente.nl, arnostienen@gmail.com, f.c.t.vanderhelm@tudelft.nl, h.vanderkooij@utwente.nl

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Address for correspondence:
E.H.F. van Asseldonk, Faculty of Engineering Technology, Laboratory of Biomechanical Engineering, University of Twente. Room: Horst W203, P.O. Box 217, 7500 AE Enschede, The Netherlands. Phone: +31-53-4892446. Fax: +31-53-4893695
E-mail: e.h.f.vanasseldonk@ctw.utwente.nl
Abstract

In (re)learning of movements, haptic guidance can be used to direct the needed adaptations in motor control. Haptic guidance influences the main driving factors of motor adaptation, execution error, and control effort in different ways. Human-control effort is dissipated in the interactions that occur during haptic guidance. Minimizing the control effort would reduce the interaction forces and result in adaptation. However, guidance also decreases the magnitude of the execution errors, which could inhibit motor adaptation. The aim of this study was to assess how different types of haptic guidance affect kinematic adaptation in a novel visuomotor task. Five groups of subjects adapted to a reaching task in which the visual representation of the hand was rotated 30°. Each group was guided by a different force field. The force fields differed in magnitude and direction in order to discern the adaptation based on execution errors and control effort. The results demonstrated that the execution error did indeed play a key role in adaptation. The more the guiding forces restricted the occurrence of execution errors, the smaller the amount and rate of adaptation. However, the force field that enlarged the execution errors did not result in an increased rate of adaptation. The presence of a small amount of adaptation in the groups who did not experience execution errors during training suggested that adaptation could be driven on a much slower rate and on the basis of minimization of control effort as was evidenced by a gradual decrease of the interaction forces during training. Remarkably, also in the group in which the subjects were passive and completely guided, a small but significant adaptation occurred. The conclusion is that both minimization of execution errors and control effort drives kinematic adaptation in a novel visuomotor task, but the latter at a much slower rate.

Keywords: motor learning, motor control, robot-aided rehabilitation, visual distortion, kinematic adaptation.
1 Introduction

Haptic guidance of movements can be used to demonstrate to a subject how fast and in which direction a movement should be performed. As such, haptic guidance is used for learning new skills in sports, but also for relearning motor control after a stroke (Kahn et al., 2006). In the latter case, the guidance was traditionally applied manually by a therapist. However, in the last decade, different robotic devices for neurorehabilitation (Colombo et al., 2000; Ferraro et al., 2003; Hogan and Krebs, 2004; Lum et al., 2002) have been developed that can provide continuous guidance during the recommended highly repetitive practicing (Kwakkel et al., 2004; Teasell et al., 2005).

With these therapy robots, different types of haptic guidance have been implemented. Soft guidance moves a limb through a pre-specified trajectory where deviations from this trajectory result in forces toward this trajectory (Aisen et al., 1997). For hard guidance, haptic tunnels are rendered. A subject can move within this tunnel (Kahn et al., 2006) but not outside the stiff walls of the tunnel. In passive guidance, the robot is position-controlled and enforces a pre-specified trajectory. Consequently, the subject does not need to contribute to the movement and can be fully passive (Hesse et al., 2003; Lynch et al., 2005). Finally, haptic force fields have also been used to increase, instead of reduce, errors in the execution of movement (Emken and Reinkensmeyer, 2004; Patton et al., 2006; Wei et al., 2005).

Our interest is to increase the understanding of the interactions between haptic guidance and the learning of a novel motor task. In the gross of computational motor control theories, the underlying principle is the minimization of both task-execution errors and control effort, (Shadmehr and Krakauer, 2008; Todorov, 2004; van der Kooij et al., 1999), which can be
defined as the required muscular energy to complete a movement. These latter two factors are also considered to be the driving factors of motor learning in different computational theories of motor learning (Franklin et al., 2008; Stroeve, 1996). Experimental studies show that minimization of both control effort and execution error indeed characterizes learning dynamics (Emken et al., 2007b; Scheidt et al., 2000). These studies made use of haptic devices, similar to those being used in neurorehabilitation, to study how subjects adapt when exposed to force fields applied to moving limbs. In the study of Scheidt and colleagues (2000), subjects first learned to reach in a viscous force field. Subsequently, the viscous force field was removed and kinematic after effects were prevented from occurring by using a rendered haptic tunnel. They showed that subjects made reaching movements while simultaneously exerting perpendicular forces to the haptic channel. These forces were similar to the forces required to compensate for the viscous force field.

Despite the absence of kinematic execution errors, subjects disadapted by decaying the forces exerted on the channel over the different movements. Still, the disadaptation occurred at a much slower rate than when kinematic errors were allowed to occur. Further evidence for a contribution of muscular effort in adaptation was recently provided by Emken and colleagues (2007b). They examined the adaptation to an externally applied force field during the swing phase of walking and showed that a model describing the temporal evolution of error (Scheidt et al., 2001; Thoroughman and Shadmehr, 2000) could be derived from minimization of a cost function, that is a weighted sum of the execution error and control effort.

Haptic guidance influences the driving factors of motor control and learning in different ways. Guidance directly influences the execution errors, either reducing or enlarging these errors. Though in a more indirect way, guidance also affects the control effort. Generally, guidance is
only applied when the movement deviates from the optimal trajectory. The exerted forces against the walls of the wall are considered to be a dissipation of effort. Minimizing these interaction forces would result in the most efficient movement and therefore in the required adaptation. It is not yet known how these manipulations of the driving factors interfere with the process of motor adaptation. The aim of this study was to assess how external guidance influences motor adaptation.

In previously discussed studies, motor adaptation was studied by exposing subjects to a force perturbation that simulates a viscous load. This kind of perturbation is unsuitable for studying the net effect of guiding force fields as the guiding forces would interfere with these disturbing forces. Therefore, we applied different types of haptic guidance while subjects adapted to a kinematic distortion, that is, a visuomotor task. In this task, subjects made center-out reaching movements while the visual feedback of hand-movement direction was rotated 30 degrees counter clockwise by making use of a virtual reality setup (Caithness et al., 2004; Ghez et al., 2000; Krakauer et al., 1999; Sainburg and Wang, 2002; Tong et al., 2002; Wang and Sainburg, 2005). To discern the adaptation based on execution errors and control effort, different types of haptic guidance that are commonly used in therapy robots were applied. All but one of these force fields applied forces only in the direction perpendicular to the target direction, which necessitates the subjects to move in the target direction themselves. Subjects in the error-enhanced group (EE) received hand forces that were proportional and in the same direction as the execution errors, defined as the deviations from the straight path toward the target. These forces effectively enlarged the execution errors. In the soft (SG) and hard-guidance (HG) groups, error-correcting forces were applied to the hand that were proportional but opposite to the execution errors. In the soft-guidance group, the low stiffness of the force field still allowed considerable execution errors. However, in the hard-guidance group, the
high stiffness formed a haptic tunnel, denying all but very small deviations (<1.5 mm) from the optimal trajectory. This tunnel was similar to the tunnel used by Scheidt and colleagues (2000). In the passive group (P), the subjects were moved along the optimal trajectory by the robot and were instructed not to intervene. In this case, execution errors were zero and the control effort did not influence task performance. In the control group (A), no additional guidance was applied.

Previous studies on adaptation to force perturbations showed that adaptation based on execution errors occurred at a faster rate than adaptation based on minimization of effort. Therefore, we hypothesize that when execution errors are increased (EE) or reduced (SG) by haptic guidance, the rate of adaptation will be faster or slower respectively, and in both cases adaptation will be complete. In case execution errors are prevented (HG) but subjects have to actively move their hand toward the target, we hypothesize that adaptation still occurs but at a much slower rate than in the A, EH, and SG groups. In this case, adaptation is driven by minimization of control effort solely. For the passive group, we hypothesize that adaptation is absent since no execution errors occur and control effort is not related to task instruction and performance.

2 Materials and Methods

2.1 Subjects

Fifty healthy subjects (age 20-50 yr, 16 female) were included, all submitting their written informed consent prior to the experiment. The protocol was approved according to the institution’s regulations. All subjects were right-handed, had no history of neurological impairments, and had a normal or to-normal-corrected vision. The subjects were randomly
assigned to one of the following training programs, “Active” (A), “Passive” (P), “Hard Guidance” (HG), “Soft Guidance” (SG), and “Error-Enhanced” (EE) training.

2.2 Experimental apparatus and recordings

The subjects were seated (see Fig. 1) and made reaching movements in the horizontal plane with their right arm while the right hand was holding the “end-effector” of a 3D haptic robot, the HapticMASTER (Moog FCS, Nieuw-Vennep, The Netherlands). The HapticMASTER was restricted to functioning in the horizontal 2D plane. The force exerted on the hand by the HapticMASTER was controlled at 2500 Hz to create the guiding forces described below in further detail. The arm robot was placed in a closet-like box. The subjects were instructed to look into a mirror to see a projection of their right-hand position on a screen located parallel and just above the mirror. The combination of a mirror and projection screen gave the illusion that the projected image was in the same horizontal plane as the hand, resulting in a veridical projection. The mirror also prevented direct sight of the arm. The right-hand position was indicated with a 6-mm blue sphere, in the following referred to as “cursor.” The targets were presented as yellow spheres with a 10-mm diameter. The visual scene was updated with a frequency of 100 Hz. The arm was supported against gravity by a support mechanism that allowed low-friction movements over the underlying surface (see Fig. 1). The arm support also prevented wrist movement. As a result, movements of the hand were restricted to the horizontal plane. Velocity and position data of the end-effector of the HapticMASTER were sampled at 200 Hz.

INSERT FIGURE 1 ABOUT HERE
2.3 Procedure

Subjects made centre-out reaching movements with their right hand to one of five different targets equally spaced (72° apart) about the perimeter of a circle of 10-cm radius. The center of movements was always in the midsagittal plane 10 cm beneath right-shoulder position. The starting posture was obtained by a shoulder plane of elevation rotation (Wu et al., 2005) of 45° and elbow flexion of 90°. At the start of each trial, a target was presented and a short “beep” triggered movement. The order of the targets was randomized in each cycle, where a cycle consisted of one trial to each target (five movements). Subjects received feedback about the accuracy of the movement duration by means of target color and a sound. The target color changed into green when the cursor was inside the target within the prescribed time interval [510-690 ms] and a normal tone was heard. Too-fast or too-slow movements were accompanied by a change in the color of the target into blue and red respectively, and a dropping and refuting sound. During all stages, the number of accurate reaches was shown on the visual display in the right upper corner. Between movements, the cursor was made invisible while the arm was returned to the starting position by the robot.

Visual distortion of hand position, during training and extended training, was a 30° CCW rotation about the starting location of movements. When exposed to the visual rotation, subjects received different force fields, depending on the group to which they were assigned. In addition to the force fields, all groups except P also felt the inertial forces of a 2 kg virtual floating mass in the virtual environment created by the admittance-controlled haptic robot.

- Group A (Active learning) did not receive any additional forces during training.
- Group P (Passive training) subjects were moved along the optimal trajectory to the target by stiff control ($K=5000$ N/m) of the robot. This optimal trajectory was defined as a straight line from centre to target position, with a bell-shaped velocity profile:
where $T$ is the movement duration ($T = 600$ ms), $t$ is time and $y_R$ is the distance between centre and target. Subjects in this group were specifically instructed not to intervene with the applied robot, so not to assist or resist the imposed movements.

- Group HG (Hard-Guided training) movements were restrained to the desired path by a stiff force field perpendicular to the optimal trajectory acting on the right hand. Since the stiffness along this optimal trajectory was zero, the subjects were free to control the progress along the path. Force $F$ is a function of deviation from a straight path from the start to the target:

$$F(e) = K \cdot e,$$

with $K = 5000$ N/m. Cursor trajectory error $e''$, same in magnitude as hand trajectory error $e$, was described as the distance between current cursor position and the y-axis, the optimal hand trajectory (see Fig. 2). $F$ is a force directed toward the optimal trajectory. The relation between force and deviation is visible as a high-gradient surface “V,” shown in Fig. 3A.

- Group SG (Soft-Guided training) experienced a similar force field as group HG but with a smaller stiffness ($K = 300$ N/m). The low gradient gray surface in Fig. 3A illustrates the soft-guidance force-error relation.

- Group EE (Error-Enhanced training) was exposed to an error-enhancing force field. When subjects deviated from the optimal path, they experienced a force that pushed them even farther away. In this case, $F$ was described as

$$F(x,y) = \begin{cases} 
A(y) \cdot \left( \frac{1}{2} - \frac{1}{2} \cos \left( \frac{2\pi e}{B} \right) \right), & 0 \leq e \leq \frac{1}{2}B, \quad \frac{3}{2}B \leq e \leq 2B \\
0, & e > 2B \\
A(y), & \frac{1}{2}B < e < \frac{3}{2}B 
\end{cases}.$$
where $B = 0.05 \text{ m}$ is a quarter of the area in which forces are present (See Fig. 3B).

Factor $A(y)$, expressed as

$$A(y_C) = -K \cdot y_C,$$

was a maximum force ($K = 500 \text{ N/m}$), dependent on current position $y$-value ($y_C$), the distance between centre and the projection of hand position on the optimal path.

Each group attended a program that consisted of four different stages, in the following order:

1. In the familiarization stage, the subject became familiar with the haptic and virtual environment. Participants executed 100 reaching movements, with every fifth movement a catch trial interspersed and the directions randomized per five movements. In the catch trials, during this stage and the washout stage, only the visual feedback of the cursor location was removed so subjects did not receive feedback on their performance and uncorrected movements were made. The last five trails were considered as baseline. During this stage, none of the groups experienced any form of haptic guidance.

2. During the training stage, participants performed the task in the visual-rotated field. All subjects performed 60 cycles of five trials (300 movements). Every 10th movement, a catch trial was interspersed to monitor the adaptation of subjects to the visuomotor rotation. In the catch trials, during this and subsequent stages, the visual feedback and group-dependent force fields were turned off. These catch trials were required to monitor adaptation to the visuomotor rotation during training. Generally, this is done based on the movement trajectory error (see Fig. 2 for error definition) in subsequent training trials (Tong et al., 2002). However, force fields influenced the magnitude of the error, which compromised error comparison of training trials in different groups. The absence of visual
feedback during the catch trials prevented active-learning movements to occur, given that reaching without additional forces with visual feedback would mimic the active-learning condition. As subjects in the passive group were not supposed to generate movements themselves during the training, the catch trials were preceded by an additional tone to make the subjects aware of when they were required to reach on their own.

3. The extended-training stage deviated from the previous stage in that movements during these generalization catch trials were directed to generalization targets that deviated 36° from the trained directions, that is, located exactly between the original targets along the circle. Furthermore, the catch trials occurred every fifth movement. Subjects performed 30 cycles of movement (150 movements), which included 30 generalization catch trials.

4. In the washout stage, visual feedback returned to “normal.” All visual distortions and force fields, if any, were turned off. This was the unlearning phase. Hand position was visible during all movements, with a total of 100 movements (20 cycles).

In total, subjects performed 130 cycles of five movements. With short time-outs between every stage, subjects spend approximately 36 minutes performing the experiment.

2.4 Data analysis

Movement position and velocity data of the hand were used to assess the reaching performance of the subjects in the different stages and conditions. We used the directional error as a measure of the execution error. Previous studies have shown that directional error is a sensitive and intuitive measure of adaptation to visuomotor rotations (Krakauer et al., 2000; Sainburg and Wang, 2002). The directional error is calculated as the angle between the vector from the starting position to the cursor position at maximum velocity and the vector from the starting position to the target (see Fig. 2). Furthermore, the directional error captures the
learning in feedforward control and is insensitive to contributions of feedback mechanism to the final portion of the reaching movement. Baseline performance was quantified as the mean directional error of the last cycle of reaching movements during the familiarization stage. The catch trials and the generalization catch trials were each divided into six blocks of five trials, and mean values of every block were calculated. The after effect was assessed by calculating the mean value of the directional errors of the first cycle in the washout phase.

As explained in the introduction, apart from using the execution errors in subsequent movements to adapt to the visuomotor rotation, subjects could also use the muscular effort. For the HG group the “haptic tunnel” prevented the occurrence of execution errors. Subjects could push into the haptic wall, however, as long as the force exerted on the end effector had a component in the direction of the target, the subject would reach the target. The force exerted in the direction perpendicular to the movement direction can be regarded as a waste of control effort. Minimizing the effort would be similar to minimizing these perpendicular interaction forces. We quantified the forces for the subjects in the HG as well as the SG and EE group by averaging them from the start to the end of every training movement during the training stage and the extended-training stage. The start was defined as the moment when the velocity in the direction of the target last exceeded the 10 cm/s before reaching the maximum velocity and the end as the moment when the velocity first dropped below zero, after having reached the maximum velocity. Subsequently, the trial averages were averaged over the non-catch trials in subsequent cycles of five movements.

2.4.1 Statistics
Baseline directional errors were compared by using an ANOVA with Group as between-subject factor. We tested whether the directional errors in the catch trails decreased in time
and whether the groups differed in the amount of adaptation by using a repeated measures ANOVA with Group as between subject factor and Time (the repeated measure of the directional errors in the subsequent catch blocks) as within subject factor. A similar repeated measures ANOVA was used to assess differences in generalization by using the generalization catch blocks for the within subject factor Time. We performed repeated measures ANOVA with Group as between subject factor and the direction errors in catch block 6 and generalization catch block 1 as repeated measures to assess if the directional errors to the generalization targets deviated from the errors in the trained directions. Differences in after effects were assessed by using an ANOVA with Group as between-subject factor. For all significant main effects, post hoc tests (with Bonferroni adjustments for multiple comparisons) were performed to deduce which groups differed significantly from each other. To assess whether the interaction forces decreased significantly during training for the HG, SG, and EE group, we performed a paired t-test for each group separately with the interaction forces in the first and last cycle as input. The level of significance was defined as p<0.05.

3 Results

At the end of the familiarization stage, subjects of all groups were accustomed to the virtual environment and had learned to reach in the virtual environment (see Fig. 4). Last movement cycles were used as baseline movements. Baseline trajectories were straight lines, and the baseline directional error did not significantly differ between the different training groups (p = 0.166).
3.1 Training trajectories

The effect of the applied forces on the hand path during early (first 25 movements) and late (last 25 movements) training is illustrated in Fig. 4 for a representative subject of each group. The group A subjects did not experience any additional forces, so as expected, these subjects showed hand paths that were initially directed roughly 30° counter clockwise to the target. During the course of the training, the subjects adapted to the visuomotor rotation as evidenced by the approximately straight trajectories during late training. The error-enhancing (group EE) and reducing (SG) forces led to larger and smaller curvatures of the initial hand paths, respectively. Also in these groups, the curvatures decreased during training. The aiming movements of group P and HG were forced along the optimal trajectory, resulting in absence of visible directional errors from the first training movement. The HG group had to generate the movement along the trajectory themselves, and consequently could show under and overshoot of the targets, as evidenced by hand paths passing the targets. On the contrary, the P group never showed an under or overshoot, as these subjects were moved by the robot along the optimal trajectory.

INSERT FIGURE 4 ABOUT HERE

3.2 Adaptation

The presence of the force fields during the training movements made a direct comparison of the directional errors during these movements impossible. Therefore, directional errors made in the catch trials were used to assess the adaptation to the visuomotor rotation. Figure 5 shows the group averages for the different catch blocks. The repeated measures ANOVA showed that there was a significant main effect of Time (p<0.001) and Group (p<0.001) and a significant interaction effect of Group and Time (p=0.015) on the directional errors in the
catch blocks. These results indicated that the groups on average adapted to the visuomotor rotation, that the directional errors in the different groups differed from each other and that the groups did not show similar changes over the different blocks of catch trials. *Post hoc* comparisons revealed that groups A and EE adapted the most to the visual rotation, expressed by directional errors that were significantly smaller than the errors of the SG (p=0.002 and p=0.024, respectively), HG (p<0.001 for A and EE) and P (p<0.001 for A and EE) group. The directional errors of the SG, HG, and P group did not differ significantly from each other.

Fig. 5 shows that all groups, except P, exhibit a gradual decrease of directional errors in the catch blocks, though the rate of change differed among groups, which was also expressed in the significant Group x Time interaction effect. To explore the different rates of adaptation further, we assessed for each combination of groups from which catch block onwards the groups showed a significant difference (see Table 1). Group A and EE did not differ significantly in the rate of adaptation as for none of the catch blocks a significant difference was found. The adaptation rate for these groups was higher than that for SG, HG, and P group. The SG group showed an intermediate adaptation rate. It took longer before group A showed a significantly smaller directional error for SG than for the HG and P group, yet the SG, HG, and P group did not show any lasting significant difference.

**INSERT FIGURE 5 ABOUT HERE**

**INSERT TABLE 1 ABOUT HERE**

In addition to the execution errors during the catch trials, adaptation could also be derived from the average forces on the hand during the training trials. As the exerted forces on the hand were dependent on the deviation from the optimal path, a decrease of the forces would
be indicative of adaptation. Fig. 6 shows the forces on the hand (averaged across subjects) as a function of the cycle. The average hand forces in the EE group were larger than those in the SG and HG groups. This could be mainly attributed to the unstable character of the EE force field, in which forces were directed to further increase execution errors. The difference in magnitude between the SG and HG group could be attributed to the larger stiffness used in the HG group. The gradual, significant (p<0.001) decrease of the forces in the SG and EE group confirmed the results of the catch trials that subjects in these groups clearly adapted to the visuomotor rotation. Remarkably, the HG group also showed a significant decrease (p<0.001) in the forces on the hand, which would point at the presence of adaptation. This adaptation is not likely to be driven by the execution errors as the “haptic channel” in the HG prevented the occurrence of large execution errors. The average hand force in the first and last cycle were 6.5 and 2.7 N, which with the used stiffness of 5000 N/m is equivalent to deviations of the optimal path of 1.3 mm and 0.54 mm, respectively.

INSERT FIGURE 6 ABOUT HERE

3.3 Generalization

By using generalization catch trials, we assessed how well subjects were able to use the learned visuomotor rotation in reaching to targets that were positioned exactly in between each pair of adjacent training targets. All groups performed equally well on reaching to the training targets as to the generalization targets, as there was neither a significant main effect of the repeated measure nor an interaction effect. Therefore, it can be expected that the differences between groups found in the generalization catch blocks are similar to those of the catch blocks. A second repeated measures ANOVA (with the six generalization catch blocks as repeated measure) confirmed these expectations. There was a main effect of Group
(p=0.001) and post hoc tests showed that directional errors for Group A and EE were significantly smaller than HG (p=0.023 and p=0.014) and P (p=0.027 and p=0.016) and that directional errors of SG, HG, and P did not significantly differ from each other (see horizontal brackets in Fig. 5). The only difference was that A and EE did not differ significantly from SG during generalization. Apart from these group effects, there was no main effect of Time or a Group x Time interaction effect. The absence of these effects indicated that none of the groups significantly increased their ability to reach to the alternative directions during the extended training stage.

3.4 After effects
The amount of adaptation in the preceding training stages was assessed by determining the after effects for the different groups when the visual rotation and any of the present force fields were turned off during the washout stage. The bottom row of graphs of Fig. 4 shows the hand paths of the first five movements for a representative subject of each group. Group A and EE showed clear after affects as their hand paths could be regarded as mirrored trajectories of those shown during initial training, as if they were learning a 30° clockwise rotation. The hand paths also show a late “hook” back toward the end of the motion, which are likely the result of feedback mechanisms. For the SG group, the hand paths also showed a clear after effect and a “hook” back, though the effects were smaller. The hand paths of the HG and P group also showed slight clockwise curvature in some of the reaching directions.

The after effects were quantified by averaging the directional errors during the first five reaching movements in the washout stage (see Fig. 5 for group averages). An after effect occurred when the directional errors during initial washout differed from the directional errors during baseline. We performed repeated measures ANOVA with Group as between subject
factor and baseline and average washout score as repeated measures to assess which groups showed an after effect. The test showed a significant Time (p<0.001) and Time x Group (p<0.001) effect, indicating that directional errors during washout were significantly different from directional errors during baseline and that this difference was not equally large for all groups. Yet, post hoc comparisons indicated that for all groups this difference was significant (P: p=0.001, other groups: p<0.001), and, as a consequence, all groups showed after effects.

To compare the magnitude of the after effects between groups, a one-way ANOVA was conducted. The ANOVA showed that there was a main effect of Group (p<0.001). The post hoc tests mainly confirmed the previously described differences in adaptation between the groups based on the catch trials. The effect between Group A, EE, P, and HG were similar: Group A and EE (p=1.00) and Group P and HG (p=0.643) did not differ significantly from each other, whereas group A and group EE showed significantly larger after effects than group P (p<0.001 for A and EE) and HG (p<0.001 for A and EE). The main deviation with the adaptation results from the catch trials lies in the comparisons between the SG group and the other groups. The intermediate status of the SG group between Groups A and EE on one side and Groups P and HG was now also supported by significant differences and not merely from the absence of differences with groups on either of the sides. The after effect of SG was significantly larger than the after effect of the HG (p=0.005) and P(p<0.001) Group and was smaller compared to the A group (p=0.039) and EE group (p=0.528), though the last effect was not significant.

4 Discussion
In this study, we investigated the effect of providing haptic guidance during adaptation to a visuomotor rotation. The amount and direction of the provided guidance was manipulated
through the use of force fields that differed in their dependency on the magnitude of the execution errors. Our data seem to provide support for the hypothesis that both the control effort and execution errors can be used for kinematic adaptation. Yet the control effort is not used as effectively as the execution errors, as they cannot prevent a decrease in the rate of adaptation as a consequence of reduced execution errors while receiving guidance. In the next paragraphs, we will further examine the role of execution errors and minimization of control effort.

4.1 Execution errors

The hypothesis that learning rate decreases when execution errors are reduced by haptic guidance was supported by the found differences in the amount of adaptation and after effect between A group and the SG and HG groups. The hypothesis that in SG and HG condition the kinematic adaptation would be complete could not be confirmed nor refuted since although at the end of training the directional error in the catch trials were significant larger than for the A and EE groups, this error still seemed to become smaller as training time progressed. The hypothesis that learning rate increases by magnifying the execution error with haptic feedback could not be confirmed since no significant differences were found between the A and EE group.

There are two possible explanations for this absence of increased adaptation (rate). First, our assessment of adaptation might not have been sensitive enough for subtle changes in the rate of adaptation. We used catch trials every 10th movement to monitor adaptation and averaged the directional error of five subsequent catch trials. Consequently, the first data point during exposure reflected the average performance over the first 50 movements (=10 cycles).

Previous studies (Caithness et al., 2004; Krakauer et al., 2000) have shown that during the
first 10 cycles, adaptation occurs at its highest rate. To have a closer look at these cycles we
omitted the averaging and compared the directional errors in the first five catch trials between
the A and EE group by using repeated measures ANOVA. This analysis showed that the
directional errors did not differ between the groups on any of the catch trials, further
confirming that adaptation occurred at an equal rate for these groups. Second, the error-
enhanced forces might have changed the nature of the task. As the forces increased the
reaching error, they made the task inherently unstable. Burdet and colleagues (Burdet et al.,
2001; Franklin et al., 2003) demonstrated that executing arm movements in an unstable
dynamic environment resulted in an increase of the impedance in the direction of the
instability. Therefore, subjects who attended the EE training program might have adapted
their impedance during reaching, in addition to the adaptations in the pointing direction. The
adaptations in impedance might have slowed down the adaptation to the visuomotor rotation,
per se. The negative stiffness we used (-500 N/m) was even more unstable than the force field
used by Burdet and colleagues (-300 N/m) so it is very likely that shaping of arm impedance
did occur in the EE group.

Wei and colleagues (2005) implemented error augmentation during learning of a 30°
visuomotor rotation by providing visual feedback in which the deviations from the optimal
straight trajectory were amplified with a gain of two. They showed that a group of subjects
receiving visual-error augmentation during learning had a more than twice as large learning
rate than a control group, which implies that magnification of execution errors without
“disturbing forces” does have a positive effect on adaptation.
4.2 Control effort

For the HG, SG, and EE group, a strategy minimizing the control effort as reflected by the reduction of interaction forces would have resulted in adaptation. These interaction forces indeed showed a small but gradual decrease during the course of training (Fig. 6.), showing that subjects little by little adapted their reaching direction, pushing less into the haptic wall. The decrease in interaction forces could have accompanied adaptation based on execution errors for the SG and EE group. However, for the HG group, the decrease in interaction forces cannot be explained from changes in execution error, as the haptic tunnel constrained the experienced execution errors to practically zero. Therefore, this adaptation is likely the result of minimizing the effort. Still, this adaptation occurred at a very slow rate as the HG group only showed a significant after affect and did not show significant adaptation in the catch trials during training.

This was the first study to show that minimization of control can also contribute to kinematic adaptation in a visuomotor task but at a much slower rate than minimization of execution errors. Previous studies (Emken et al., 2007b; Scheidt et al., 2000) have already shown that minimization of control effort plays a role in kinetic adaptation to novel dynamic environments and that it is less effective than minimization of execution errors.

4.3 Possible other mechanisms underlying adaptation

Our prediction that kinematic adaptation would be absent in the P condition was not in accordance with the significant after effect we found for the P condition. Neither minimizing execution errors nor minimizing control effort can explain the small amount of adaptation we found in the P group. This implies that another mechanism underlies this adaptation.
Candidate mechanisms are based on use of a cognitive strategy and on resolving a conflict between the different sensory modalities. First, subjects in the P group could have used a cognitive strategy during training. This could explain the large variation in the response in the catch trials of the subjects in the P group as some of these subjects might have been aware of the rotation and used a cognitive strategy during catch trials, whereas others did not. The use of cognitive strategies can explain the large variation, however it is not likely that it can explain the small adaptation as reflected in the after effect (Mazzoni and Krakauer, 2006).

Second, the rotation of the visual feedback resulted in a conflict between the proprioceptively and visually perceived hand position. This mismatch could, in theory, be used to drive adaptation (Baraduc et al., 2001). However, a major role of this mechanism is also not likely as the magnitude of the inter-sensory discrepancy was equal for all groups (including the P group), whereas the groups showed different rates and levels of adaptation. Still, if only this mechanism plays a minor role it could explain the small after effects for the P as well as the HG group. The decrease of the forces in the HG group could be a secondary effect of resolving the inter-sensory mismatch. In fact, based on the results of this study, we cannot discern whether minimizing the control effort and/or the inter-sensory discrepancy drives the small adaptation seen in HG.

4.4 Generalization

For all groups, the kinematic adaptation generalized well to other reaching directions than those trained. The generalization catch trials showed that the direction error during reaching to untrained directions were not statistically significant from reaching to trained directions. So by only learning five directions, the subjects were able to interpolate the locally learned directions, to the intermediate directions without significant degradation of the performance. The difference in performance on the generalization catch trials between the groups could be
explained by the differences in performance on the catch trials. Therefore, it can be concluded that the difference between the groups in nature and extent of the error signals only affected generalization through the amount of adaptation and did not affect generalization in a different way, for example, by inducing more locally learned directions.

4.5 Limitations of study

In this study, we assumed that interaction forces are indicative for control effort. Control effort can be defined on various levels, like on joint torque, muscle tension, or metabolic energy consumption level. In realistic musculo-skeletal models, an energy-related cost function appeared to be a better measure for muscle energy consumption than muscle stress cost functions and led to more realistic predictions of muscle activation (Praagman et al., 2006). Such realistic models should be used to verify the assumption that minimization of control effort results in minimization of interaction forces when moving in haptic fields. A more direct measure of control effort could be the measurement of muscle activity of the major arm muscle groups (Franklin et al., 2008).

4.6 Implications for motor (re)learning in neurological rehabilitation

Robotic devices are used more and more to facilitate movements of the impaired limb using guiding forces similar to those in this study (Hogan and Krebs, 2004). The reasoning behind this is that relearning the control of movements in stroke patients is akin to motor learning (Hogan et al., 2006; Krakauer, 2006). Systematic overviews of clinical studies have shown that the effect of training in stroke patients is task-specific and largely dependent on the intensity (Kwakkel et al., 1999; Van Peppen et al., 2004). This is in concordance with studies showing that possibly similar neural correlates (Ward, 2006) underlie recovery (Ward et al., 2003) and motor learning (Hikosaka et al., 2002). The exact nature of neural plasticity is not
yet known, yet it seems that repetitive time correlated motor and sensory stimulation of brain regions is required.

Different algorithms have been implemented to calculate the required guiding forces, including algorithms similar to our “soft guidance” (Aisen et al., 1997), “hard guidance” (Kahn et al., 2006) and “passive” (Hesse et al., 2003; Lynch et al., 2005) conditions. In one study (Ferraro et al., 2003), an algorithm was used that adapted the amount of assistive forces during the course of rehabilitation to the motor abilities of the patients. Patients trained with this performance-based progressive therapy showed larger decreases of impairments compared to stroke patients whose assistive forces were not adapted (Hogan et al., 2006).

Based on this and our results here, we suggest that for optimal relearning, patients actively generate the movements and learn from the execution errors. However, guiding forces could be used to keep the execution errors within reasonable bounds. To prevent an over reliance on guiding forces -potentially slowing down further relearning -we suggest that the amount of support should be progressively lowered in the course of rehabilitation (Cai et al., 2006; Emken et al., 2007a).

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5 References


Figure legends

**Fig. 1.** Schematic overview of experimental setup. Subjects sat behind a closet-like box and held with their right hand the end-effector of a haptic robot. Subjects looked into a mirror just below shoulder level to a projection of their (rotated) right hand position and the targets. The mirror prevented sight of their right arm. The arm was supported by a surface through a mechanism that allowed horizontal movements with low friction.

**Fig. 2.** Definitions in the calculation of the guiding forces and the direction error, and the five types of therapeutic guiding forces used. In the top-left figure, error (e) is the distance x’ from current cursor (small sphere) position to the y’-axis, which is also the optimal cursor trajectory from centre to target (large sphere). Force F, dependent on hand position error (e = e’), acts on the arm and is perpendicular to the y-axis and parallel to the x-axis. The cursor path is 30° CCW rotated from the actual hand position. Symbol α represents the angle between cursor position at maximum velocity (v_{max}) and optimal trajectory. In the other five figures, the ’active’ condition had no guiding forces, the ’error-enhanced’ forces which increase any error made, ’soft-guidance’ forces which decrease these errors, ’hard-guidance’ forces which kept the hand from making any rotational errors, and finally in the ’passive’ condition, the hand was passively moved towards the target.

**Fig. 3.** Forces exerted on the hand as a function of the deviation of the optimal trajectory (x) and the distance to the target(y). The forces are exerted in a direction perpendicular to the optimal trajectory. In A) the forces for soft guidance (300 N/m) and hard guidance (5000 N/m) are depicted. These forces “pushed” the hand of the subject toward the optimal trajectory in order to decrease the reaching errors. (B) indicates the error-enhancing forces, which were directed away from the optimal trajectory (indicated by the negative magnitude of the forces).
to increase the reaching errors. In A and B, the magnitude of the forces increases with the grayscale, though equal grayscale do not correspond with equal force magnitude in both figures.

**Fig. 4.** Representative hand-paths of a subject from each of the groups are compared to illustrate differences between hand paths during training (while they are exposed to the guiding forces) and wash out. The top row shows baseline hand paths, which are the last five movements during the familiarization stage. Hand paths of the first 25 movements (with the exception of the catch trials) performed during the training stage are shown along the second row, whereas the hand paths of the last 25 movements of the training stage are shown along the third row. The bottom row shows the after effects, which occur during the first cycle of movements during the wash out phase.

**Fig. 5.** Mean directional errors for the different groups and for the different stages. The circles indicate the average directional errors over the last cycle of movement during the baseline. The squares show the average value of the subsequent blocks of catch trials during the training stage. For the generalization catch trials, the average value over all blocks is depicted (triangle) as the different generalization blocks did not differ significantly from each other. The stars show the average directional errors over the first cycle of movements during the wash out, the after effects. The error bars indicate the standard deviation. The horizontal brackets in the gray shading on the top and bottom indicate the significant differences (assessed with repeated measures ANOVA) between the groups in the overall average of the catch blocks, the generalization and after effect.
**Fig. 6.** Average forces on the hand during the different training cycles for subjects in the Error Enhanced, Soft Guidance, and Hard Guidance group. Each point on the curve represents the mean of subjects means, across the five movements within a cycle (excluding the catch trails and generalization trials). The shading around the solid line indicates the standard deviation across the subjects. The first 60 training cycles are part of the training stage, whereas the last 30 cycles are part of the extended training stage.
Tables legends

**Table 1.** Rate of adaptation. The values indicate the catch block number from which on the directional error of the group indicated on the top was significantly (p<0.05) smaller than the group indicated on the left side. A smaller directional error indicates a faster adaptation to the visuomotor rotation. “—” indicates that there was no statistical significance between these groups for any of the catch blocks.

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Error-enhanced  Soft-guidance  Hard-guidance

Force on hand [N]  30  25  20  15  10  5  0
Training cycle  90  60  30  0

Figures showing force on hand (N) over training cycles for error-enhanced, soft-guidance, and hard-guidance conditions.