Effects of kinesthetic and cutaneous stimulation during the learning of a viscous force field

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Abstract—Haptic stimulation can help humans learn perceptual motor skills, but the precise way in which it influences the learning process has not yet been clarified. This study investigates the role of the kinesthetic and cutaneous components of haptic feedback during the learning of a viscous curl field, taking also into account the influence of visual feedback. We present the results of an experiment in which 17 subjects were asked to make reaching movements while grasping a joystick and wearing a pair of cutaneous devices. Each device was able to provide cutaneous contact forces through a moving platform. The subjects received visual feedback about joystick’s position. During the experiment, the system delivered a perturbation through (1) full haptic stimulation, (2) kinesthetic stimulation alone, (3) cutaneous stimulation alone, (4) altered visual feedback or (5) altered visual feedback plus cutaneous stimulation. Conditions 1, 2 and 3 were also tested with the cancellation of the visual feedback of position error. Results indicate that kinesthetic stimuli played a primary role during motor adaptation to the viscous field, which is a fundamental premise to motor learning and rehabilitation. On the other hand, cutaneous stimulation alone appeared not to bring significant direct or adaptation effects, although it helped in reducing direct effects when used in addition to kinesthetic stimulation. The experimental conditions with visual cancellation of position error showed slower adaptation rates, indicating that visual feedback actively contributes to the formation of internal models. However, modest learning effects were detected when the visual information was used to render the viscous field.

Index Terms—Cutaneous stimulation, kinesthetic stimulation, haptic force feedback, adaptation, dynamic perturbation, rehabilitation, visual perturbation

1 INTRODUCTION

In the last two decades, there has been a rapid increase in the number of research groups and companies developing robotic interfaces for the rehabilitation of persons with movement disabilities [1]. A variety of assistive control strategies have been designed, including robots that move limbs rigidly along fixed paths, robots that take action only if the patient’s performance fails to stay within some spatial or temporal boundary, and soft robots that form a model of the patient’s weakness [2], [3]. Mechanical devices for rehabilitation are, in fact, designed to interact with humans, guiding the upper limb through repetitive exercises based on a stereotyped pattern, and providing force feedback for sensorimotor type rehabilitative training [4].

One of the most important issues facing robotic movement therapy is the lack of knowledge on how motor learning during neuro-rehabilitation works [5]. Many researchers have studied motor adaptation to altered dynamic environments. A typical setting in this field consists of applying a viscous curl field during the execution of point-to-point reaching movements in the horizontal plane [6], [7]. Following the initial deviation from a straight trajectory (direct effect), subjects tended to adapt to the altered dynamic environment restoring the initial motion path (adaptation). The presence of aftereffects, as a result of perturbation removal, proved that the nervous system creates an internal model of the environment, able to predict the expected perturbing forces [8]. Feygin et al. investigated the use of haptics for skill training [9]. Subjects learned a 3D motion under three training conditions: haptic, visual, and visuo-haptic. They were then required to manually reproduce the movement under two recall conditions, i.e. with and without vision. Results indicated that haptic guidance is effective in training: while visual training was better for teaching the trajectory shape, temporal aspects of the task were more effectively learned from haptic guidance. Regarding the interaction between visual and haptic feedback during the adaptation of human reaching movements, Scheidt et al. showed how eliminating visual feedback of hand-path deviations from a straight-line reach prevents compensation of initial direction errors induced by perturbations [10]. Results showed that when visual feedback of movement was eliminated entirely, proprioception was enough to guide adaptive recovery of straight and smooth hand trajectories directed towards the final target. However, eliminating visual feedback of just the orthogonal hand-path errors did not lead to reduced direction errors. Finally, it is worth mentioning the work of Morris et al., who explored
the use of haptic feedback to teach an abstract motor skill which requires recalling a sequence of forces [11]. Participants were guided along a trajectory and asked to learn a sequence of one-dimensional forces via three paradigms: haptic, visual, and visuo-haptic. Results showed that recall following visuo-haptic training was significantly more accurate than recall following visual or haptic training alone, although haptic training was inferior to visual training.

Although many works analyze the role of haptics in the learning of a perceptual motor skill, it is still not clear how the central nervous system combines concurrent stimulation, such as proprioceptive, visual or haptic feedback. Moreover, the way the kinesthetic and cutaneous components of haptic feedback can influence such a process has not yet been clarified. We believe that this topic is fundamental for a better understanding of the role of haptic feedback in motor rehabilitation, and will help optimize the design of novel technological aids in this field.

1.1 Cutaneous and kinesthetic feedback

Most of the grounded haptic and rehabilitation devices provide a combination of kinesthetic and cutaneous stimuli to the user, if we assume that the interaction is mediated by a stylus, a ball, or any other tool mounted on the device [12], [13]. Cutaneous stimuli are sensed by pressure receptors in the skin, and they are useful for recognizing the local properties of objects, such as shape, edges, embossments and recessed features [14], [15]. On the other hand, through muscle spindles and the Golgi tendon organ, kinesthesia allows the user to sense the movement of neighbouring parts of the body and the forces being exerted [16], [17], [18].

The cutaneous and kinesthetic stimuli applied by a grounded haptic device, however, cannot be decoupled: the force provided is felt by the user both at the fingertips (cutaneous component), and at the muscle and joint level (kinesthetic component) [12], [13]. An interesting approach consists of using cutaneous devices to activate only the cutaneous component of the haptic interaction, which has been found to be a simple but effective solution for reducing the mechanical complexity of haptic devices, while guaranteeing adequate performance [12], [19], [20], [21], [22]. On the other hand, using a cutaneous device together with a grounded haptic interface allows one to independently control how much kinesthetic and cutaneous stimulation is provided to the user [13]. The authors of [23], for example, exploited this idea to design a stability controller which enhanced transparency of passive teleoperation systems with force reflection. A similar approach was used in [24] to enhance the transparency of a 7-DoF robotic teleoperation system.

1.2 Contribution

The aim of this paper is to investigate the role of the two components of haptic interaction during the learning of a viscous curl field, taking into account at the same time the influence of visual feedback in such a process.

Toward this challenging objective, we present the results of an experiment in which healthy subjects were required to make reaching movements while grasping a joystick handle, receiving visual feedback about joystick position and wearing, at the same time, a pair of cutaneous devices. The cutaneous devices were chosen with the specific goal of simulating, as close as possible, the cutaneous sensations provided by the contact with a haptic handle. Various experimental conditions were tested, using different combinations of kinesthetic, cutaneous and visual stimuli, with the aim of untangling what actually causes the adaptation: kinesthetic sensations, cutaneous sensations, and/or visual sensations. We hypothesize that all three separate components of the stimulation would cause adaptation, even though the two components of haptic feedback may have different roles. This hypothesis is based on the results of a previous study [12], in which cutaneous stimulation was effectively used in substitution of full haptic feedback during the execution of a needle insertion task.

Section 2 describes the design of the experiment and hardware setup, Sec. 3 presents the results of statistical analysis, and Sec. 4 addresses the discussion and outlines prospective work.

2 METHODS

2.1 Subjects

A total of 17 healthy subjects participated in the experiment. They were aged between 20 and 29 years (mean age 23.6 ± 3.0 years, 13 males, 4 females), 16 right-handed and one left-handed. All participants reported normal vision with no color blindness, and no hearing or cutaneous-sensibility problems. Written informed consent for participation in the experiments and for the publication of this report was obtained from all the subjects. The experiment received the ethical approval of the Scientific Commission of the University of Padua.

2.2 Setup

The experimental setup is shown in Fig. The subject sat on a chair, in front of an LCD screen and a 2-DoF haptic joystick [25]. A white panel prevented the subject from seeing the hand and the joystick. A custom plastic support was mounted at the top of the handle, housing two cutaneous devices, one for the thumb and one for the index finger (Fig. 2b). The other fingers were closed into a fist. In this way, the subject grasped the handle only with the fingers wearing the cutaneous devices. The direction of grasping (z) was always transversal with respect to the direction of motion (y), which was parallel to the sagittal plane.
Fig. 1: Experimental setup and feedback system. A 2-DoF haptic feedback joystick, equipped with two cutaneous devices, was placed on a table in front of a LCD screen, while a white panel prevented the subject from seeing the hand and the joystick.

of the subject. To prevent changes in the perceived direction of force and allow for a comfortable grasp, the subjects were instructed to keep the wrist slightly extended (Fig. 2b).

Each cutaneous device consisted of a static part, connected to the joystick, and a mobile platform (Fig. 2a). Three springs kept the platform in a reference configuration when the device was not actuated. Three servo-motors controlled the length of three wires connecting the static part to the mobile platform, allowing the latter to apply the requested force at the user’s fingertip [24]. An estimation of the exerted force was derived through a simple elastic model of the fingertip, with a linear relationship between platform displacement and resultant wrench. In other terms, we assumed that the platform configuration $\xi = K^{-1}w_p$, where

$$K = \begin{bmatrix} k_t I_3 & 0 \\ 0 & k_r I_3 \end{bmatrix}$$

with $k_t = 0.5$ N/m and $k_r = 0.5$ Nm/rad representing the translational and rotational stiffness constants, respectively [25]. This approach has been validated by the experiments carried out in [19], [19], [24].

In our experiments the cutaneous interfaces were used as 1-DoF devices (all motors pulled the cables together), so that only the forces in the sagittal plane of the finger were generated, roughly normal to the longitudinal axis of the distal phalanx.

2.3 Experimental protocol
Subjects were asked to perform forward ($+y$ direction) and backward ($-y$ direction) 13 cm-long reaching movements (reaches) between two fixed targets, as straight as possible. The exercise was divided into groups of 60 reaches (task), corresponding to 30 forward and 30 backward movements. The position of the hand with respect to the joystick was checked before the beginning of each task.

A fixed, red circular cursor on the LCD screen indicated the position of the current target. The target’s diameter was 0.5 cm in the joystick space, corresponding to 1 cm on the screen. A green circular cursor of the same size was printed on the screen, whose position along the $y$ axis corresponded to the position of the joystick in the back and forth direction. The $x$ position of the green cursor either denoted the lateral position of the joystick (actual visual feedback: VFA), or was set to zero (straight visual feedback: VFS). The latter mode corresponded to a cancellation of the left-right position error.

Subjects were asked to complete each reach (either forward or backward) in the time between two beeps of
a metronome playing at 33 bpm (one beep every 1.8 s). The metronome was used to standardize the duration of the reaches among subjects. Subjects were allowed a 30 second warm-up to practice the rhythm dictated by the metronome. The devices, the metronome and the graphic rendering were controlled by a real-time software (Matlab/Simulink R2012b) running at 200 Hz.

During each task, a dynamic perturbation was introduced from the 11th to the 50th reach, after which it was removed. The perturbation consisted of a viscous curl field, rendered to the subject in five different ways:

- **Cutaneous + Kinesthetic Stimulation (CS+KS)**
  The perturbation consisted of a viscous force \( f_x \), generated by the joystick. The lateral force was computed as a function of the velocity along the motion axis \((y)\):

\[
\mathbf{f} = \begin{bmatrix} f_x \\ f_y \end{bmatrix} = \begin{bmatrix} b_{1,1} & b_{1,2} \\ b_{2,1} & b_{2,2} \end{bmatrix} \cdot \begin{bmatrix} v_x \\ v_y \end{bmatrix}
\]

where all the elements of the viscosity matrix were set to zero except for \(b_{1,2} = 20 \text{ Ns/m}\). The endpoint force \(\mathbf{f}\) is given in Newtons, the velocity \(v\) in meters per second. It is worth noting that both the cutaneous and kinesthetic stimuli were provided by the haptic joystick, while the cutaneous devices were turned off.

- **Cutaneous Stimulation (CS)**
  The perturbation, as of Eq. 2, was provided by the cutaneous devices, while the haptic joystick was used to track the position of the hand only (it provided no force feedback). According to the sign of \(f_x\), the cutaneous force was applied either to the index finger \((f_x > 0)\) or to the thumb \((f_x < 0)\). This stimulation resembled the force field presented in the previous mode, but without the kinesthetic part of the perturbation. This approach of subtracting kinesthesia from the complete haptic interaction by means of cutaneous devices was introduced in [12], and it is called sensory subtraction.

- **Kinesthetic Stimulation (KS)**
  The joystick provided the same force feedback as in the first modality (CS+KS). Concurrently, the cutaneous devices were used to produce a 5 N force on the fingertip pushed by the joystick. In this way, the cutaneous stimulation originated by the joystick was completely masked. In fact, above a threshold of \(\sim 2 \text{ N} \) [27], [28], [29], the cutaneous receptors do not provide any perceivable sensation of increasing force. This condition is the closest to a pure kinesthetic stimulation.

- **Visual Distortion (VD)**
  In this mode, both the joystick and the cutaneous devices were switched off, and the perturbation was generated by providing altered visual information on the lateral position of the hand (visuo-motor transformation). The lateral \((x)\) position of the green cursor on the screen was set equal to the position error \(e_x\), computed as the difference between lateral joystick position \((x_j)\) and a viscous distortion \((x_r\), reference position) :

\[
e_x = x_j - x_r = x_s - b \cdot v_y
\]

where \(x_s\) and \(e_x\) are given in meters, \(v_y\) in meters per second, whilst \(b\) was set to \(-0.15\) s. This distortion emulated the effects of a lateral viscous force field, without providing any kinesthetic or cutaneous stimuli.

- **Visual + Cutaneous Stimulation (VD+CS)**
  The visual feedback provided to the subjects was the same as in the previous mode (VD). Concurrently, a cutaneous stimulation was generated as computed in the cutaneous mode (CS). This stimulation augmented the quality of the emulated force field, by combining the visuo-motor transformation with the stimulation of fingertips.

The five perturbations were combined with the visual modes (VFA and VFS) into eight experimental conditions (see Table 1): A, B and C included visual information about the actual position of the hand (VFA), combined with the active stimulation (CS+KS, CS and KS, respectively); F, G and H were the counterparts of A, B and C, with elimination of visual feedback on lateral position error (VFS); D and E included the visuo-motor transformation (VD), while the subjects received actual visual feedback (VFA) at baseline and after removal of the perturbation; E included cutaneous feedback also (CS).

The protocol consisted of eight tasks, each one corresponding to one of the experimental conditions. The conditions were alternated using randomized sequences. No information about the experimental conditions was provided to the subjects, neither on their nature nor on the particular order with which they were going to be presented.

### 2.4 Data analysis

We grouped the reaches of each task into 8 main phases, according to the motor adaptation literature [6], [7], [30]:

1) **Baseline**: the initial movements performed without perturbation (reaches 1–10).
2) **Direct effect**: the first reach with exposure to the perturbation (reach 11).
3) **Adaptation (Early)**: the following 12 reaches, during which the subjects started to adapt to the perturbation (reaches 12–24).
4) **Adaptation (Medium)**: the central phase of adaptation (reaches 25–37).
Visual feedback (VF) - Straight (S)

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<th>Straight (S)</th>
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<tr>
<td>Haptic stimulation (CS+KS)</td>
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<td>F</td>
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<td>Cutaneous stimulation (CS)</td>
<td></td>
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TABLE 1: Experimental conditions. Each subject performed eight different tasks in a randomized sequence. Visual feedback was provided during all the experiment, while perturbations were provided from the 11th to the 50th reach. Note that in these reaches, for both the VD and VD+CS case, the visual feedback modality was switched from VFA to VD in order to generate the viscous visual distortion.

5) Adaptation (Late): the last 12 reaches before removing the perturbation (reaches 38–50).
6) After effect: the first reach after removing the perturbation (reach 51).
7) Re-adaptation (Early): the phase during which the subjects started to re-adapt to movements without perturbation (reaches 52–55).
8) Re-adaptation (Late): the last phase of re-adaptation (reaches 56–60).

For each participant, both position errors (along the x direction) and movement speeds (along the y direction) have been analyzed in each reach.

The left–right average weighted position error was calculated as follows:

\[
\frac{1}{M_k} \sum_{h=1}^{M_k} \left( \sum_{i=n_{1h}}^{n_{2h}} \frac{-\text{sign}(v_{yi}) \cdot (x_{si} - x_{ri})}{n_2 - n_1 + 1} \right)
\]

where \(k\) denotes the phase and \(h\) the reach number; \(M_k\) is the number of reaches in phase \(k\); \(x_{si}, x_{ri}\) and \(v_{yi}\) are, respectively, the current \(x\) position, the \(x\) reference position and the \(y\) velocity of the hand \((i-th\) samples); \(n_{1h}\) and \(n_{2h}\) define the portion of the reach being analyzed. The reference position was \(x_{ri} = 0\) for all the experimental conditions except for conditions D and E, in which \(x_{ri}\) was the viscous distortion computed as in Eq. 3.

Let \(N_h\) be the number of samples in reach \(h\). The following portions of the reach have been considered: \(n_{1h} = 1, n_{2h} = N_h\) (entire reach); \(n_{1h} = 1, n_{2h} = N_h/2\) (first half of reach, in terms of travel); \(n_{1h} = N_h/2 + 1, n_{2h} = N_h\) (second half of reach). The first and the second half of the reach were analyzed separately with the aim of catching differences in terms of feedforward control during adaptation. In fact, according to motor adaptation studies, the initial error in a reach can be interpreted as a result of predictive or feedforward control while the remainder of the trajectory is likely determined by feedback control.

Regarding movement speeds, the peak of \(v_y\) and its temporal location within the reach (peak time) were computed for each reach and averaged within the phase.

Normality tests (Shapiro-Wilk normality test and D’Agostino-Pearson omnibus normality test) indicated a Gaussian distribution of all position and velocity measures. We run a two-way within-subjects ANOVA for each metric, with the phases and the experimental conditions as within factors. In the presence of significant effects, pair wise post-hoc comparisons (Tukey’s test) were performed.

For each experimental condition in which motor adaptation was found, we calculated the left-right weighted position error of the first half of each reach when perturbation was applied (reaches 11–50). For each subject, such data were least-square fitted with one-phase exponential curves, after smoothing with a 2-trial central moving average, to model the learning process as a function of trial number. The decay constants of the curves were compared by means of a one-way within subjects ANOVA, using the experimental condition as repeated measure, and post hoc comparisons were performed (Sidak’s test).

Two participants exhibited large variable errors and when questioned after the experiment it was apparent that they had misunderstood the task; thus their data were excluded.

## 3 Results

The mean trajectory and the average intra-subject standard deviation are shown in Fig. 3, 4, 5 for each experimental condition and phase.

The measures of peak movement speeds indicated interaction between the two factors (i.e., experimental condition and phase), with a prominent effect of phase (interaction: \(F(49, 686) = 1.675, p = 0.0033\); condition: \(F(7, 98) = 0.5396, p = 0.8026\); phase: \(F(7, 98) = 8.207, p < 0.0001\)). Comparable results were obtained from the analysis of peak time (interaction: \(F(49, 686) = 1.606, p = 0.0065\); condition: \(F(7, 98) = 0.7406, p = 0.6381\); phase: \(F(7, 98) = 5.748, p < 0.0001\)).

A limited number of significant comparisons resulted from Tukey’s test, mostly for conditions A and F (where full haptic feedback was used) and when the direct or after effects were compared to baseline.

These results indicate that the use of metronome roughly standardized velocity profiles among phases and conditions. Only the external perturbation, especially when provided in the form of full haptic interaction, tended to induce variations in the profiles, although limited to the cycles immediately following the introduction or removal of the perturbation.

The average peak movement speed was \(0.149 \pm 0.033 \text{ m/s}\), while peak time was \(0.555 \pm 0.071 \text{ s}\) on average (nearly one third of average reach time). The position of the peak, measured along the direction of reach, was at about 45% of the travel.
Fig. 3: Trajectories of experimental conditions A (VFA+CS+KS), B (VFA+CS), C (VFA+KS) in the different phases of the experiment. Average trajectory (solid lines), reference path (dashed lines), and average intra-subject standard deviation (patches) of the group are shown. Forward and backward movements are shown in orange and green respectively. The reference path is a vertical line fixed at $x = 0$. The average intra-subject standard deviation is the mean of the standard deviation for the every single experimental condition in each phase, obtained by calculating the variance for each subject in each phase from the sample data.
Figure 4 shows the position metric and its inter-subject standard deviation in all phases, for the entire reach (Fig. 4h) and for its first (Fig. 4b) and second half (Fig. 4c). Statistical analysis indicated a significant interaction between experimental condition and phase (interaction: $F(49,686) = 31.09$, $p < 0.0001$; condition: $F(7,98) = 30.40$, $p < 0.0001$; phase: $F(7,98) = 216.80$, $p < 0.0001$).

### 3.1 Direct and after effects

Pairwise post-hoc analyses indicated that all the conditions, except from B and G, exhibited significant direct effects when the force field was first applied ($p < 0.0001$, comparison with baseline). Indeed, conditions with CS alone, in presence of either VFA or VFS, showed no significant direct effects (B: $p = 0.9998$; G: $p = 0.8175$), regardless of whether the LCD screen provided information on the lateral position (comparison B–G: $p = 0.7931$).

Regarding the magnitude of the direct effect, no difference was found between A and D ($p = 0.6530$), indicating that the visual perturbation, as provided in D, was effectively tuned to simulate the dynamic perturbation applied in A. Direct effects were comparable between conditions with the same visual feedback (A–C: $p = 0.3546$; D–E: $p = 0.7931$; F–H: $p = 0.0661$) when the position metric was calculated on the entire reach. However, C showed a significantly greater direct
Fig. 5: Trajectories of experimental conditions F (VFS+CS+KS), G (VFS+CS), H (VFS+KS) in the different phases of the experiment. Average trajectory (solid lines), reference path (dashed lines), and average intra-subject standard deviation (patches) of the group are shown. The reference path is a vertical line fixed at $x = 0$. Forward and backward movements are show in orange and green respectively. The average intra-subject standard deviation is the mean of the standard deviation for the every single experimental condition in each phase, obtained by calculating the variance for each subject in each phase from the sample data.
Fig. 6: Average weighted position error in the x direction of all the experimental conditions (A: VFA+CS+KS; B: VFA+CS; C: VFA+KS; D: VD; E: VD+CS; F: VFS+CS+KS; G: VFS+CS; H: VFS+KS), for different phases of the experiment. The error bars represent the inter-subject standard deviation, i.e. the standard deviation computed in each phase by using the weighted position error of each subject as data set.
effect with respect to A in the first half of the reach ($p = 0.0208$), while H had a greater direct effect with respect to F in the second half of the reach ($p = 0.0004$).

Thus, the first result is that the participants exhibited comparable direct effects when what was applied was a sudden perturbation in the presence of either a kinesthetic or an altered visual feedback, i.e., cutaneous feedback alone was not sufficient to generate direct effects. On the other hand, when used in addition to kinesthetic stimulation, cutaneous feedback played a role in reducing the direct effect, at least in selected portions of the reach. However, this last point needs deeper investigation.

The direct effect was also compared between similar perturbation modalities with different visual feedback (VFA and VFS respectively), without finding significant effects (A–F: $p = 0.2893$; C–H: $p = 0.0514$). This result was confirmed when direct effects were calculated in the first half of the reach (A–F: $p = 0.9993$; C–H: $p = 0.2481$). However, F and H showed significantly greater direct effects with respect to A and C in the second half of the reach (A–F: $p = 0.0283$; C–H: $p < 0.0001$). This result is in accordance with Fig. 3a and Fig. 5f, where the direct effect traces indicate little to no late movement compensation, due to the lack of visual information on the lateral position of the hand.

All the experimental conditions presenting direct effects showed also significant after effects when the perturbation was unexpectedly removed (A, C, F, H: $p < 0.0001$; D: $p = 0.0014$; E: $p = 0.0125$; comparison with baseline). Such effects were comparable in magnitude between conditions without visual distortion (A–C, F–H, A–F, C–H: $p > 0.9999$), while conditions D and E presented significantly smaller after effects with respect to the others ($p < 0.05$).

3.2 Adaptation

Following the direct effect, in the experimental conditions with VFA and VFS (A, C, F, H), the subjects adapted to the alteration provided, reducing their position error. Indeed, the error in the last adaptation phase differed significantly if compared with the direct effect ($p < 0.0001$). Instead, D and E didn’t present significant adaptation ($D: p > 0.9999$; $E: p = 0.9227$), and the final errors were similar between the two conditions ($p > 0.9999$). These results suggest that kinesthetic stimulation plays a primary role in adaptation.

One-way ANOVA on the decay constants indicated significant effect of experimental condition ($F(3, 42) = 7.790$, $p = 0.0003$). The decay constants were smaller for the conditions with VFA if compared with the ones with VFS (A–F: $p = 0.0320$; C–H: $p = 0.0478$), suggesting that the visual information on lateral error helped the subjects to gain higher adaptation rates. On the other hand, adaptation rates were comparable in conditions sharing the same visual condition (A–C: $p = 0.1570$; F–H: $p = 0.9971$), indicating that cutaneous feedback had little or null effect on adaptation.

By analyzing the first half of the reach, where feedforward control is likely to play a major role, conditions D and E showed significant differences between direct effect and late adaptation ($p < 0.0001$). This result lies in accordance with [34], where subjects exposed to a visual viscous perturbation showed adaptation in the first portion of the reach. On the other hand, the second half of the reach revealed no reduction of the position error in the reaches following direct effect.

4 DISCUSSION AND CONCLUSION

4.1 Cutaneous and kinesthetic stimulation

In our experimental setting, cutaneous cues simulating the presence of a viscous force field did not bring any significant direct or after effects when used alone, regardless of the visual feedback provided to the subject (with or without cancellation of position error). Only small contributions, in terms of reduced direct effects, were found in selected portions of the reach when cutaneous stimulation was delivered together with kinesthetic stimulation. On the other hand, all experimental conditions including kinesthetic stimulation (A, C, F, H) brought significant adaptation, aftereffects and re-adaptation, regardless of the cutaneous or visual feedback concurrently being provided. This result suggests that kinesthetic stimulation plays a primary role in robot-induced motor adaptation, while little contribution is provided by the cutaneous part of haptic interaction.

The lack of importance of cutaneous feedback in our experiments, partly conflicts with our initial hypothesis, and with the numerous works highlighting the prominent role of cutaneous forces in recognizing shapes [35], in curvature discrimination tasks [19], [36], and, more generally, in improving the illusion of presence in virtual and remote environments [12], [37], [38]. One explanation may be that the deformation of the finger pads, if not supported by a consistent measure of force by kinetic receptors, is not sufficient to produce the perception of viscosity [39]. It may also be that using wearable cutaneous devices, leaving the participant free to interact with the joystick in a more natural way [12], [13], would have helped in better outlining the role of cutaneous stimulation.

For example, in [12], Prattichizzo et al. analyzed the role of cutaneous feedback in teleoperation. They substituted haptic force feedback, provided by a common single-contact haptic interface, with cutaneous stimuli only, and registered the performance of 16 subjects during a 1-DoF telemanipulation task. Their results showed improved performance with respect to traditional sensory substitution techniques, but still not as good as employing a kinesthetic stimulation. A similar result was also presented in [24], where the role of cutaneous force in a more challenging telemanipulation task was analyzed. The participants were asked to perform a peg-in-hole experiment in a
virtual scenario employing (1) cutaneous feedback only, (2) cutaneous and kinesthetic feedback, (3) kinesthetic feedback only, and (4) no force feedback at all. Similarly to [12], cutaneous force showed worse performances than for experimental conditions where kinesthesia was provided, but, unlike the results presented in this work, it showed better performances than for the case providing no force feedback at all.

The discrepancies between the results presented in this work and the ones in [12], [24] can be related to the fact that they dealt with very different environments as well as tasks. The cutaneous and kinesthetic feedbacks provided in the previous works were related to the properties of the virtual environment (i.e. the presence of an object) and were always coherent with the visual information being provided. Force feedback was always directed opposite to the motion of the user’s hand and proportional to its displacement, as the haptic interaction was designed according to the god-object model [40]. Instead, in the work presented here, the force perturbation was always perpendicular to the motion of the user’s hand and proportional to its velocity, measured along the direction of motion. Moreover, in [12], [24], visual feedback provided very limited information about the task being performed. This may have led users to concentrate more on the force cues than they did in the experiments presented here, where visual cues had a prominent role.

4.2 Viscous visual and video-cutaneous perturbations

The importance of kinesthetic stimulation is also clear if we compare tasks with visual distortion (D, E) to the ones in which kinesthetic stimuli were provided (A, C, F, H). All of them showed significant direct effects, but the latter had greater aftereffects and adaptation.

It must be underlined that, in conditions D and E, the subjects were forced to learn a velocity-dependent trajectory model that consisted of moving along a non-straight curve (see reference paths in Fig. 4). On the opposite, in all other tasks the target trajectory was straight. To this regard, tasks D and E appeared different if compared to the other experimental conditions. Nonetheless, conditions in which viscous visual (D) and video-cutaneous perturbations (E) were provided to the subjects showed some learning effects, indicated by significant aftereffect and reduced hand-path error following direct effect (limited to the analysis of first half of each reach). This result is consistent with Bock et al. [41]. In that study, subjects were instructed to point on a digitizing tablet when a viscous visual distortion was introduced, by displacing a feedback cursor proportionally to hand velocity. Also, a viscous force field was provided to another group of subjects. By analyzing the average position error in the first part of motion, they found that participants were able to adapt to both the visual distortion and to the force field. The adaptation rate of the group receiving visual distortion, however, looked slower with respect to that obtained with the force field.

Another similar study was performed by Wolpert et al. [41], in which the visual feedback of hand position was altered so as to increase the perceived curvature of the movement during self-paced point-to-point arm movements. Increasing the perceived curvature of normally straight sagittal movements led to to significant corrective adaptation in the curvature of the actual hand path: the movement became curved, thereby reducing the visually perceived curvature. However, in this case the distortion was not related to velocity.

We can summarize by saying that the contribution of kinesthesia to motor adaptation can only partially be replaced by visual information reproducing the alteration of motion which would result from the application of a lateral force field. This suggests that the information provided through the visual sensory channel, if not corroborated by kinesthesia, is not sufficient to produce the same alterations in the subject’s motor control. This conclusion is supported by Hwang et al. [42], who tested the hypothesis that proprioceptive states in which the limb is perturbed dominate the representation of limb state, by performing a task where position of the hand during a reach was correlated with patterns of force perturbation.

The additional cutaneous stimulation provided in our experiment during task E, which reproduced the same effect on the fingertips which would result from the application of a lateral force field, did not bring major improvements. In fact, tasks D and E were comparable in terms of direct and after effects, regardless of the presence of cutaneous stimuli, even though small increases of direct effect were observed in task E, in comparison with task D.

4.3 Contribution of visual feedback

By comparing tasks A vs F and C vs H, we can notice that when visual feedback correctly resembles hand movements (A, C), motor adaptation becomes faster with respect to when visual cues are not informative on position error (F, H). This suggests that visual feedback, if properly delivered, can influence adaptation to a dynamic environment.

The role of visual feedback may not be limited to affecting adaptation rates only, as evidenced by our experiment. For example, Melendez-Calderon et al. [43] found that subjects provided with reduced proprioceptive information were able to gradually adapt to a viscous force field, using visual information discrepant from proprioception. This happened when providing visual information about the position error, in addition to a constraining channel created by a robotic interface, which closed down lateral movements. In this setting, small proprioceptive errors were used during the exposure phase but always in the presence of kinesthetic information. Another important
finding is presented by Sarlegna et al. in [44]. They examined the motor behavior of a deafferented patient, deprived of proprioception below the nose, to assess adaptation to new dynamic conditions in the absence of limb proprioception. Although her impairment was obvious in baseline reaching performance, the proprioceptively deafferented patient clearly adapted to the new force conditions. This finding shows that motor adaptation to a modified force field is possible without proprioception, and that vision can compensate for the permanent loss of proprioception and update the central representation of limb dynamics.

In our experiment, during tasks F and H, a straight visual feedback was provided to the users that is known in the literature as a visual channel [10]. This condition can be considered as a “false visual feedback” case, wherein the green cursor represented a projection of the hand’s trajectory onto the straight line passing through the targets. Scheidt et al. [10] performed a series of experiments exploring the integration of visual and proprioceptive estimates of hand-path error during adaptation of reaching movements to a novel dynamic environment. Subjects grasped and moved the handle of an instrumented robot, which pushed the hand away from its intended target. They employed three visual feedback conditions: accurate visual feedback (concurrent visual and proprioceptive feedback), no visual feedback (proprioception feedback only), and visual channel feedback. The latter condition significantly impaired correction of initial direction errors during reaching. In fact, these errors increased with repeated exposure to the field. This result apparently contrasts with that found in our experiment. However, one must notice that the motion task in Scheidt’s experiment differed from the one presented here, since it included the reach of eight target locations equally spaced around the periphery of a circle in the horizontal plane, and the viscous force field was a function of both directions \( x \) and \( y \). Secondly, no subject in that study reported being aware of the visual channel manipulation when asked to describe his/her experience after that session. On the contrary, in our experiment most subjects declared they had realized that the visual information had been altered. Implicit, in this case, is the possibility that the subjects used unaltered proprioceptive feedback of movement errors to drive adaptive improvements in motor performance, disregarding the visual information.

4.4 Concluding remarks

A limitation of the present study is that the reaching task was essentially one-dimensional, whereas future studies should examine how kinesthetic and cutaneous feedback can drive adaptation during multidimensional arm movements. Moreover, we did not systematically explore how the rate of introduction of the perturbation may affect the motor system’s ability to use cutaneous, kinesthetic and visual information.

In designing our experiment, we were inspired by the protocol of the classic motor adaptation study by Shadmehr and Mussa-Ivaldi [6], in which the authors abruptly introduced a dynamic perturbation. However, studying the effect of a gradual introduction of the perturbations, especially in the case of a visual distortion, may be very interesting. Recent studies have suggested that the rate of introduction of a perturbation may affect the duration of the aftereffects, the amount of retention, and the pattern of generalization [45]. Moreover, this may also call into play different neural substrates to drive the adaptation [46]. It is therefore possible that the rate of introduction of the perturbation, and the type of feedback, may interact to affect these factors as well.

It is also worth underlining that the results presented in this paper may have been influenced by the particular cutaneous devices employed. To this regard, future studies should investigate the usage of more wearable cutaneous interfaces, making the operator able of interacting with the joystick handle in a more natural way.

Finally, in this study we totally excluded auditory feedback from the protocol, although this stimulation modality, when properly delivered, has proven to influence both motor performance and motor adaptation during the execution of reaching tasks [30], [31].

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