Is a robot needed to modify human effort in bimanual tracking?

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***Abstract*— Robotic bimanual training can benefit from understanding how to modify human motor effort in bimanual tasks. We addressed this issue by carrying out a study to investigate whether and how penalizing the use of one hand could alter the hands' effort distribution. Actuated haptic perturbations and alterations of the visual feedback of the right hand were tested on a bimanual tracking task with 16 healthy right-handed participants. For each feedback modality (haptic or visual), both a disturbance and a perturbation requiring additional effort from the right hand were implemented. The results showed that the participants were able to adjust to these four perturbations, and perceived them correctly as something that disturbed the dominant hand. Contrary to our expectations, the bimanual effort distribution changes induced by the haptic perturbations were not uniform across subjects. However, the visual disturbance induced most participants to use only their unperturbed left hand (with only 2/16 participants reporting a different behaviour). This suggests that a visual disturbance could be used to alter the effort distribution among the two hands. Clinical validation of these findings on hemiplegic patients may help simplify the design of robotic training interfaces.**

I. INTRODUCTION

Robotic interfaces for bimanual training assist in rehabilitation by helping therapists guide patients' movements, thereby alleviating some of their workload. Typically, to facilitate bimanual training, these devices (e.g. Diego [1]) make use of actuation to support the affected arm's weight and provide movement guidance [2]. Some devices like the MIME [3] offer self training modes where hemiplegic patients can guide their affected arm through the mirrored motions of their non-affected. However, more complex robotic interfaces increase the safety risk and cost of assistive technologies, restricting their portability and preventing patients from using them independently.

How can robots for bimanual training be simplified? Actuation can typically be used to penalize the use of the non-affected hand, preventing overcompensation [4]. For example, the Driver's SEAT [5] achieved this by independently measuring the force exerted by each hand when holding an actuated steering wheel and actively counteracting forces exerted by the non-affected hand. This encouraged patients (and controls) to produce more motor effort with the affected (or non-dominant) hand. However, since the motor behaviours during bimanual tasks have been shown to depend on factors such as the task goals [6], the provided sensory information [7], [8] or biomechanical constraints [9], there may be other ways to alter the distribution of effort between the hands during bimanual tasks.

One alternative could be to use different forms of feedback to discourage the use of one hand. For example, visual feedback corresponding to the input of that hand could be altered, e.g. by introducing disturbances or reducing its impact on the visualized motion. Indeed, visual feedback changes altering the contribution of the two hands to a shared cursor during bimanual reaching have previously been shown to reduce the variability of the highest weighted hand in chronic stroke survivors, showing that the coordination between their arms was sensitive to these task demands [10]. Finding if actuation is not required for altering bimanual effort distribution could enable the design of simplified bimanual training robots.

This study explored whether and how perturbing one hand could increase the contribution of the other hand in a bimanual tracking task. On healthy right-handed participants we tested the effect of visual and actuated haptic perturbations applied to the right hand. In each of these modalities, we tested both a disturbance and a perturbation requiring additional effort from the right hand.

We hypothesized that penalizing the use of one of the hands would change the distribution of effort among them. We expected haptic perturbations to the dominant hand to be an effective way of restraining its use, inducing participants to compensate with the contralateral as in [5]. It was however unclear if the non-actuated visual perturbations would similarly affect the resulting motor behaviours.

II. MATERIALS AND METHODS

A. Participants and experimental setup

The experiment was approved by the Joint Research Compliance Office at Imperial College London (reference 15IC2470) and carried out by 16 healthy participants (six female and ten male), aged 20-33 years (mean=24.12, sd=3.26). Participants were naïve about the experimental conditions and gave their written informed consent prior to starting the experiment. Their handedness was determined using the Edinburgh Handedness Inventory [11], and participants were required to be "right-handed" with a Laterality Quotient greater than 70 (maximum 100, minimum -100).

A tracking experiment was conducted using the Hi5 dual robotic interface (Fig. 1a, [12]). This one degree-of-freedom (per wrist) interface can independently apply computer controlled torque on each wrist's flexion/extension, while measuring angle, torque and muscle activity. The Hi5 was controlled at 1000 Hz, while data was recorded at 100 Hz. A

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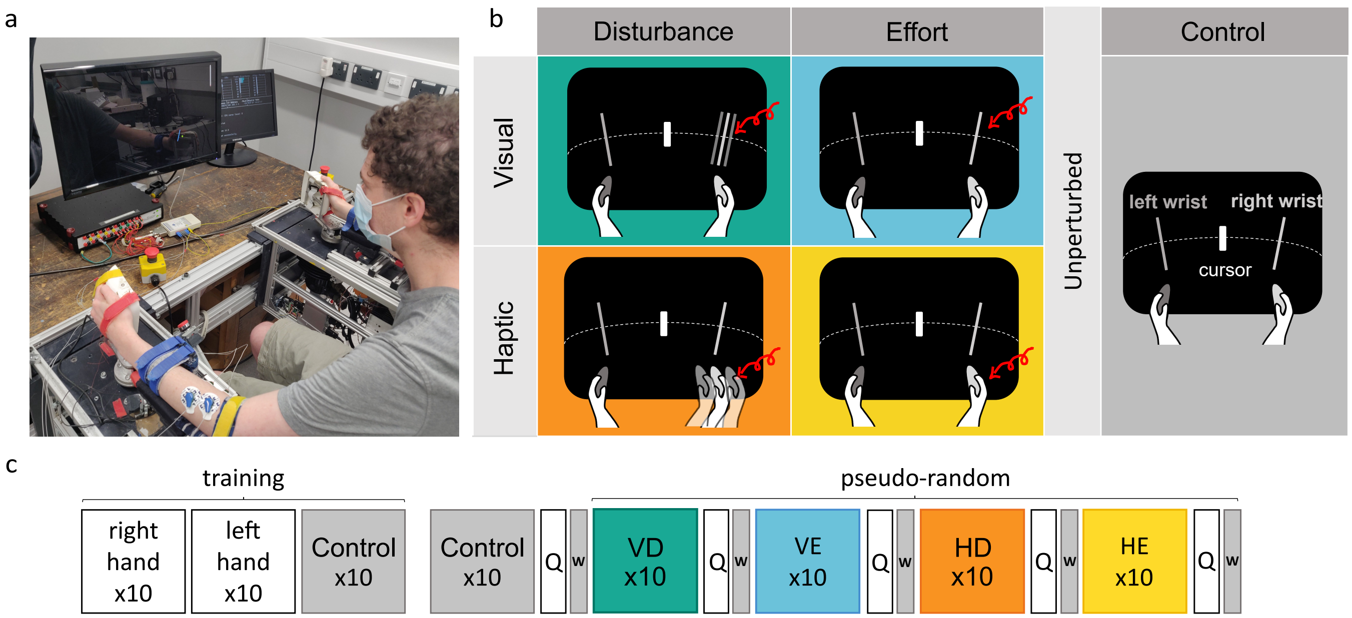

Fig. 1. Experiment description. a) Participants held the handles of a dual robotic interface and sat in front of a monitor displaying a bimanual tracking task. b) Four perturbation types were applied on the right hand: visual disturbance and visual effort, haptic disturbance and haptic effort. Additionally we had a control condition without any perturbation. c) Participants first trained using each hand individually before training with one block of the control condition, after which they experienced the five experimental conditions. After each experimental condition they answered a short series of questions (Q), followed by three washouts with the control condition (w).

g.GAMMASYS system recorded surface electromyography (EMG) at 1000 Hz from the wrists' flexor carpi radialis (FCR) and extensor carpi radialis longus (ECRL).

B. Tracking task

Participants sat in front of a monitor displaying the task (see Fig. 1a). They were asked to control a cursor using their wrists' flexion/extension to track "as accurately as possible" a target $q^*(t)$ moving (in degrees) according to a smooth pseudo-random trajectory:

$$q^*(t) = -7.8\sin(0.48\,t^*) + 1.6\sin(1.12\,t^*) + 9.4\sin(1.48\,t^*) - 10.6\sin(2.56\,t^*)\,, \quad t^* = t + t_0\,, \quad 0 \le t \le T, \tag{1}$$

where t is the time in seconds. Each trial ($T = 25$ s long) started from a randomly selected starting time $\{t_0 \in [0, T]\,,\, q^*(t_0) \equiv 0\}$ to minimize learning of the trajectory.

In all of the experimental conditions, the cursor's angle $q(t)$ was controlled by a weighted sum of the left and right wrist positions, $q_l(t)$ and $q_r(t)$ respectively, so that the hands were virtually coupled and the task was redundant. An unperturbed condition was used as a control, with the cursor's position given by:

$$q(t) = (q_l(t) + q_r(t))/2, \tag{2}$$

such that the weightings added up to 1, with no torque τ applied on either wrist by the interface.

C. Visual and haptic perturbations

Four perturbations were designed, two visual and two actuated haptic perturbations (see Fig. 1b). These were tuned in pilot testing to be strong enough to be noticeable and disturbing, but not so strong as to cause discomfort. In the visual perturbations, the interface applied no torque to either wrist. During the haptic perturbations, the cursor position was controlled to be the average of the wrist angles as in (2). There were two disturbances that penalized the right hand's use by introducing error into its tracking and two effort perturbations which instead would require more effort from the perturbed hand to produce the same cursor motion.

The ***visual disturbance*** **(VD)** condition added a sinusoidal disturbance (ν) to the right hand's position, affecting the centre cursor: $q(t) = (q_l(t) + q_r(t) + \nu)/2$, where

$$\nu(t) = \begin{cases} 5\sin(24\,t) & |\dot{q}_r| > 25\,°/s, \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

In the ***visual effort*** **(VE)** condition, the right hand's influence on the cursor was decreased according to: $q(t) = (q_l(t) + q_r(t)/2)/2$. Therefore, this condition had weightings that did not add to 1, such that the right wrist would have to move twice as much as the left wrist to obtain the same response, thus requiring more effort.

In the ***haptic disturbance*** **(HD)** condition, a sinusoidal disturbance was applied to the right hand. This disturbance had a ramping perturbation amplitude to avoid jerk, such that the applied torque τ was given by:

$$\tau(t) = \begin{cases} 0.15\sin(62.83\,t) & |\dot{q}_r| > 50\,°/s, \\ 0.003\,|\dot{q}_r|\sin(62.83\,t) & 25\,°/s \le |\dot{q}_r| \le 50\,°/s, \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

In the ***haptic effort*** **(HE)** condition, a counteracting torque was applied to the right hand to increase the effort required to move the cursor. The load τ was set according to the right wrist's torque sensor τ_r at time t_k such that $\tau(t_{k+1}) = -0.6\tau_r(t_k)$.

D. Experimental protocol

The experiment lasted approximately one hour and its protocol is depicted in Fig. 1c. Each participant started with a *training phase* in which they had to track the moving target first with their right hand, then with their left hand, and then with the average between the two hands' position, for ten trials each. For the first two training blocks, participants were told to use the hand relevant to the task dynamics, while for the rest of the experiment subjects were told that they could use either hand or both hands. During a *testing phase*, the five experimental conditions were presented in blocks of 10 trials each, with the control block always being first to serve as the baseline for comparison. The order of the remaining blocks was pseudo-randomized. After each block, participants performed three washout trials of the control condition and were asked to state their level of agreement with four statements (S1: *I felt forces in my (L/R) hand*; S2: *I could move the (L/R) handle as intended*; S3: *I could influence the cursor with my (L/R) hand*; S4: *I used my (L/R) hand*), for their left (L) and right (R) hands.

E. Data analysis

Raw EMG activity was high-pass filtered (cutoff at 20Hz), notch filtered (50Hz and 150Hz, to filter the power line noise and 3rd harmonic), rectified and then low-pass filtered (cutoff at 5Hz, all second-order Butterworth filters). The activity of the wrist flexor and extensor muscles in both hands, measured in volts, was calibrated by linearly regressing the activity of each muscle with the torque produced by the muscle during isometric contraction as in [13].

After preprocessing in MATLAB, all data was analyzed using RStudio. It was evaluated in terms of the overall performance and the motor behaviour during the experimental trials. To focus on the tracking behaviour without including participant reaction times, the data from the first second of every trial was removed. The overall performance was assessed by computing the root mean squared *tracking error* between the controlled cursor and the target.

Two metrics were used to assess the participants' motor behaviour. Firstly, the *normalized standard deviation (NSD)* was computed for each wrist (w) as:

$$NSD_w = SD_w / SD^*, \tag{5}$$

where SD^* is the standard deviation (*SD*) of the reference (q^*). In this way, values close to 1 would imply that the wrist moved as much as the target, while values that are lower than 1 would imply that the wrist moved less than the target. Secondly, to measure the motor effort of each wrist, the *torque normalized total muscle activity (TMA)*, was computed as the sum of the flexor and extensor absolute values obtained from the calibrated EMG activity. Additionally, answers to the questionnaire were analyzed for subjective evaluation of each condition.

To determine if subjects adjusted their motor behaviour within each block, the tracking error, NSD and TMA along the first five and the last five trials of each condition were explored using linear mixed effects (LME) analysis via restricted maximum likelihood, with the trial number as a fixed slope (s) and a random intercept for each grouping factor (subject id). The Satterthwaite method was used to calculate an approximation for the degrees of freedom.

During the last five trials of each experimental condition, subjects had stable tracking error (non-significant slopes, $p > .05$) except for both disturbances, where some learning may still have been happening (VD: s=-0.05, t(63)=-2.09, p=.041; HD: s=-0.06, t(63)=-2.17, p=.034). However, the motor behaviours were found to be stable for both hands in all conditions (all non-significant slopes, $p > .05$). For this reason, the data was averaged for each participant across the last five trials of each block for the rest of the analysis.

Shapiro-Wilk tests showed that some groups were not normally distributed in all metrics. Therefore, a Friedman test was used to explore the effect of the perturbation type on the performance. Two-way repeated measures Aligned Rank Transformed ANOVA (ART ANOVA) was used to explore the effect of the perturbation type and the hand on the NSD, TMA and subjective assessment. Post-hoc analysis in all cases was conducted by performing a series of tailored pairwise comparisons using Wilcoxon signed-rank tests. For the performance the following comparisons were explored: (i) the control was compared to the each of four perturbations, (ii) the perturbations were compared across feedback modalities and perturbation type (VD-VE, HD-HE, VD-HD and VE-HE). For the NSD, the TMA and each question of the subjective assessment (i) and (ii) were explored for each hand. Additionally, left-right hand comparisons for each condition were tested (iii). P-values were adjusted using the Holm-Bonferroni correction to control for type I error in multiple comparisons.

III. Results

A. Do the perturbations alter effort distribution?

The perturbation type affected both the performance (χ^2(4)=34.9, p<.001) and the motor behaviours, in terms of the NSD (F(4,60)=74.45, p<.001) and TMA (F(4,60)=3.64, p=.010). Additionally, analysis of the motor behaviors also revealed a main effect of the hand (NSD: F(1,15)=51.89, p<.001, TMA: F(1,15)=5.99, p=.027) and significant interactions of the two factors (NSD: F(4,60)=19.99, p<.001, TMA: F(4,60)=10.58, p<.001). These results show that the perturbation type did alter the participants performance and effort distribution (differently for the two hands).

B. How do the perturbations alter effort distribution?

As seen in Fig. 2, the participants' tracking error was larger during the visual effort condition than in the control (V=0, Z=-4.17, p<.001). However, during the visual disturbance and both haptic perturbations participants were able to track the target as well as during the control (all p>.30).

Fig. 3a shows that in both visual perturbations the left hand moved more than in the control (VD: V=2, Z=-3.91, p=.002; VE: V=0, Z=-4.17, p<.001). Moreover, for the visual disturbance, the motion of the right hand was reduced

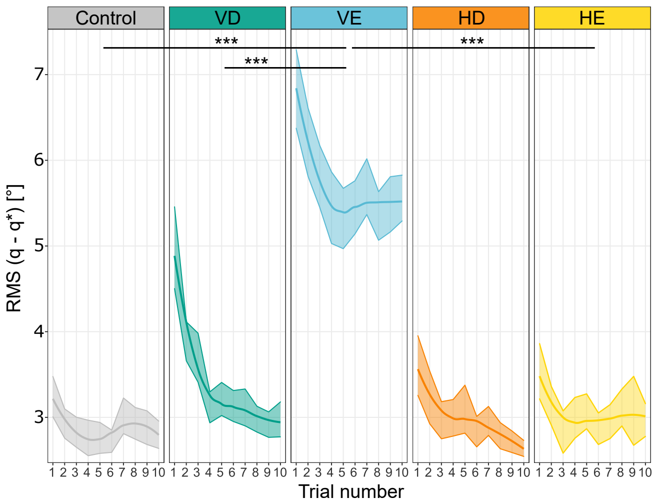

Fig. 2. Overall tracking performance during the experimental conditions. The lines present the mean tracking error (computed over all participants) from the visualized cursor to the target on each trial and the shaded areas represent the standard error among the subjects. $*** : p < .001$. Comparisons not shown were not found to have significance.

compared to the control (V=135, Z=-4.01, p=.001), such that in this condition the left hand moved significantly more than the right (V=135, Z=-4.01, p=.001). Interestingly, despite none of the haptic conditions having an effect on the motion of any hand compared to the control, the left hand did move more than the right in the haptic disturbance (V=128, Z=-3.37, p=.012). This suggests that both disturbance-based perturbations may have induced asymmetry in the motor behaviours, causing the left hand to move more than the right. However, only the visual perturbations implied a different amount of hand motion compared to the control.

Similarly, only the visual disturbance condition was found to alter the TMA compared to the control (Fig. 3b), by increasing the TMA of the left hand (V=3, Z=-3.79, p=.003) and reducing the TMA of the right hand (V=128, Z=-3.37, p=.014). Interestingly, in the control condition the right hand exerted a higher TMA than the left (V=9, Z=-3.29, p=.017), a difference that was not found for any of the perturbed conditions (all p>.05).

From these findings, it is observed that while the chosen disturbance-based perturbations were able to induce asymmetric motor behaviours, only the VD condition clearly altered all considered metrics with respect to the control.

C. How do the responses to the perturbations compare?

The performance during the first half of each block had a negative slope s (Fig. 2), suggesting that participants adjusted to the received feedback to track the target in all conditions. This was confirmed by the LME analysis (none: s=-0.11, t(63)=-3.34, p =.001; VD: s=-0.43, t(63)=-6.24, p<.001; VE: s=-0.38, t(63)=-4.68, p<.001; HD: s=-0.13, t(63)=-2.89, p=.005; HE: s=-0.11, t(63)=-2.76, p=.007).

Participants adjusted the NSD and TMA differently for the different perturbations. The penalized right hand decreased its NSD along the first five trials in all conditions, and did so with larger slopes for the perturbed conditions (none: s=-0.03, t(63)=-3.51, p<.001; VD: s=-0.16, t(63)=-7.97, p<.001; VE: s=-0.10, t(63)=-4.36, p<.001; HD: s=-0.06, t(63)=-3.41, p=.001; HE: $s = -0.07$, t(63)=-3.20, p=.002). Subjects also adjusted the TMA of the right hand by decreasing it, but only for the visual conditions (VD: s=-0.09, t(63)=-4.55, p<.001; VE: s=-0.05, t(63)=-3.77, p<.001). In contrast, the left hand's NSD and TMA was stable along the first five trials of every condition (all p>.2), except during the visual disturbance, where it increased both its NSD (s= 0.11, t(63)=5.07, p<.001) and TMA (s=-0.03, t(63)=2.51, p=.015). These results show that participants adjusted to the visual perturbations by decreasing the penalized right hand's NSD and TMA. In the VD condition, this was additionally accompanied by an increase in the left hand's NSD and TMA.

Comparisons among both visual perturbations (Fig. 3a and b) showed that the visual disturbance induced higher left hand TMA (V=133, Z=-3.79, p=.003) and NSD (V=123, Z=-2.98, p=.042) than the visual effort. Similarly, the disturbance caused a lower right hand TMA (V=5, Z=-3.61, p=.006) and NSD (V=1, Z=-4.01, p=.001) than the visual effort. Moreover, participants tracked better (Fig. 2) during the visual disturbance (V=0, Z=-4.17, p<.001).

The two haptic conditions, however, were similar both in their performance and motor behaviors, with no differences in the hands' TMA or NSD (all p>.1). Interestingly, under both perturbations (more clearly for the haptic disturbance), the NSD measurements seemed very distinct across subjects. Participants either showed a strong preference for a higher amplitude of motion in their left hand compared to the right, or a similar amount of motion in both hands.

Participants performed similarly well in both disturbance conditions (Fig. 2). However, the right hand had a lower amount of motion in the visual compared to the haptic case (V=12, Z=-3.09, p=.030), suggesting that the chosen virtual perturbation may have been more effective at penalizing the right hand's use (Fig. 3a). Comparisons among the effort-based perturbations showed that the performance was significantly worse for the visual than the haptic case (V=135, Z=-4.01, p<.001). Moreover, the visual effort induced the right hand to contribute significantly more to the task in terms of its NSD (V=122, Z=-2.98, p=.042), suggesting its use did not have such a penalizing effect.

In summary, compared to the other chosen perturbations, (i) the VD condition induced larger NSD and TMA in the left hand and reduced these measures for the right hand, (ii) the VE condition showed a lower level of tracking accuracy, and (iii) the haptic perturbations altered the amount of motion in a non-uniform manner across participants.

D. Subjective assessment

To evaluate the participants' perception of the different conditions, we asked them to express their level of agreement with four statements (see Fig. 4). For all statements, we found a main effect of the perturbation type (S1: F(4,60)=38.35, p<.001; S2: F(4,60)=23.86, p<.001; S3: F(4,60)=15.12, p<.001; S4: F(4,60)=12.98, p<.001),

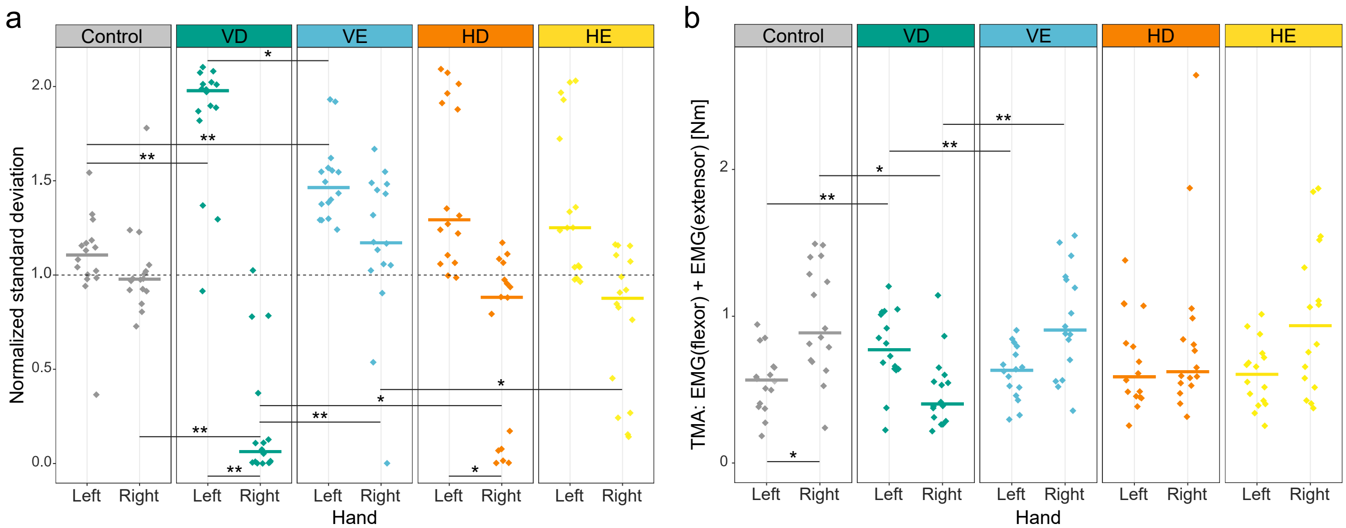

Fig. 3. Measures of motor behaviour induced by the different conditions. a) Normalized standard deviation for left and right hands. b) Torque normalized total muscle activity, as the sum of calibrated EMG from flexor and extensor muscles in each hand. $*$: $p < .05$, $**$: $p < .01$. Comparisons not shown were not found to have significance.

the hand (S1: $F(1,15)$=507.19, p<.001; S2: $F(1,15)$=78.28, p<.001; S3: $F(1,15)$=142.70, p<.001; S4: $F(1,15)$=53.32, p<.001) and the interaction between these two factors (S1: $F(4,60)$=52.88, p<.001; S2: $F(4,60)$=28.44, p<.001; S3: $F(4,60)$=20.61, p<.001; S4: $F(4,60)$=25.26, p<.001).

Participants strongly agreed to be "*feeling forces*" (S1) on the right hand during the haptic conditions, compared to the control (HD: V=0, Z=-2.74, p=.006; HE: V=0, Z=-2.66, p=.008) and to the respective visual conditions (VD-HD: V=0, Z=-2.72, p=.006; VE-HE: V=0, Z=-2.56, p=.010). Moreover, they perceived more force on the right hand than on the left for both haptic conditions (HD: V=0, Z=-2.87, p=.004; HE: V=0, Z=-2.72, p=.006).

Similarly, participants were less able to "*move the handle as intended*" (S2) with their right hand in the haptic conditions, compared to the control (HD: V=91, Z=-2.35, p=.019; HE: V=78, Z=-2.12, p=.034) and to the respective visual conditions (VD-HD: V=103.5, Z=-2.35, p=.019; VE-HE: V=66, Z=-2.00, p=.003). Moreover, they were less able to move the right handle than the left for both haptic conditions (HD: V=0, Z=-2.49, p=.013; HE: V=0, Z=-2.11, p=.035).

Subjects felt less able to "*influence the cursor*" (S3) with their right hand for both disturbances, compared to the control (VD: V=136, Z=-2.64, p=.008; HD: V=113, Z=-2.00, p=.045). In the visual disturbance they felt their right hand influenced the cursor less than in the visual effort (V=0, Z=-2.12, p=.034) and haptic disturbance (V=0, Z=-2.37, p=.018). They also felt their right hand was less able to influence the cursor than the left in the visual disturbance (V=0, Z=-2.44, p=.015), visual effort (V=0, Z=-2.09, p=.037) and haptic disturbance (V=4.5, Z=-2.63, p=.008).

Only during the visual disturbance did participants report to not "*use*" (S4) their right hand, compared to the control (V=119, Z=-2.46, p=.014) and the visual effort (V=3, Z=-2.10, p=.036). Additionally, they reported to use it less than the left hand (V=0, Z=-2.48, p=.013).

These results suggest that participants were able to discern when and where haptic forces were applied and that these forces prevented them from moving the right handle as intended. Despite this, it was only during the disturbance conditions where they felt less able able to influence the cursor with their right hand. Here, only in the VD condition this translated to a lower reported use of the right hand.

IV. Discussion

This study investigated whether and how penalizing the use of the dominant hand through actuated and non-actuated perturbations could alter the hands' effort distribution during a bimanual tracking task in healthy right-handed participants. Our results showed that participants could adjust to both haptic perturbations and to the visual disturbance, performing the task with similar tracking accuracy as without perturbation. However, the selected perturbations impacted the motor behaviours differently, with only the visual disturbance condition leading to a consistent change in the behaviour of both hands across all metrics.

Both visual perturbations induced the left hand to move more than in the control. In the visual disturbance condition most subjects performed the task with the left hand (thus neglecting the right). Only two participants reported that they used their right hand (Fig. 4). However, the visual effort condition did not impact the use of the right hand. Contrary to our hypothesis, the chosen haptic perturbations were not effective at modifying the contribution of the hands in a uniform manner across participants. Instead, some participants moved only the left hand with twice the amplitude, while others moved both hands with similar amplitudes (Fig. 3a).

Why were all perturbations not equally effective? Typically, during common goal bimanual tasks, the motor system distributes work across the two hands to minimize error and effort [6], [14]. We hypothesized that if effective, our perturbations could alter this natural distribution. However, unaltered effort patterns could be the result of participants not being able to discern that something was different in the

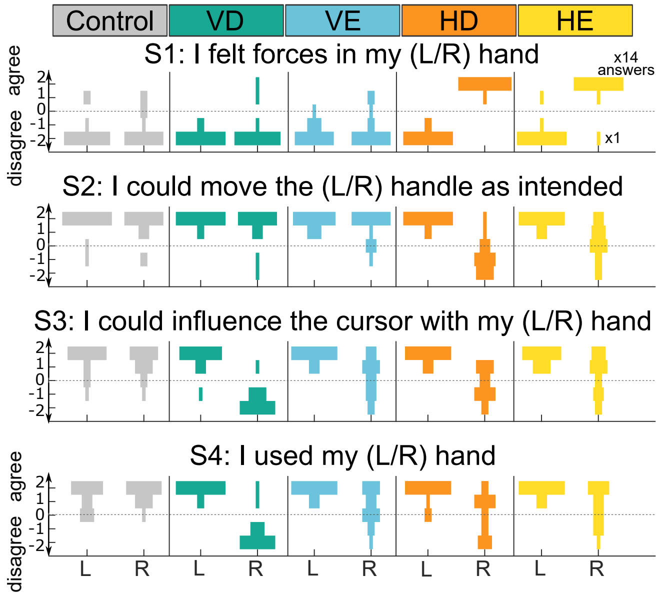

Fig. 4. Subjective assessment of statements S1 to S4: the width of each bar denotes the proportion of subjects that gave that answer in a Likert scale ranging from -2 (strongly disagree) to +2 (strongly agree), for left (L)/right (R) hand. Statistical comparisons are presented in section III-D.

task and therefore not changing their behaviour. However, the questionnaire responses show that participants were aware that the right hand was being disturbed in all conditions (Fig. 4). In both visual cases, participants could not influence the cursor with their right hand as much as with their left. However, for the visual effort this was not perceived as being different from the control and led to reduced tracking accuracy (Fig. 2). This may suggest that despite recognising this perturbation, participants may have not been able to compensate for it with the available information.

Interestingly, while the haptic perturbations were perceived as impeding the right hand's motion, they did not hinder performance. This suggests that participants used some form of compensation that did not necessarily imply the reduced use of the penalized hand. Instead, some participants could have used different mechanisms than those available to counteract the chosen visual perturbations, such as increasing their wrist co-contraction to absorb the haptic disturbance [15]. These additional mechanisms may have allowed them to maintain symmetric coordination patterns, which tend to be more stable in healthy adults [16], [17]. Alternatively, despite our haptic perturbations being clearly noticeable, their amplitude (restricted for safety purposes) may not have been large enough to enforce motor behavioural change. However, actuated perturbations have previously been used to penalize the use of the dominant/non-affected hand [5].

How could these results be used to improve bimanual training robotic systems and protocols? We observed (in healthy adults) that a visual disturbance can modulate the effort between the hands in a bimanual tracking task. Previous findings have suggested that simpler bimanual rehabilitation devices may be as efficient as more complex interfaces [18], [19]. Our findings indicate that the design of rehabilitation robots for bimanual training may be simplified by using visual feedback to alter the effort distribution between the hands, while actuation targets other training aspects (e.g. proving movement assistance). Visual perturbations offer further safety advantages relative to haptic perturbations, which could cause discomfort, pain or even instability. However, before applying these findings to bimanual rehabilitation robots, it is critical to conduct clinical studies in patients with hemiplegia to validate this solution.

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