Dissociating haptic feedback from physical assistance does not improve motor performance

Ekaterina Ivanova[1,2], Nuria Peña-Perez[1,2], Jonathan Eden[1,3], Yammi Yip[4,5] and Etienne Burdet[1]

***Abstract*— In robots for motor rehabilitation and sports training, haptic assistance typically provides both mechanical guidance and task-relevant information. With the natural human tendency to minimise metabolic cost, mechanical guidance may however prevent efficient short term learning and retention. In this work, we explore the effect of providing haptic feedback to the not active hand during a tracking task. We test four types of haptic feedback: task- or error-related information, no information and irrelevant information. The results show that feedback provided to the hand not carrying out the tracking task did not improve task performance. However, irrelevant information to the task worsened performance, and negatively influenced the participants' perception of helpfulness, assistance, likability and predictability.**

I. Introduction

Robots can be used to assist motor learning, from sports training to stroke rehabilitation. Here, physical assistance is commonly provided to learners, supporting them in completing the required motions. Many different assistive strategies have been developed for robot assistance, however some issues have been encountered. First, providing continuous non-compliant physical guidance can lead to slacking behaviour, hindering the learning transfer [1], [2], [3]. Second, while more compliant strategies, like model predictive control [4], interaction with a human partner [5] and a reactive robot partner [6] tend to be more learning-efficient [3], they also assist by providing combined force and information transfer. Therefore, it is unclear if the observed performance improvements result from the physical support or the enhanced task knowledge. Can we provide assistance using task relevant information without physically assisting movements to ensure active participation?

The impact of task relevant information has been studied previously by "spatially separating" the guidance and task forces. For example, by providing guidance forces to the back of the hand that is performing the task ("acting hand") [7], or through cutaneous skin stretch feedback, which has been shown to be as effective as kinesthetic guidance during training [8]. Alternatively, the inter-hemispheric connection [9] available during bimanual interactions has been used to provide guidance forces to the non-acting hand (nAH), while participants moved the acting hand (AH) [10], [11]. In rhythmic tasks this led to participants perceiving lower overall reported workload and physical demand than the absence of assistance or the direct guidance of the AH [10]. However, providing feedback in this manner did not necessarily lead to improved performance. Moreover, different aspects of the task and guidance parameters have been observed to differently impact the resulting motor behaviours and the participants perception in this bimanual setting [11].

In summary, while haptic feedback provided to the nAH has shown the perception of reduced workload, it has only been tested for trajectory guidance (TG) [10], [11], where it has not yet displayed the potential to improve performance. It is therefore still unclear if haptic feedback on the nAH can improve performance, if this differs with different kinds of haptic information and if this feedback can interfere with assistance on the AH. Therefore, in this experiment we provided haptic feedback to the nAH, while a tracking task was executed with the AH in a bimanual setting. Several forms of haptic feedback for the nAH were chosen to systematically investigate this type of information exchange: (i) no feedback, (ii) information about the task trajectory, (iii) feedback of the participants' error and (iv) not relevant feedback. We explored the impact of these modalities on the participants' performance and perception, as well as the changes in their feedback usage and their possible interference with a simultaneously given AH haptic assistance.

II. Materials and methods

A. Participants

The study was granted ethical approval by the Research Ethics Committee of Imperial College London (reference 15IC2470) and had 21 participants (5 female, 16 male) without known motor impairment aged between 20 and 38 (mean: 26.85, standard deviation: 5.62). All participants were right handed, where 18 participants reported previous experience with haptic devices and eleven reported experience playing a musical instrument. All participants gave informed consent before partaking in the experiment.

B. Experimental setup and task

The study was conducted on the Hi5 robotic interface [12] (Fig.1A, top-right). This flexion/extension dual wrist

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[1]Department of Bioengineering, Imperial College of Science, Technology and Medicine, London, UK. {e.ivanova17, e.burdet}@imperial.ac.uk. [2]School of Electronic Engineering and Computer Science, Queen Mary University of London, London, UK. n.penaperez@qmul.ac.uk. [3]Mechanical Engineering Department, the University of Melbourne, Victoria, Australia. eden.j@unimelb.edu.au. [4]Department of Physiology, Development and Neuroscience, University of Cambridge, Cambridge, UK yhyy2@cantab.ac.uk. [5]Queen Square Institute of Neurology, University College London, London, UK

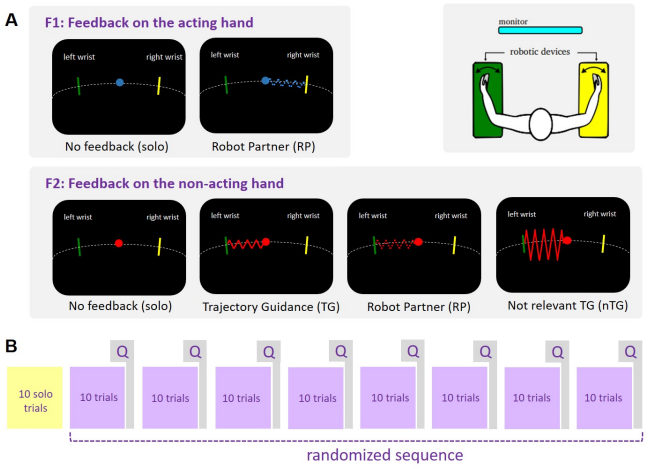

Fig. 1. **Experiment description. A: Participants tracked a randomly moving target with their AH's wrist flexion/extension movement, where their AH was either free or connected to a RP and their nAH had one of four feedback modalities. B: The experimental protocol: following ten solo training trials (yellow), the eight experimental conditions were presented in a randomised order in blocks of ten trials each. Subjective questionnaires were presented at the end of each condition.**

interface provides computer-controlled haptic feedback. Each of the participant's hands were attached to a separate Hi5 handle. The Hi5 interface was controlled at 1000Hz, while wrist angle data was recorded at 100Hz.

The task involved tracking a pseudo-randomly moving dot, "as accurately as possible" by moving a cursor whose position was mapped to the dominant wrist's flexion/extension. In this way, the dominant (right) hand was chosen as the AH and the non-dominant (left) hand as the nAH. Visual feedback of the target and the AH cursor was presented on the Hi5 monitor, with the target trajectory given by:

$$q^*(t) \equiv -7.8\sin(0.48\,t^*) + 1.6\sin(1.12\,t^*) + 9.4\sin(1.48\,t^*) - 10.6\sin(2.56\,t^*),\ t^* = t + t_0,\ 0 \le t \le 25s \quad (1)$$

where each trial started from a randomly determined time $\{t_0 \in [0, 20]s \,|\, q^*(t_0) \equiv 0\}$ to minimize trajectory learning.

Prior to the experiment, participants were instructed that they "may or may not feel haptic feedback on one or both hands" and that they could track with one or both hands.

In the experiment, two factors were varied (Fig.1A). First, the haptic feedback on the AH with two levels – no interaction or interaction with the robot partner (RP) of [6]. The second factor was the type of feedback provided on the nAH, which had four levels: (i) no feedback (solo); (ii) full reference trajectory information in the form of trajectory guidance (TG); (iii) participant error information provided in the form of the same RP interaction forces that would be provided on the AH; (iv) information that was not relevant to the task in the form of TG for another trajectory (nTG):

$$q^{nTG}(t) \equiv 22.21\sin(3.14t)\sin(1.31t) \quad (2)$$

In those conditions with a haptic interaction, it was provided to the relevant wrist through the Hi5 generated torque

$$\tau(t) \equiv \kappa(q_g(t) - q(t)) \quad (3)$$

where κ denotes the connection stiffness, q_g the 'guidance' angle and q the measured angle. For the AH, q_g evolved according to the neuromechanical goal sharing model of [6], which identifies the user during the movement and reacts correspondingly to improve target prediction and thus tracking performance, while q was set to the AH's flexion/extension angle. This exact assistance was used in the RP condition for the nAH, where the only difference was the hand that the torque was applied to. In contrast, for the TG and nTG conditions, q_g was set to be that of the target's trajectory (1) or of the non-relevant target (2), respectively, while q instead corresponded to the nAH's flexion/extension angle.

The connection stiffness (κ) of the haptic feedback was the same in all conditions and was set to $\{2.86\}$ Nm/rad. This stiffness was previously evaluated as a medium-compliant connection, which allowed for an independent motion while providing good perception of the haptic interaction [13].

Fig.1B illustrates the experimental protocol. During the first training block, participants experienced the tracking task by performing it with their AH without any haptic connection. These solo trials were used to minimise the learning effect during the experimental conditions. The RP's motor noise parameter [6] was then set using the deviation observed in the participant's tracking movement during the last trial of the solo block, to ensure that the participant and the RP had a similar skill level. After training, all eight (two AH $\times$ four nAH) conditions were presented, in blocks with ten trials each, in a randomised order. After each experimental block, participants filled in a questionnaire to describe their subjective evaluation of the feedback modality.

C. Metrics

Data was processed in R and Matlab and statistical analysis was conducted in R. Data of the first 0.8 s of each trial was excluded to remove the reaction time.

To evaluate how the AH tracking performance changed depending on the feedback, the *Improvement in Mean Absolute Error (IMAE)* between the target ($q^*(t)$) and the cursor ($q(t)$) trajectories was calculated. Each participant's IMAE was computed as the mean absolute error for each trial divided by its average over the last five training trials.

The *Normalized Standard Deviation (NSD)* evaluated how much participants moved their AH or nAH during the trials with respect to the target. This metric was defined as the standard deviation of the wrist's trajectory divided by that of the target. Therefore, values higher than 1 imply that in that trial the wrist moved more than the target, while values lower than 1 mean that the wrist moved less than required.

Additionally, after each experimental block, participants reported their subjective perception of the predictability, likability and helpfulness of the interaction, as well as whether they felt assistance on either hand or a connection between them (see Fig. 3A-E for question formulations and results).

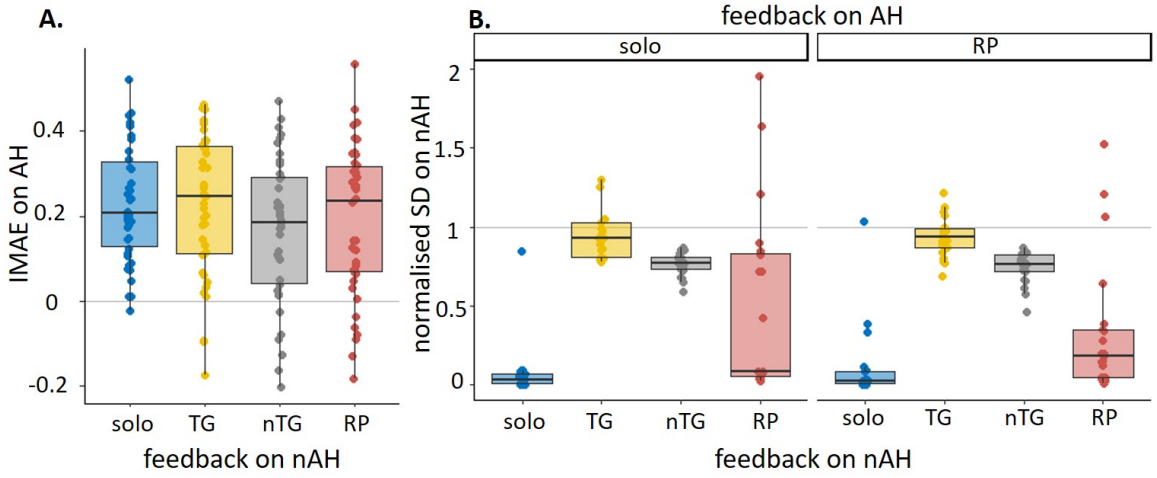

Fig. 2. **Performance: A. Improvement in the tracking error (IMAE) of the AH for both the solo and RP conditions combined, since the interaction between feedback conditions on AH and NAH was not significant; B. Normalised standard deviation for the nAH presented separately for solo and RP conditions.**

D. Statistical methods

The Shapiro-Wilk test was used to check data normality in each condition for each metric. Only the IMAE data was normally distributed. For the analysis of the IMAE and NSD, we used the average data for each block excluding the first trial of the block to avoid trials where participants were adapting to a new condition.

Since we had a full factorial design with two factors – feedback on the AH and nAH – we used two-way repeated measures Analysis of Variance (rm ANOVA) for normally distributed data and two-way rm Aligned Rank Transform (ART) ANOVA for not-normally distributed data.

If a factor or interaction was significant ($p < 0.05$), a tailored paired t-test contrast or a Wilcoxon signed-rank test was used to compare single groups as parametric and non-parametric post-hoc analysis, respectively. Holm–Bonferroni adjustment was used to account for multiple comparisons and control for type I error.

III. Results

A. Performance

ANOVA showed an influence of the feedback on the AH ($F(1, 20) = 356.691$, $p < 0.0001$) as well as the nAH ($F(3, 60) = 6.386$, $p = 0.0008$) on the AH IMAE (Fig.2A). However, no interaction between the factors was observed ($F(3, 60) = 1.917$, $p = 0.1364$). The accuracy improvement was higher for the blocks where the dominant hand was assisted by the RP. Moreover, the addition of the nTG feedback on the nAH caused a reduction in accuracy improvement when compared to the solo condition ($t(60) = 3.746$, $p = 0.0024$, difference between the group means for IMAE of 0.064) and to the TG conditions ($t(60) = 3.480$, $p = 0.0047$, difference in IMAE of 0.060).

The amount of motion (NSD) of the AH was not influenced by any feedback condition (all $p > 0.20$). However, feedback on both the AH and nAH, as well as the interaction between them affected the NSD of the nAH ($F(1, 60) = 4.317$, $p = 0.0080$, Fig.2B). Here, no differences were found between corresponding nAH conditions for either AH condition (all $p > 0.20$). However, when looking at each AH condition separately we found that when no feedback was given on the AH (Fig.2B,left) the NSD for the nAH was similar between nTG and RP ($W = 66$, $Z = -1.721$, $p = 0.3552$, difference between the group means for NSD of 0.254), while the same conditions were different when assistance was present on the AH ($W = 29$, $Z = -3.007$, $p = 0.0112$, difference in NSD of 0.412, Fig.2B,right). All other conditions were different from one another: when no feedback was given to the nAH, participants moved it less than in other conditions (all pairwise $p < 0.002$); during TG, the nAH motion was closest to the motion of the trajectory and was higher than in all other conditions (all pairwise $p < 0.02$).

B. Perception of interaction

Although the participants' hands were never physically connected, in some conditions participants felt a connection. This was stronger when the AH was supported by the RP ($F(1, 20) = 8.400$, $p = 0.0089$). nAH feedback provided (Fig.3A) through the TG or RP led to a stronger feeling of connection between the hands than the solo (solo-TG: $W = 23$, $Z = -4.345$, $p < 0.0001$; solo-RP: $W = 63$, $Z = -2.905$, $p = 0.0070$) or nTG (nTG-TG: $W = 459.5$, $Z = -4.177$, $p < 0.0001$; nTG-RP: $W = 50$, $Z = -2.920$, $p = 0.0070$) conditions. Moreover, the TG was more strongly perceived as connected ($W = 282.5$, $Z = 3.273$, $p = 0.0025$), possibly because of its direct connection to the target trajectory. No differences were found between the solo and nTG groups ($W = 82.5$, $Z = -0.136$, $p = 0.9133$).

Participants were also asked whether they felt assistance on their hands during the tracking task (Fig.3B). For the

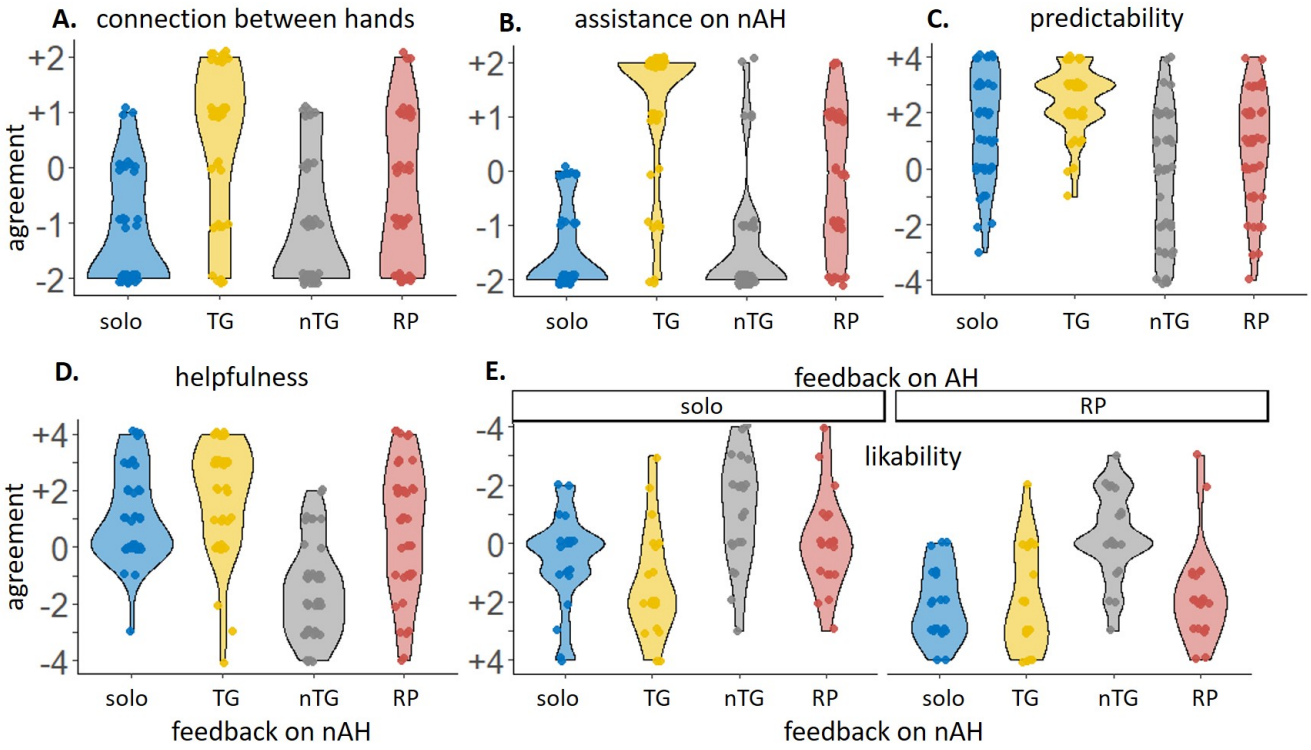

Fig. 3. **Assessment of the participants' perception. A: How the feel of interacting with an agent depended on the connection stiffness, where -2/+2 corresponds to strongly dis/agree. A-H: Histograms of interaction assessment:A: "It seemed like both of my hands were physically connected" (-2/+2: strongly dis/agree). B: "I felt haptic assistance on my left hand?" (-2/+2: strongly dis/agree). C: "How predictable was the interaction?" (-4/+4: un/predictable). D: "Was the interaction disturbing or helpful?" (-4/+4: disturbing/helpful). E: "Was the interaction likable or dislikable?" (+4/-4: dis/likable). A-D present the data for both the AH solo and RP conditions combined, since the interaction between feedback conditions on AH and NAH was not significant.**

AH, the result was self-consistent and they perceived assistance more strongly during the interaction with the RP ($F(1,20) = 61.882$, $p < 0.0001$). The perception of assistance on the nAH strongly depended on the feedback applied ($F(3,60) = 29.485$, $p < 0.0001$). The TG was highest rated compared to all other conditions (TG-solo: $W = 666$, $Z = 5.329$, $p < 0.0001$; TG-nTG: ($W = 496$, $Z = 5.031$, $p < 0.0001$; TG-RP: $W = 521.5$, $Z = 3.865$, $p = 0.0001$). The RP was also perceived as more assistive than solo ($W = 29$, $Z = -4.012$, $p < 0.0001$) or nTG ($W = 408$, $Z = 3.642$, $p = 0.0002$). However, the users' opinions were divided for the RP with the frequency of ratings for dis/agreement almost equal: 40.5% participants reported to "agree" or "strongly agree" and 47.6% reported to "disagree" or "strongly disagree", while 11.9% remained neutral. There was no observed difference between solo and nTG conditions ($W = 68.5$, $Z = -0.384$, $p = 0.6960$).

The predictability of the interaction strongly depended on the presence of the assistive forces on the AH: an RP assistance led to a higher perceived predictability ($F(1,20) = 12.664$, $p = 0.0020$). Here, the perception of how predictable the interaction was, was influenced by the information provided on nAH ($F(3,60) = 19.110$, $p < 0.0001$) (Fig.3C). The most predictable interaction was found when there was no interaction on the nAH (solo-nTG: $W = 540.5$, $Z = 3.721$, $p = 0.0003$; solo-RP: $W = 499.5$, $Z = 2.258$, $p = 0.0467$) and when providing task information with TG (TG-nTG: $W = 655$, $Z = 5.078$, $p < 0.0001$; TG-RP: $W = 621$, $Z = 4.101$, $p < 0.0001$). There was no difference between the TG and solo conditions ($W = 468.5$, $Z = 2.560$, $p = 0.0795$), and the RP had a tendency to be more predictable ($W = 450$, $Z = 2.239$, $p = 0.0467$).

The interaction was assessed as more helpful when the RP assistance was provided on the AH ($F(1,20) = 35.623$, $p < 0.0001$). The nAH feedback also influenced the perceived helpfulness ($F(3,60) = 15.389$, $p < 0.0001$, Fig.3D): the nTG was evaluated as the most disturbing (solo-nTG: $W = 828$, $Z = 5.180$, $p < 0.0001$; TG-nTG: $W = 805$, $Z = 5.326$, $p < 0.0001$; RP-nTG: $W = 576$, $Z = 4.298$, $p < 0.0001$). Other feedback modalities were perceived similarly to one another (all $p > 0.05$).

Finally, participants were asked whether they found the interaction likable, with both factors and their interaction influencing the rating: assistance on the AH ($F(1,20) = 43.347$, $p < 0.0001$, where RP assistance was more likable), feedback on the nAH ($F(3,60) = 25.753$, $p < 0.0001$) and interaction of both ($F(3,60) = 2.935$, $p < 0.0405$), see Fig.3E. When no assistance was present on AH, the difference in likability was only found for the nTG and TG conditions ($W = 7$, $Z = -3.445$, $p = 0.0023$, other

$p > 0.08$). When the AH was assisted by RP, the nTG was perceived as more dislikable than all other conditions (nTG-solo: $W = 168$, $Z = 3.615$, $p = 0.0007$; nTG-RP: $W = 150.5$, $Z = 3.524$, $p = 0.0011$; nTG-TG: $W = 91$, $Z = 3.195$, $p = 0.0032$). Interestingly, likability increased when assistance was present in the form of the RP on the nAH ($W = 155$, $Z = 3.0573$, $p = 0.0146$) and during the solo condition ($W = 144$, $Z = 3.241$, $p = 0.0068$) compared with the same feedback conditions without assistance on AH.

IV. Discussion

We studied the impact of different haptic feedback forms on the performance and user perception during tracking. Our results show that while physically assisting the AH improved performance, feedback on the nAH only resulted in reduced or similar improvement compared to additional solo training. The different forms of nAH feedback did however have an effect on user perception, where the TG was clearly identified as assisting the tracking, the nTG was disliked and perceived as disturbing and the RP resulted in mixed responses.

The observed superior task performance with assistance on the AH is consistent with similar findings using the RP [6], [3], which have been shown to derive from a combination of the force transfer from the mechanical connection and an additional information transfer [6]. Interestingly without AH force transfer, we do not find performance improvement when the same information was conveyed to the nAH (Fig.2A). This suggests that participants might not have been able to infer that the information was task-relevant when there was no associated force transfer. Here, it is noted that participants were split in whether they perceived the RP to be assisting the nAH (Fig.3B) and that the NSD showed a large variance across participants, where some moved both hands while others kept their nAH still, suggesting an overall lack of a common strategy in using this information.

Perception of assistance did however not necessarily lead to improved overall performance, where while the TG condition was perceived to be assisting the nAH (Fig.3B), it did not show improved performance compared to the solo or RP conditions (Fig.2A). This result was contrary to the findings of [8], where feedforward information, giving a clear mapping between the task target and the given cues (in analogy to our TG condition), was more effective than feedback information (like our RP condition). Our lack of improvement may be caused by a number of factors. First, the delay introduced by the inter-hemispheric connection may be a limitation. However, while adjusting for this delay has resulted in a perception of more realistic bimanual interaction [11], it has not improved performance in previous work. Alternatively, it is possible that the lack of improvement reflects that either the information alone cannot help the performance, which is in contrast to the findings of [8], or that the task difficulty may limit the benefits of this added information, where our chosen task could have been too simple. Both of these aspects require further investigation.

Interestingly, while haptic feedback on the nAH did not improve performance, it could worsen the performance as observed in the nTG condition. In bimanual tasks, moving both hands together with similar directions, amplitudes and frequencies tends to be more stable [14], [15]. Therefore, it is possible that even if the participants were not actively considering the nTG feedback, the resulting motion of the nAH may have led to worse AH performance and a decreased perception of helpfulness. This may also be linked to the stronger perception of a connection in the TG condition (Fig.3A), where the haptic feedback on the nAH matched the visual feedback associated to the AH tracking. This could have favoured similar motions among the hands, which may have been understood as a "connection".

Our findings therefore suggest that haptic feedback on the nAH cannot improve performance, and can instead in some instances create interference in the AH's motion. Further research is however required to determine if our results are task specific and to identify which forms of nAH feedback lead to interfering behaviour.

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