Haptic Coupling to Negotiate Motion Plans

C. De Vicariis, E. Ivanova, V. Sanguineti, and E. Burdet

***Abstract*—Haptic coupling is integral to everyday life, enabling humans to collaborate on tasks without the need for verbal agreement of every detail. However, collaborative partners often have differing plans and use haptic coupling to negotiate a common strategy. While previous studies have focused on tasks where partners share the same plan, little is known about haptic negotiation when plans diverge. This study investigates how the motion plans of two mechanically connected partners evolve during repeating a via-points arm-reaching task when they start from differing initial plans. In one group, partners had plans requiring similar effort, while in another group, plans were unbalanced, requiring different levels of effort. The analysis of shape and movement metrics shows that all dyads coordinated their plans through practice, influencing subsequent movements even when disconnected. For symmetric plans, partners exhibited slight mutual adaptation toward each other. In contrast, for asymmetric plans, the partner with the simpler plan tended to lead the movement, while the partner with the more complex plan complied and relaxed their plan. These findings suggest that, during collaboration, partners leverage mechanical interaction to simplify tasks and minimize effort.**

***Index Terms*—Haptic coupling, negotiation, motor planning, haptic interaction.**

I. INTRODUCTION

WHEN two individuals manipulate a large piece of furniture together, they may perceive the scene differently and therefore plan their actions differently. However, they can rely on the exchange of haptic information during the interaction to understand each other and negotiate a shared motion strategy. This paper investigates how mechanically connected individuals search for consensus among possible solutions [1] to determine their common action.

To understand the exchange of haptic information in mechanically connected individuals, previous studies have considered tasks in which they have to track the same target [2], [3], [4]. These studies showed that this *haptic coupling* (HC) benefits both partners' performance [4], [5], [6] and learning [7], [8]. These benefits of HC arise from partners sharing their motion plan through the haptic channel, which augments their sensory feedback [9], [10], [11].

But how do connected individuals handle conflicting plans? The haptic channel enables interacting agents to recognize negotiation behaviors [12], [13], often leading to better performance compared to visual-only connections [14]. In presence of slight noise, connected subjects adapt muscle impedance in a stochastically optimal manner to improve HC [15], [16]. Moreover, partners with different task constraints can comply to minimize interaction forces [17] when the collaborative solution is unambiguously identifiable [18].

This study investigates how individuals with different plans adapt their behavior when mechanically connected. To this end, we developed a paradigm in which pairs (or *dyads*) of connected individuals, free from external constraints, could choose to compete [19], [20], [21], or negotiate a common plan. Pairs of participants performed planar movements with their dominant arms while being connected through a dual robotic interface implementing a virtual elastic band. Participants were free to move as they wished in a clockwise manner through the four via-points, however, each partner adopted a different plan induced by the presentation of a possible path before the initial trials [22]. Consistent with previous studies [22], here we refer to motion plan as the way participants perform a redundant task which can be solved adopting different strategies.

Using this experimental paradigm, we observed that visual cues influences participants' individual motion plans. We then investigated whether mechanically connected partners - each starting with different (incongruent) motor plans - could learn to coordinate their movements in both time and space. Additionally, we aimed to understand whether and how their motor plans evolved based on the features of their initial plans. In particular, by comparing conditions where the physical effort required by participants movement plans was either balanced or unbalanced, we sought to better understand the dynamics of their interaction.

In the present study we investigated whether partners with incongruent plans learn to coordinate their movements in both time and space during repeated interaction (Aim 1).

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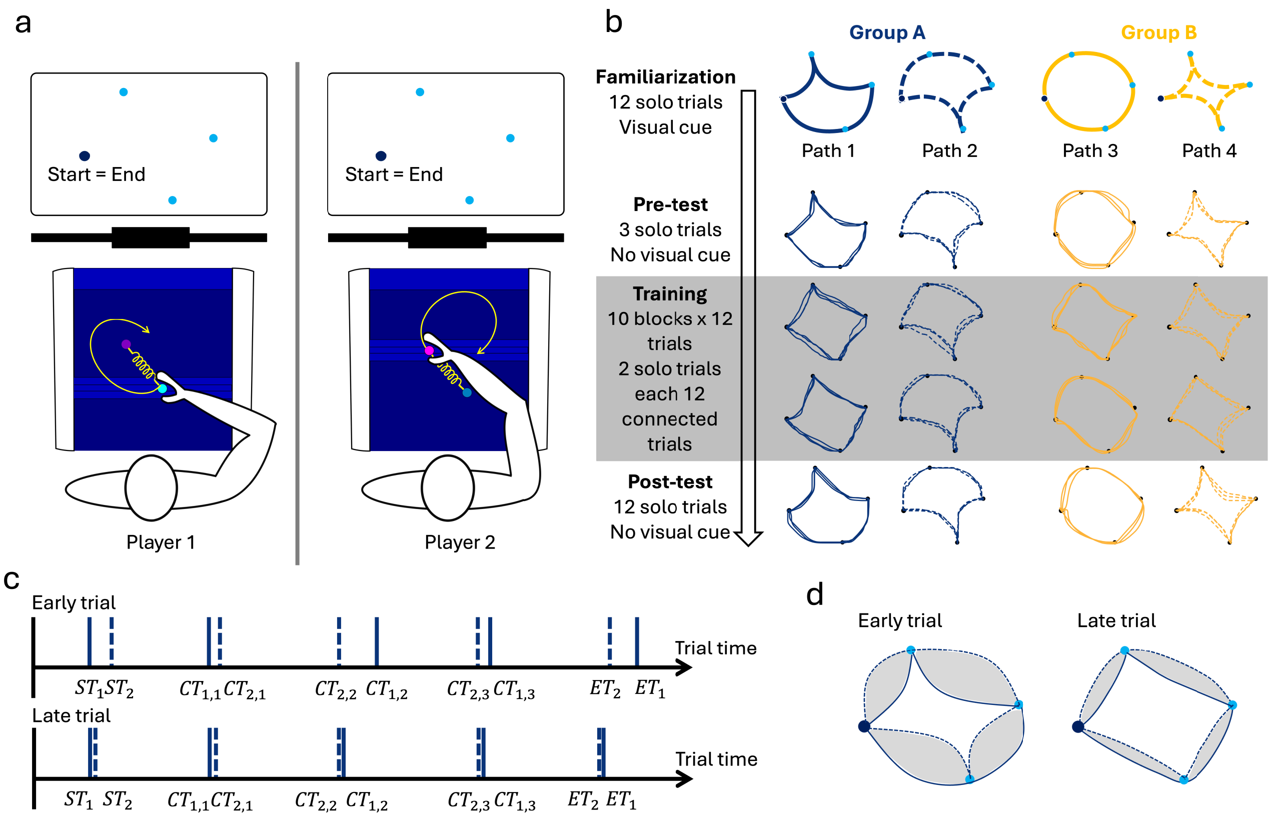

Fig. 1. Experimental setup/protocol and metrics hypothesis. (a) The two connected individuals moved a cursor on their screen by controlling the handle of their individual planar robotic interface. They were instructed to move the cursor from a start point (blue) through a sequence of via-points (turquoise) back to the start with no time constraint. The yellow spring and arrow represent the mechanical connection and the clockwise movements. (b) The protocol starts with a familiarization phase (12 solo trials), during which a visual cue about one of the possible trajectories was displayed prior to the 'Go!' signal. In the pre-test phase (3 solo trials), subjects performed the same task without a visual path. During the training phase (120 trials) players performed the same task while being mechanically coupled, without visual suggested path through the via-points. During training, two randomly selected catch trials were used within each 12-trial block, where the mechanical coupling was removed. During the post-test (12 solo trials) players were not coupled and did not have visual cues, as in the pre-test. (c) Hypothetical time vector of a typical trial at the beginning and end of the training, with Start (ST_i), via-point Crossing (CT_i) and End Time (ET_i) for the two partners ($i = 1, 2$) indicated. One can expect that with connected practice (late trials) the time difference between two partners should be minimized. (d) Area is expected to be greater at the beginning of the experiment and to decrease with coordination.

We further explored how partners evolved their respective plans depending on the initial plan features (Aim 2), and whether such adaptations are associated with the emergence of distinct interaction dynamics at the dyadic level (Aim 3). These exploratory aims guided the analysis linking observed coordination patterns, plans evolution, and push-pull strategies across trials.

II. MATERIALS AND METHODS

A. Apparatus and Task

Each dyad's individual sat in front of their own H-MAN robotic interface [23] and grasped its handle with their dominant hand to control the motion of a cursor on the screen (Fig. 1a). Seat position and height were adjusted to enable comfortable arm movement within the robot workspace. The two partners could not see or hear each other and were not allowed to talk during the experiment. They were instructed to stay at the start position until a 'Go!' signal appeared on their monitor, then perform a smooth movement in the clockwise direction through all the via-points and finish at the starting point. During movements participants had continuous visual feedback regarding their position on the workspace. Participants were not constrained to follow a particular path. Only during the initial 12 trials were participants within a dyad visually cued with two different paths. These cues did not constrain the motion, and participants were explicitly informed that they were free to follow the suggested path or to use a more comfortable one.

B. Experimental Protocol

The protocol is illustrated in Figure 1b. In an *initial familiarization phase* of twelve trials, participants performed the task in solo condition (with no mechanical connection). Importantly, a possible path through the via-points was displayed on the screen, overlaid to the Start and the via-points, for three seconds just before the start of each trial in this phase (see Fig. 1b), where the two partners received a different visual cue. These suggested paths were only presented in the familiarization trials of the experiment. Only the via-points were displayed during trials' movements, and the task did not require participants to adopt the presented path. However, we expected that experiencing such visual path during the familiarization should influence the individuals' motor plan [22], thus leading the two partner's to plan the way to perform motion differently. After this initialization phase, the partners carried out three *pre-test* solo trials and, consequently, a 120-trial *training phase* with mechanical coupling. After training, players performed a *post-training test phase* consisting of twelve control solo trials. The experiment lasted approximately one hour.

Two groups of dyads received visual cues suggesting different paths during the familiarization phase (Fig. 1b), which were designed to elicit conflicting motion plans in the interacting participants. In group A, the path suggested to one of the partners in the first half of the motion was mirrored and presented to the other partner for the second part of the motion. With this first pair of paths (group A), we aimed to create a condition in which the overall effort on a trial is similar among the partners. In group B, the effort associated with the two suggested motion plans was not balanced. Indeed, while participants receiving path 3 could move along the circle in a single and continuous stroke, partners with path 4 should stop at each via-point and change motion direction. We expected that the differences in the suggested paths would lead to different individual motion plans during the initial solo trials, consistent with previous literature [22]. Using this paradigm we aimed to investigate whether different initial motion plans, elicited by distinct visual cues, lead to changes in the interactive behavior while mechanically connected to a partner, and whether such changes depends on the specific combination of motion plans in groups A and B. Specifically, in group B the two partners may converge to the simpler solution 3, whereas in group A may comply more equally to one another.

C. Participants

The experiments were approved by the ethics committee at Imperial College London (15IC2470) and 60 naive participants (25 females) without known sensory or motor impairment were recruited. Participants, aged between 21 and 35 (25.74 ± 4.06 yo), completed and signed a consent form and demographic questionnaire before starting the experiment. They were randomly grouped into 30 dyads and randomly assigned to one of the two experiments, differing in the visual path through the via-points that was provided in the initial phase of the experiment.

D. Data Analysis

During experiments, hand trajectories were sampled at 100 Hz and stored for subsequent analysis. Movement trajectories were smoothed using a fourth-order Savitzky-Golay filter with a 370 ms time window. The same filter was used to estimate velocity and acceleration. For each trial, we estimated the start and end times of each player based on a 0.1 m/s speed threshold. On occasion, in the initial trials, participants explored a counterclockwise trajectory even though they were explicitly instructed to move clockwise. 12 trials were identified in total among all the 4410 trials of the 60 subjects, which were excluded from further analysis. Trials were distributed among three dyads in Group A and 4 dyads in Group B. Data pre-processing, metrics and plots were performed using Matlab (MathWorks, Natick, MA).

Interpersonal coordination: To address features of temporal coordination we considered the correlation coefficient between the speed profiles of the two partners ($i = 1, 2$). We considered the correlation coefficient between the two time-series defined over the time interval defined as the joint movement time (MT_{joint}):

$$MT_{joint} = max(ET_1, ET_2) - min(ST_1, ST_2), \tag{1}$$

which is calculated as the difference between the longer end time (ET_i) and the shorter start time (ST_i). This allowed us to consider the effective movements of the two players without truncating one of the two time series. Temporal coordination is higher when speed correlation increases.

To analyse possible delays between the partners, we also looked at the average temporal asynchrony between partners:

$$Asynchrony = \frac{1}{5}\Bigg\{|ST_1 - ST_2| + |ET_1 - ET_2| + \sum_{vp=1}^{3}\left|CT_{1,vp} - CT_{2,vp}\right|\Bigg\} \tag{2}$$

For each trial asynchrony is computed considering the average reciprocal delay in the starting times (ST_i), the via-points crossing times ($CT_{i,vp}$) and returning to the end point (ET_i)–as represented in Fig. 1c. Small values indicate well-coordinated movements.

To address coordination in space we used a measure of shape similarity. Dynamic Time Warping (DTW) [24] is a distance metric between two time series, which stretches two vectors onto a common set of instants to minimize the sum of the Euclidean distances between corresponding points. Low values of this metric indicate that trajectories are similar in space.

An intuitive metric of movement shape similarity is the area between the paths used by the two interacting agents' movement - see Fig 1d. If participants solve the task using the same path then the area should be close to zero, conversely, if participants use different paths then the area increases.

Individual behaviors: To disentangle how individual motor plans were affected by the initial visual path we analyzed each trajectory segment and via-points crossing event. To understand to which extent participants deviated from the trajectory that could be a compromise between the two plans, we considered the signed area between participants used trajectories connecting consecutive via-points and the corresponding straight lines–as illustrated in Fig. 2b. Positive values indicate that participants were tracing a concave path, negative values a convex path.

We considered via-point crossing relative to the total individual movement time and speed at the via-points. The normalized crossing times provide information on the individual timing, while speed at via-points allow to observe whether people used a single continuous movement (as expected for those participants who planned with path 3, circle like) or used multiple segmented movements (as expected for participants who received path 4, diamond like).

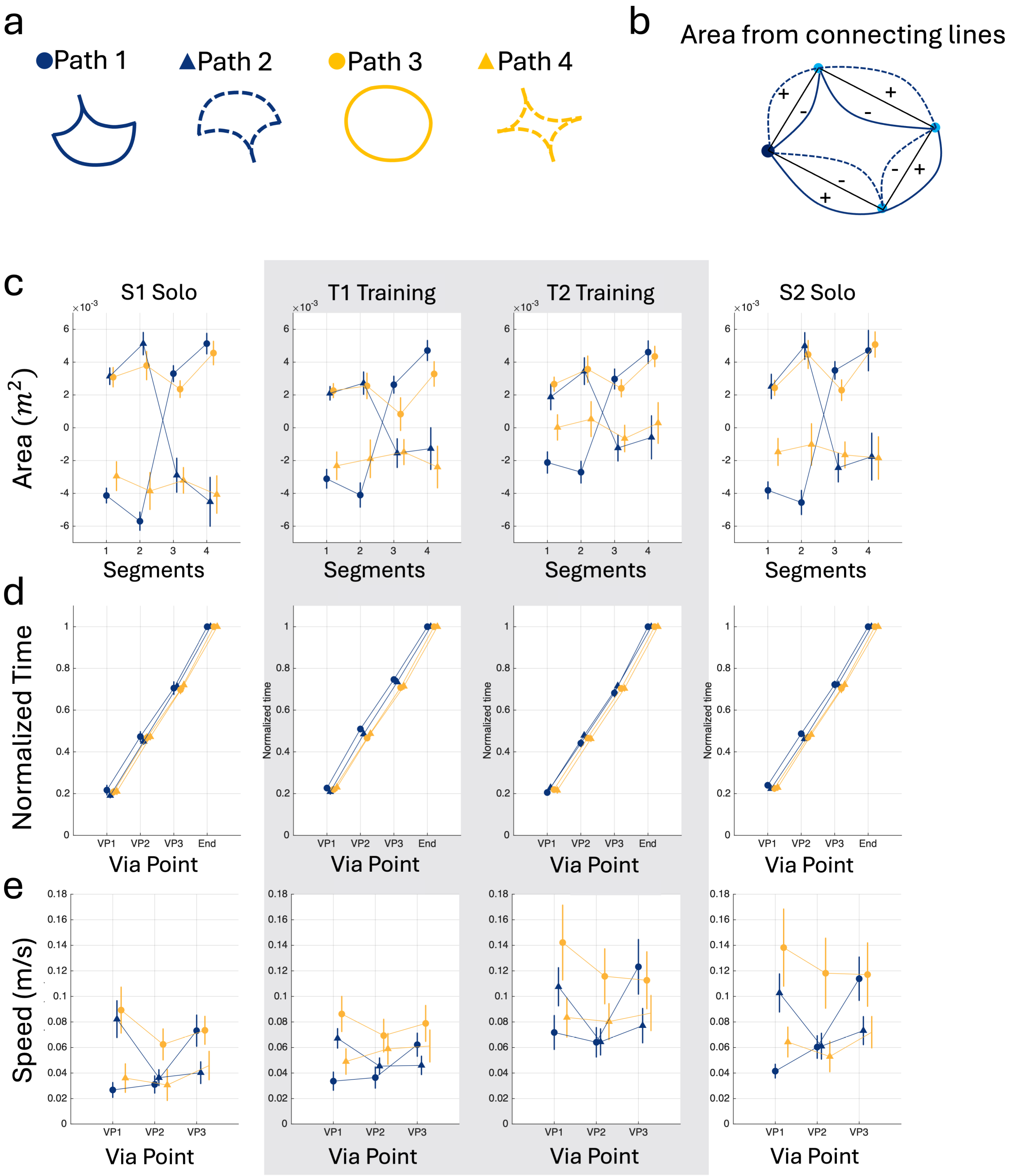

Fig. 2. Individual motion plans in the different experimental phases. (a) Path legend. (b) Signed area between performed trajectory and straight line connecting consecutive via-points. (c) For each trajectory segment the area between the performed path and the straight line connecting two consecutive via-points changed in sign depending on the initial visual cue. (d) Normalized crossing times does not seem to be affected by initial cues or the connection. (e) Speed at the via-points is affected by the initial visual cue, little by the connection.

Continuous or segmented movements should also correspond to different movement costs. To this end we considered execution cost as the *normalized velocity cost*

$$\frac{\sum_{t=1}^{N-1}\sqrt{(v_x^t - v_x^{t+1})^2 + (v_y^t - v_y^{t+1})^2}}{\sum_{t=1}^{N-1}\sqrt{(v_{x_s}^t - v_{x_s}^{t+1})^2 + (v_{y_s}^t - v_{y_s}^{t+1})^2}}, \qquad (3)$$

where the normalization factor corresponds to a smooth fifth order polynomial trajectory [25] through the four via-points. Smaller values of this metric indicate that participants optimize their motions toward a smoother strategy, making also their movements more predictable and possibly facilitating interpersonal coordination.

Leader-follower interaction dynamics: Given the asymmetries introduced by the initial suggested paths, we expect that interaction strategies emerge differently in the two tested groups. Looking at the power developed by each player provides information on whether they actively lead the movement, or are passively pulled by the partner through the mechanical coupling [26], [27]. To quantify this, we calculated the power $P_i(t) \equiv F_i(t)\, v_i(t)$, defined as the scalar product of the interaction force vector F_i and velocity vector v_i. At a given time *t*, a negative power means that the player is moving against the mechanical coupling, which we define as 'leading' the movement. Conversely, a positive power would indicate that the player is being pulled toward the other, i.e., they are behaving as a 'follower' [17], [26], [27].

E. Statistical Analysis

We analyze how performance changes from the initial solo block (S1), over the connected training period at the beginning (T1) and at the end (T2) to the solo block after the training (S2), and how it is affected by the different visual solutions. For S1, T1, T2 and S2, we used three first trials from pre-test, the first and last blocks of the training and post-test, which then were averaged for the analysis. We then checked whether the data was normally distributed using Shapiro-Wilk test. Since all metrics were not normally distributed, we used two-way ART ANOVA with block factor (S1, T1, T2, S2) as within factor and group as in-between factor. To characterize how individual behaviors changed, we, similarly, used two-way ART ANOVA with the block as within-subject factor and initial visual cues (Path 1, Path 2, Path 3, Path 4) as an in-between-subject factor. For the analysis including individual visual cues we used random intercepts for each individual nested in dyad.

If significant effects were found, we conducted tailored post-hoc tests using (un)paired t-test contrasts and (Mann–Whitney U test) signed-rank Wilcoxon test as a parametric and non-parametric option, correspondingly. The Holm-Bonferroni correction was applied to adjust p-values. The statistical analysis was performed in R.

III. RESULTS

A. Initial Visual Cues Induce Individual Motion Plans

We first explored individual motion plans to understand whether the method introduced in [22]could be used to create individual motion plans. As in [22], the presentation of a path through the sequence of via-points prior to each initial trials manipulate individuals motor plans. Indeed, even though participants were not instructed to do so, they adopted this *plan* in particular for complex trajectories such as for visual paths 1,2,4 in Fig. 1b. To show this here, we divided the task into four segments and considered the signed area between the straight lines and the portions of trajectory used by participants to go from one via-point to the other (Fig. 2b,c). In S1 - see left plot in Fig. 2c - where participants were neither shown the visual path neither connected to the partner, we observed that the movement was greatly affected by initial visual path presentation. Indeed, in group A (blue) participants had symmetrical trends. Those who were cued with path 1 (blue circles) had positive Area values in the first two portions of the movements and negative values in the second two portions. Vice versa for those who were cued with path 2 (blue triangles). Looking at group B, we observed that participants cued with path 3 (yellow circles) had positive values for all the motion portions, while partners cued with path 4 (yellow triangles) had negative values. The discrepancy between groups of participants receiving the same cues was retained to some extent during (T1,T2) and after (S2) training as we will analyze in the next section.

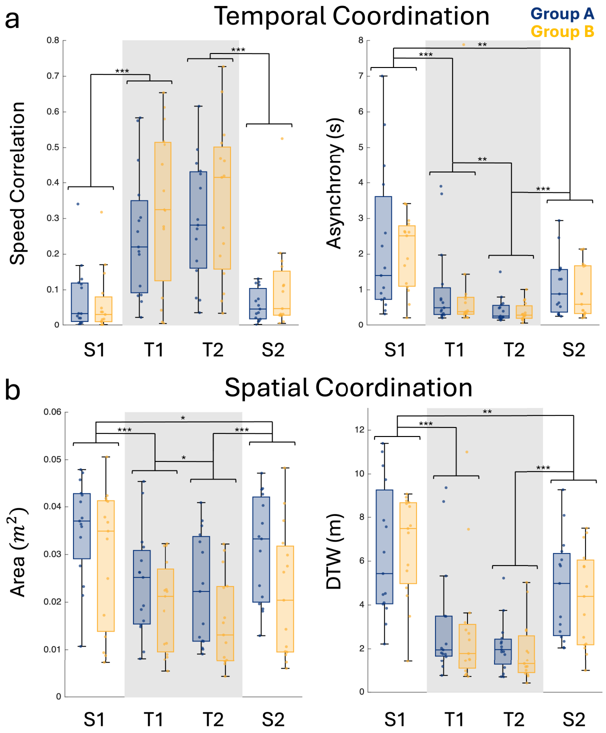

Fig. 3. Coordination performances in time (a) and space (b). Data are reported in blue for group A and in yellow for group B. The figures show the results in S1 (pre-test), T1 (initial training), T2 (end of training) and S2 (post-test). Connected training phase are indicated in grey. Overlapped data-points represent the average performances of the single dyads.

As observed in [22] the via-point were crossed at regular times (normalized by the total movement time) and were consistently similar regardless the initial visual path presented and the connection (Figs. 1b,2d). However, looking at the speed at the via-points we observed differences between groups which suggest that initial displayed paths indeed affect the individual motion plans in S1 - see Fig. 2e With the mechanical connection we observed slight reciprocal changes toward the partner's behaviors, but also a time effect in T2, where participants became overall faster.

B. Coordination Changes in Mechanically Connected Dyads

Temporal coordination Overall, dyads increased their coordination in time when mechanically coupled - see Fig. 3a. Participants within dyads changed their speed correlation between experimental blocks ($F(3, 84) = 28.267, p < 0.001$). Dyads had more coordinated speed while connected compared to solo performance (S1 vs. T1: $t(84) = -6.434, p < 0.001$; T2 vs S2: $t(84) = 6.65, p < 0.001$). However, the coordination did not change during training and the changes were not maintained after training ($p > 0.05$ for T1 vs. T2 and S1 vs. S2). Similarly, temporal asynchrony significantly varied within the blocks ($F(3, 84) = 31.821, p < 0.001$). It also changed between S1 and T1 ($t(84) = 5.859, p < 0.001$) as well as T2 and S2 ($t(84) =$

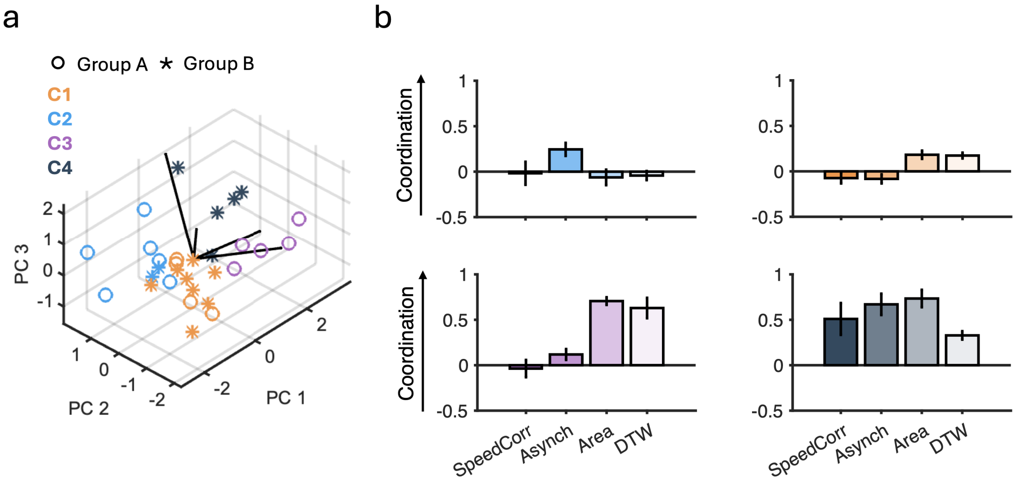

Fig. 4. Clustering. (a) Data projected in the principal component space. Identified groups are represented using different colors, circles refer to dyads that performed in group A while asterisks refer to dyads that performed the task in group B. (b) For each identified cluster we reported the average and standard error of the coordination changes in the considered metrics between S1 (pre-test) and S2 (post-test).

-5.777, $p < 0.001$). Additionally, we observed a decrease in asynchrony within the training (T1 vs. T2: $t(84) = 3.685$, $p < 0.001$) and between solo blocks before and after training (S1 vs. S2: $t(84) = 3.766$, $p < 0.001$).

Spatial coordination Trajectory similarity, as temporal synchronization, was generally higher when participants within dyads were mechanically connected as shown in Fig. 3b. Looking at shape similarity in terms of area between partners' trajectories, we found significant changes between the experimental blocks ($F(3, 84) = 26.473$, $p < 0.001$). Differences were found between solo and training trials (S1 vs. T1: $t(84) = 6.481$, $p < 0.001$; T2 vs. S2: $t(84) = -4.944$, $p < 0.001$), and dyads coordinated more in space even after the mechanical connection was removed, compared to the initial performance (S1 vs. S2: $t(84) = 3.316$, $p = 0.003$). Consistent with the other metrics, the dynamic time warping was affected by block effect ($F(3, 84) = 43.955$, $p < 0.001$). Dyads coordinated more while being connected (S1 vs. T1: $t(84) = 8.088$, $p < 0.001$; T2 vs. S2: $t(84) = -6.932$, $p < 0.001$), improved the spatial coordination with training (T1 vs. T2: $t(84) = 2.454$, $p = 0.016$), and remained more coordinated after training in comparison with the first solo trials (S1 vs. S2: $t(84) = 3.611$, $p = 0.001$). Overall, there was no significant difference between the two groups ($p > 0.05$ for the main effect of the group for all metrics) with different initial visual cues.

We compared coordination before training (S1), at the beginning (T1) and at end (T2) of the connected training, and after training (S2), in both conditions with different initial plans (as analyzed in Fig. 3).

Coordination behavior clusters We observed a variety of different behaviors across the two groups and in the different dyads. As a not-planned post-hoc analysis for each dyad and each metric, we considered the difference of the average blocks performances. In particular, to address how coordination performances changed with mechanically coupled training, considering the differences between the coordination performances at the end of training (T2) and in the pre-test phase (S1). To address changes after coupled training in the unconnected phase, we considered the differences between coordination performances after training (S2) and in the pre-test phase (S1). We obtained two datasets, corresponding to N dyads (rows) and M features (columns), consisting in the coordination performances differences between the initial pre-test and the end of training or after-effects in group A and B. For each of the two standardized dataset we partitioned the N dyads into k clusters, using the k-means algorithm,in which each dyad belongs to the cluster with the nearest mean (cluster centers or cluster centroid). To identify the optimal number of clusters k we considered the average within-cluster sums of point-to-centroid distances and we visualized it with the elbow graph. To visualize clusterization results, we displayed dyads in the principal components space. For each group, we reported the average and standard error for the normalized changes of the evaluated metrics in the identified groups.

The four metrics of Fig. 3 show that there is a great variability of behaviours between dyads. To identify possible different patterns, we performed a cluster analysis on coordination changes between the initial and final phases of the experiment S1 and S2. Considering changes in performances between initial and final unconnected phases (S1:S2) we can observe four clusters in Fig. 4a, two of them with dyads from group A and the other two with dyads from B. Further, the purple circles cluster of dyads from group A retained coordination mainly in terms of dynamic time warping and area (Fig. 4b), which corresponds to a spatial coordination. On the other hand, the black asterisks cluster retained coordination in terms of both spatial and temporal coordination. The two other clusters of dyads returned to the initial performance, retaining little coordination. We did not find clear patterns when addressing coordination changes between the initial unconnected phase (S1) and final connected training (T2). Although, the statistical analysis did not show a group effect, this explorative analysis confirms the great variability of behaviours but suggests also that some common patterns of coordination emerged in a fraction of dyads in each group.

C. How Does the Initial Cue Affect Individuals' Behavior?

Dyads changed their motion plans, negotiating a coordination strategy during the connected phase. Some dyads kept the coordination strategy after removing the mechanical connection as appears in Figures 1 and 4.

Considering the segment- and via-point wise plans' changes depicted in Fig. 2c,d, we observe that in group A the two partners tended to change their individual behavior to a similar extent in terms of signed area from connecting lines and speed at the via-points. Both partners on average contracted their curvature values toward zero, and, while they crossed via-point 2 with a similar speed already during S1, they also crossed via-points 1 and 3 with more similar speed. As expected, participants who received path 1 (blue circles) changed predominantly in the initial phase of movement (segments 1 and 2) while their partner who received path 2 (blue triangles) changed more in the second phase (segments 3 and 4). This is arguably connected to these portions of movements requiring more effort then the circular stroke. With training, participants refined their behavior toward a more coordinated one with the partner. When the connection was removed, partners returned to their initial curved trajectory with the exception of the second half movement for those who received path 2 (blue triangles).

We observed a different negotiation behavior in group B. On average, participants who received path 4 (yellow triangles) visual feedback changed their curvature toward the zero-value, while those who received path 3 (yellow circles) kept their behavior almost unchanged throughout the experiment. Consistently, partners who received path 4 changed their speed at the via-points as connection was activated. When the connection was removed they even slowed down respect to the final connected phases. Altogether, this suggests different patterns of negotiation in the two groups, consistent with the clustering results presented in the previous section.

We hypothesized that the negotiation patterns differ depending on the initial individual plans. The experimental design used visual path suggesting corresponding motion plans with similar effort and symmetrical curvatures in group A, and different effort and opposite curvatures in group B. Notably, the initial visual path presentation indeed affected the normalized velocity cost ($F(3, 37.258) = 18.8582$, $p < 0.0001$) - as illustrated in Fig. 5a. This previous qualitative observations that participants incorporated the cued paths in their motion plans (even though they were not constrained to follow them). In particular, we observed significant cost differences between participants who received path 3 (solid yellow) and those with either path 1 (solid blue $t(34.2) = 2.882$, $p = 0.0407$), path 2 (striped blue $t(34.2) = 3.484$, $p = 0.0096$, or path 4 (striped yellow $t(28) = -7.294$, $p < 0.0001$). This confirms that the movement corresponding to the circular path requires less effort than the movements corresponding to other paths, which involve abrupt direction and velocity changes.

Considering the results of the last two sections, it appears that in group A partners with a similar effort level changed their motion plan in opposite directions toward each other. In group B those who have lower-effort plans (path 3) tend to stick more with that plan while partners who received the higher effort path 4 tended to change their plan.

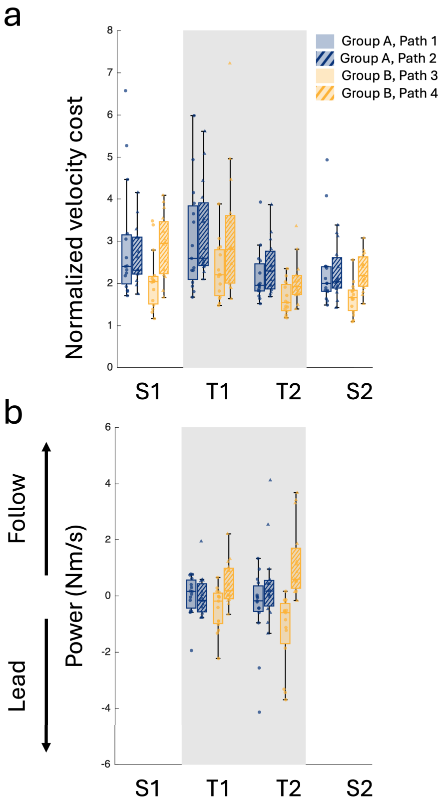

Fig. 5. How different cues influence behaviour changes and leadership. (a) Individuals reduced their normalized velocity costs, more if the initial visual path was more complicated (paths 1,2,4). (b) Power exchanged suggests that leadership arises when partners have greater and more unbalanced initial differences in their motor plans (group B - yellow).

Given these observations, we argued that these different adaptation behaviors may correspond to different interactive strategies in the partners that may have emerged in the two tested groups. We therefore analyzed a *leadership* index as the average power during each trial. Fig. 5b illustrates how pull-push strategies and therefore leadership emerged differently in the two groups. At the beginning of training (T1), leadership was comparable in all groups despite their different plan ($p > 0.05$) without leader/follower dynamics. However, at the end of the coupled training (T2) participants who had received path 3 (solid yellow) behaved as leader with respect to their partner with path 4 plan (striped yellow), ($W = 5$, $p < 0.001$). In contrast, no difference was observed between partners in group A. These results suggest that initial cued shapes affect not only the individual motion plans but also the negotiation of an interaction strategy through the emergence of leader-follower dynamics.

IV. DISCUSSION

This study aimed to investigate whether and how people exchanging haptic information negotiate a coordinated strategy while carrying out planar arm movements through four via-points. We tested two groups in which we initially presented two different pairs of visual cues, suggesting two different paths through the same sequence of via-points to the interacting partners.

Looking at the movement shape and movement cost associated to the adopted plans we observed that the initial visual cues effectively manipulated the individual motion plans as in [22].

After a familiarization phase where a visual path was presented on their individual monitor before each trial, participants completed an unconnected test phase without path suggestions. They then trained while mechanically connected to their partner, experiencing force perturbations as they pursued the same task but with a differing motion plan. Finally, the mechanical connection was removed, and participants performed the task again. Importantly, the subjects had no temporal [17], [28] or spatiotemporal [4], [9], [29], [30] constraints. Unlike previous studies that emphasized improved individual performance [4], [5], [6] and learning [7], [8], our focus was on how motion plans evolved through haptic interaction, characterizing planning at both the coordination and individual levels.

Analyzing movement shape and coordination metrics, we found that *haptic coupling led interacting partners to negotiate a coordinated strategy in space and time*, allowing to respond to our first question (Aim 1). Mechanical connection immediately increased speed correlation while reducing temporal asynchrony and trajectory differences. Once the connection was removed, coordination decreased, yet post-test coordination remained higher than in the pre-test, indicating that connected training influenced individual motor plans, transferring to the subsequent unconnected phase.

Successful joint action requires coordination in both space and time [31], but prior studies have typically focused on only one of these aspects. Our via-points task with differing motion plans allowed us to disentangle these elements. Our findings align with previous research [31], [32], [33] on temporal motion coordination in social contexts and are consistent with studies where connected partners maintained a jointly developed strategy despite perturbations [28], [29]. By allowing partners to start with different plans, we specifically observed how coordination evolved.

Using cluster analysis, we *identified distinct coordination strategies after training, shaped by initial individual plans*. A fraction of dyads in group A predominantly maintained spatial coordination, while a fraction of dyads in group B exhibited coordination in both space and time. Moreover, *initial individual motion plans influenced adaptation during connected training*. Mechanical connection prompted at least one partner to adjust their motor plan, depending on the two partners' initial plan. This alignment between coordination patterns, individual behaviors, and initial solutions provide insights regarding our second question (Aim 2). Our interactive task thus provided insights into motion plan negotiation and adaptation.

Furthermore, *individual motor plans affected execution costs of the partners and led to the emergence of leader-follower dynamics*, allowing us to answer to our third question (Aim 3). In particular, we observed that participants using a trajectory similar to path 4 (diamond-like, in dashed yellow) requiring higher cost than their partner whose plan was affect by the visualization of path 3 (circle-like, solid yellow) tended to depart more from it. Indeed, they reduced their motion-related cost by decreasing their trajectory curvature - computed as the area between used path and the straight lines connecting consecutive via-points. In contrast, the partner with plan that followed from the visualization of the circular path (3) tended to stick to this plan, not changing much the cost associated to it, as observed in Figure 5a. Interestingly, this different behavioral change in the partners of group B was associated with the emergence of leader-follower interaction dynamics, where the partner with more simple plan tended to take the lead. In group A, where cost distribution was initially balanced, both partners adjusted their plans similarly to comply of the partner, reducing their movement cost likewise.

These results extend previous findings on cost minimization and leader-follower dynamics [15], [20], [34], [35], [36]. Unlike [20], where partners increased effort when they were instructed to compete, the 'competition' induced in the present study by the differing initial plans resulted in reduced effort with connected practice. A collaborative strategy was achieved in both the tested groups A and B, where partners tend to adopt the least effortful of the two plans they initially used. Similar to [34] and [35], this evolution was accompanied by the emergence of a consistent leader–follower relationship. When partners have a symmetric motion plan requiring similar effort no leader-follower dynamics emerge between the partners [34]. In contrast, when partners have initial plans requiring a different level of effort, these plans change in an asymmetric way and leader-follower dynamics emerge [35]. In [34] and [35] role specialization, rather than collaboration itself, was the main factor improving dyadic performance. Similarly, in group B leader-follower dynamics also lead to greater coordination retention in both space and time. Our results also align with findings that suggest that in connected dyads the more effective performer naturally assumes the leads [15], [36], where in our study the partner offering the more favorable motor plan tends to lead.

In conclusion, this study demonstrates that haptic coupling enables individuals to negotiate and adopt coordinated strategies in both space and time, with coordination retention influenced to some extent by the initial motion plans of the partners, so that the most simple plan yielding least effort tends to prevail. This highlights the nuanced interplay between individual priors knowledge and preferences and collaborative adaptation. Understanding the mechanisms underlying haptic-mediated coordination and the factors driving its emergence may provide insights for designing effective human-robot physical interactions that use haptic feedback to infer human intent and enhance robot interpretability.

In the context of neuromotor rehabilitation, an emerging body of work—including early pilot studies and theoretical frameworks—highlights the potential of approaches that combine the clinical expertise of therapists with the sensing, feedback, and actuation capabilities provided by robotic systems [37], [38]. Such hybrid human–robot strategies represent a promising direction for enhancing the effectiveness and individualization of rehabilitation pathways. Further, knowledge of these interaction strategies may inspire alternative control architectures for next-generation robotic devices used in conventional robot-assisted therapy, potentially leading to systems that better adapt to patient intent, promote active participation, and more closely emulate the beneficial aspects of therapist–patient interaction.

Beyond physical training, insights gained from studying human–human physical interaction may also inform the design of technologies aimed at augmenting human motor capabilities, with potential applications ranging from industrial collaboration and skill amplification to adaptive assistance in automation. A deeper understanding of how humans coordinate, negotiate effort, and share control during physical cooperation can provide valuable principles for developing more intuitive and responsive assistive devices.

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