# Human-Human Connected Dyads Learning a Visuomotor Rotation in a Targeted Reaching Task

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*Abstract*— Little is known about how two people physically coupled together (a dyad) can accomplish tasks. In a pilot study we tested how healthy inexperienced and experienced dyads learn to repeatedly reach to a target and stop while challenged with a 30 degree visuomotor rotation. We employed the *Pantograph* investigational device that haptically couples partners movements while providing cursor feedback, and we measured the amount and speed of learning to test a prevailing hypothesis: dyads with no experience learn faster than an experienced person coupled with a novice. We found significant straightening of movements for dyads in terms of amount of learning ($2.662 \pm 0.102$ **cm and** $2.576 \pm 0.024$ **cm for the novice-novice and novice-experienced groups) at rapid rates (time constants of** $17.83 \pm 2.85$ **and** $18.17.17 \pm 6.72$ **movements), which was nearly half the learning time as solo individuals' studies. However, we found no differences between the novice-novice and experienced-novice groups, though retrospectively our power was only 3 percent. This pilot study demonstrates new opportunities to investigate the advantages of partner-facilitated learning with solely haptic communication which and can lead to insights on control in human physical interactions and can guide the design of future human-robot-human interaction systems.

## I. INTRODUCTION

Human-computer interfaces (HCI) involving two people have received increasing attention and are potentially beneficial in many applications. However, little is known about how dyad (two people working together) might physically accomplish tasks, and how robotic devices might facilitate the process. Recent studies in this area have focused almost entirely on augmenting human performance using HCI rather than improving humans' intrinsic skills. The few works that studied human-human interaction using a device show promising results: dyads complete many tasks faster and more accurately than individuals [1], [2], [3]. There are few systems in the state of the art that exploit dyadic interaction to enable learning of intrinsic motor skills. In fact, dyadic interaction may not be an end goal, but a natural extension of HCI. One prospect is that dyadic training can facilitate and augment learning.

Here in this preliminary study, we investigated possible changes in performance during a typical targeted reaching

task in two different dyads: a dyad performing the experiment for the first time was considered as a *novice-novice* dyad, whereas a dyad composed by an experienced user and a novice was defined *experienced-novice* dyad. We considered experienced users as those who had done the experiment once. Moreover, we investigated which dyadic interaction method gives the best outcome in terms of learning of a visuomotor rotation in a targeted reaching task. Learning is defined as improvement in the ability to perform the straightest movement to the target, even during the visuomotor rotation. Moreover, this study investigated how motor adaptations occurred when there was a mechanical connection between two subjects – a dyad. The goal was to make some foundational measurements on the timing and magnitude of dyad learning that can be used as a pilot for future experiments that look at HCI enhancements of learning.

We hypothesized that during the experiment, dyads would improve performance, learning how to move when a visuomotor rotation was imposed. Our second hypothesis was that a novice collaborating with another novice learned faster to perform the task rather than collaborating with an individual who is familiar with the experiment – experienced user.

## II. RELATED WORK

### A. Performance of dyads versus single users

Many studies have focused on HCI and their effectiveness on dyads while performing a variety of tasks. The results have outlined how motor tasks are performed faster and more accurately by dyads than single users [4], [5], even in controversial situations where the coordination strategies were not optimal, such as the two people in the dyad exerting opposing forces [6]. Dyads can be composed by two people with equal roles, such as two novices, but it could even be constituted by two people with different abilities, such as a novice and an expert, or different roles in terms of leader-follower couple or simply one person is given more information about the task than the other [7], [8], [9]. In all these scenarios, the dyad needs to develop a particular coordination strategy [6], [2] using haptic information to accomplish the task; such information can not be extrapolated when a single user is collaborating with a robot pretending to be human [2], [3].

However, it is still unclear and undefined how dyadic interaction, whether it is visual, haptic or spoken, affects the performance and how the dyads develop a specialized strategy rather than others. Indeed, it is difficult to quantify the effects of the different types of interactions on coordination and performance [10], [11], [12], [13], [14],

which seems to benefit improves in dyadic human-computer interfaces, especially when visual and haptic information are exchanged. Depending on the task [15], [16], one information channel is preferred and more effective than the others and sometimes the combination of multiple information could be less successful than a single type of information [17].

### B. HCI-enhanced motor learning in dyads

The most relevant recent study on dyadic interaction was done by Ganesh et al. [1]. His group highlighted on one hand the potential benefits of this connection in terms of motor learning, on the other the limited research studies done so far in this field [7]. The aim of Ganesh's work was to investigate motor learning via robot-assisted dyadic interaction, using sensory feedback through haptic signals. This study supports the idea that dyadic interaction allows people to learn (or relearn) a physical skill more effectively than with state-of-the-art HCI: fields such as motor rehabilitation, sports and other areas where motor training is crucial could take advantage from this paradigm, saving costs and manpower. The outcomes of his study revealed that motor learning through the haptic coupling was faster and more effective than several different strategies for solo motor learning. In addition, even couples of novices seemed to benefit from the exercise. However, further studies need to be done to prove that dyadic HCI are helpful for motor learning in real-world applications [1].

Another important study on dyadic human-computer interface was done by Lanini et al. [18], in which two ARMin arm rehabilitation exoskeletons were included to perform two different control study: unilateral teleoperation, achieved using proportional-derivative controllers, and bilateral tele-operation, that can be obtained with compliance control and torque feedback [18]. Lanini et al. have demonstrated that such haptically coupled devices can be used by informed users (who have already practiced a motion) to teach two-dimensional motions to uninformed users [18].

However, haptic devices connected over a local area network are not optimal for dyadic haptic interaction: even small network delays cause the quality of haptic interaction to degrade, an issue also observed in non-dyadic haptic studies [19]. Therefore, a direct mechanical coupling that haptically connects two people's motions without a digital connection could be a possible solution to this limitation. The system we built aimed at maintaining a constant and non degradable mechanical connection between two subject. The mechanical connection guarantees that users provide all the energy for motion. It also guarantees that haptic forces of one subject directly influences the other without any of the delays seen in telehaptic systems. In this study we employed this simple Pantograph system to ask the initial question of whether novice-novice dyads learn more readily than novice-expert dyads.
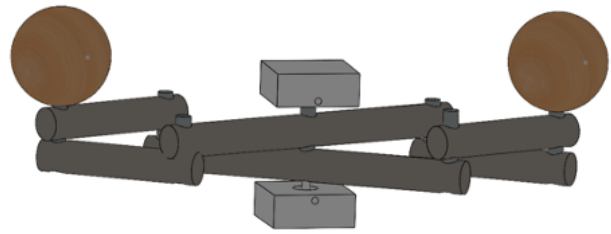


Fig. 1. SolidWorks mockup of the Pantrogaph device: the six-steel dark gray tubes allow the mechanical connection of dyads, while the brown balls are the handles that the two subjects need to grasp in order to perform the experiment. The two gray boxes contain the two rotary encoders that are connected to the longer tubes using couplings. Moreover, the boxes are connected to the 80/20 aluminum structure upon which a display is positioned.

## III. METHODS

### A. Design of the Pantograph device

The technology of the entire system is thought to be as simple and safe as possible: the Pantograph includes a set of hardware components that comprises a 80/20 aluminum-structure, empty steel-tubes, steel-pins, two handles, two incremental rotary encoders and a display, as well as the software that enables the device to read real-time handles position (Figure 1). The 80/20 aluminum-structure is meant to be solid in order to allow a correct and safe usage of the device, it grants the movement of the handle in the desired zone, a semicircular area with a radius of 25cm, and it is used to lay the display on it to provide the required visual feedback. The ideal length of the steel-tubes, that have an internal diameter of 2.3cm and external one of 4cm, was obtained using a band saw: two tubes are equally long 25.5cm and positioned at the center of the device and connected to each other thanks to a common central pin, which represents the center of rotation of the whole system. The other four shorter tubes, half long than the other two, are linked with steel-pins both to the central tubes and to the two handles and pass though the tubes thanks to holes realized with the drill machine; the diameter of them observes the requirement of minimum friction between pin and tube allows the movement. The function of all the pins is twofold: first of all they connect all the components of the system, then they also act as joints that allow the relative movement between the different rods and the central pin allows the movement of the whole device. The handles have been realized with wooden balls in which a hole has been made to rigidly constrain the pin to it. This choice of this shape allows the usage of the device even by people with diminished ability in grasping a handle or other upper limbs impairment: the sphere-shaped handle does not require to apply any pressure on the handle to activate the movement of it.
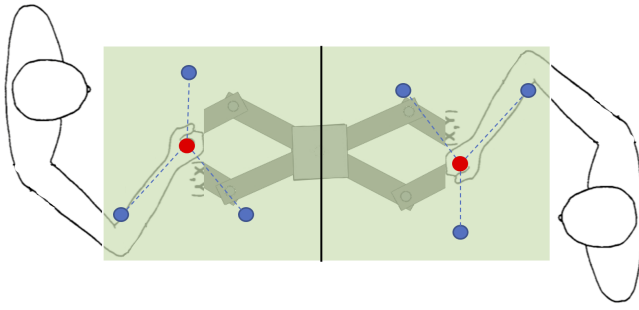
Fig. 2. **Schematic of the study design and the task**: The screen mounted on the Pantograph covers part of the participants limbs and displays the visual feedback where the cursor (red circle) is moved in the planar virtual environment using the handle of the device to reach the targets (blue circles). During the experiment targets appear one by one and change position according to the phase. In this schematic targets' position during Training phase is illustrated.

### B. Data Acquisition System

The central tubes are connected to two incremental rotary encoders that read the rotation of each tube through pins rigidly constrained (through a press-fit method) to the tubes. Rotary encoders are powered and read with an average sampling rate of 58Hz by the Arduino Mega 2560, which we found to be the best solution because they have specific pins, called interrupt pins, that ensure always catching incremental pulses from the rotary encoders.

### C. User Interface

The User Interface was implemented using Unity ®. The experiment was in 2 dimensions since the Pantograph device allows movement in a planar environment. The interface was projected on a screen that laid just above the aluminum structure that supports the whole system (Figure 2). The display was divided in two parts, one for each subject, and a separator prevented a person seeing his/her partner's game field. On the display the handle, represented as a red circular cursor, moved on a green colored environment while the targets were blue circular sprites and the start zone was a gray circular sprite.

### D. Experimental Setup

As in accordance with the Northwestern University Institutional Review Board (IRB), twenty neurologically normal right-handed adults, aged between 19 and 32 years, gave informed, written consent to participate in this study. This IRB also specifically approved this study and follows the principles expressed in the Declaration of Helsinki.

The procedure to recruits participants followed this process: the first week only groups of novices performed the experiment. The second week, the novices who came the week before were contacted to come as experienced users. If none of them could not come, the novices were assigned to the novice-novice experiment. Otherwise, if experts could come, novices were assigned to the experienced-novice experiment. When the novice-novice group reached 5 dyads, novices were re-assigned to the second group – experienced-novice group.

The experimental protocol replicates the one described in [20]. We asked the seated subjects to grasp one of the handles of the Pantograph with their dominant hand and reach one the six targets located on a circle of radius $r = 0.1m$ from the starting zone making movements as fast and accurate as possible. Each movement included the reaching of the target and the return movement to the starting position. We used a screen to provide the visual feedback and prevent subjects from seeing their forearm and the robot linkage. In this way, when the visuomotor rotation was implemented during the experiment, the subjects did not adapt their motion following their hand position but they only focus on the cursor position. To be considered as a complete movement, subjects had to reach the target and stay on it for 0.5 seconds; moreover, in order to move on to the next reaching and activate the next target, subjects had to stay for 0.5 seconds in the center of the field. The experiment was divided in 3 phases:

- **Baseline phase**: in the first phase, composed of 165 movements, there were two sub-phases, Baseline 1 and Baseline 2. In the former sub-phase (comprising 45 movements), initial movements of dyads to reach three targets displayed in preestablished positions, which were $0°$, $120°$, $-120°$ with respect to the subject, were evaluated. Baseline 2 included 120 movements, and during this sub-phase subject's response to the $30°$ counter-clockwise rotation (at least once every 8 movements and never two in succession) was intermittently evaluated. Targets were rotated $90°$ counter-clockwise in Baseline 2 sub-phase with respect to the previous one.
- **Training phase**: it was composed of 390 movements during which adaptation to a constant $30°$ counter-clockwise rotation was evaluated. Hence, cursor motion rotated $30°$ counter-clockwise about the starting point relative to hand motion. Targets' positions were displayed as in the Baseline 2 sub-phase.
- **Washout phase**: in this phase targets' positions were $0°$, $120°$, $-120°$ with respect to the subject as in Baseline 1 sub-phase. During this part of the experiment, 165 movements were performed with no visual distortion implemented, thus the reaching was unperturbed and time course of recovery of each subject's original performance was evaluated.

### E. Data Analysis

We did not analyze data from return movements to the starting point. We defined trajectory error as the maximum perpendicular distance between the actual hand path and the straight-line path between start and target positions. Reaching-by-reaching errors in the Training and Washout phases were fit using nonlinear Nelder-Mead least-squares regression, which has been used in previous studies to fit exponential decays [20], since Levenberg-Marquardt method seemed to have difficulty with these curves:

$$E_i = Ae^{(-i/B)} + C \tag{1}$$

where $E_i$ is the trajectory error, A is the amount of learning (the change of the trajectory errors due to training), B is the time constant (number of trials for error to decrease 67%), and C is the asymptotic terminal or residual error at the end. One way to simply measure learning could be to quantify the average error after the error has leveled, but we measured relative change as the amount of learning from start to finish, A. In addition, running 95% confidence intervals were estimated across the Training and Washout phases to quantify uncertainty.

Data were averaged for both groups making two dataframes (novice-novice and novice-experienced groups). Statistical test were then implemented to compare the quality of learning between the two subjects groups: one-way ANOVA could be a possible method to compare the amount and the rate of learning (fitting curve parameters A and B respectively in the training phase). Though, one-way ANOVA assumptions must be verified before proceeding with this test; in case normality was not satisfied, we used the non-parametric Mann-Whitney rank test for observations greater than 20, otherwise we used the Kruskal-Wallis H-test.

## IV. RESULTS

Movements of dyads without challenging the visual distortion were not significantly different from the best trajectory line, almost approximating a straight line. Proceeding with the study, a 30° counter-clockwise visuomotor rotation was implemented during the reaching of specific targets. When the visual rotation was turned off, the movements approximated a straight lines as in the Baseline 1 sub-phase, while with the visuomotor rotation enacted, the reaching motions were still relatively straight but in the wrong direction distant from the target. Training resulted in clear changes in the trajectory (Figure 3).
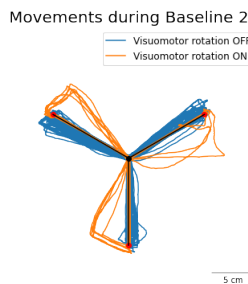


Fig. 3. **Representative trajectories during Baseline 2 of representative dyad**: The blue and the orange lines are the movements of the dyads from the starting position to the targets (in red), without visuomotor rotation and with the visuomotor rotation turned on, respectively. During normal reachings, the movements have shape similar to the previous sub-phase, while trajectories have an elbow shape when the visual distortion is active.

While the visual distortion was active during the reaching of specific targets, the elbow shape persisted for all the Baseline 2 sub-phase, regardless the position of the targets and the number of the target to be reached: thus, during this part of the experiment, the dyad did not adapt to the visuomotor rotation. Analyzing the Training phase,

the trajectories (Figure 4) were curved on initial exposure to the imposed rotation, but subjects regained straight-line movements by the end of training. Results from the Training phase show a change in the performance for novice-novice and novice-experienced groups (Figure 5); for each reaching, the error (maximum perpendicular distance from the best line trajectory) was analyzed and plotted versus the correspondent target. During this part of the experiment, the error reached its peak at the beginning of the phase, then it decreased following a curve similar to an exponential decay; this is true for all the three targets to be reached. The curve we obtained, typical in studies where participants are required to perform and learn a task, defines the learning curve. Dyads adapted to the visuomotor rotation and changed their movement in order to compensate the visual distortion for all the three targets to be reached during the Training phase.

The Washout phase reveals a similar behaviour: the distance between the actual path and the ideal one was really large at the beginning, then it decreased with time. Thus, removing the rotation caused change in the trajectories, which provides strong evidence that the dyad had adapted their movements to the visuomotor rotation. After-effects of learning faded out proceeding with the number of reachings, since the error decreased with time.

Each dyad learning curve related to the Training phase provided its quantitative parameters of the exponential decays, hence the amount of learning, the rate of learning and the steady-state error. Novice-novice group had a change of the trajectory errors (parameter A in Eq 1) due to training equal to $2.662 \pm 0.102$ cm , while the other group had an amount of learning of $2.576 \pm 0.024$ cm (Table I). Regarding the rate of learning (parameter B in Eq 1), dyads composed by two novices the error decreased 67% of the way to asymptote after $17.83 \pm 2.85$ number of reachings, whereas the novice-experienced groups after $18.17 \pm 6.72$ number of trials (Table I). Though, one group did not statistically differ from the other: Kruskal results for the amount and the rate of learning were statistic=0.0982, p-value=0.7540. In the end, the novice-novice group had a steady-state error (parameter C in Eq 1) of $0.996 \pm 0.061$ cm, and the other group an error of $0.861 \pm 0.043$ (Table I).

## V. DISCUSSION

In this preliminary investigation we wanted to contribute to the literature on dyadic human-computer interfaces. We designed and developed a new device, named Pantograph,
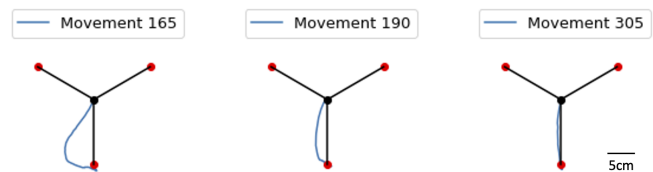


Fig. 4. **Representative trajectories during Training of representative dyad**: these reachings show how dyads initially moved following an elbow-shape when exposed to the 30 degree visual distortion, but increasing the number of movements they regained a straight-line trajectory.

| Error values and their changes | | | | |
|---|---|---|---|---|
| | | **Learning Amount** | **Time Constant** | **Steady-State** |
| **Group** | **N** | cm | movements | cm |
| *Novice-Novice* | 5 | $2.662 \pm 0.102$ | $17.83 \pm 2.85$ | $0.996 \pm 0.061$ |
| *Novice-Experienced* | 5 | $2.576 \pm 0.024$ | $18.17 \pm 6.72$ | $0.861 \pm 0.043$ |

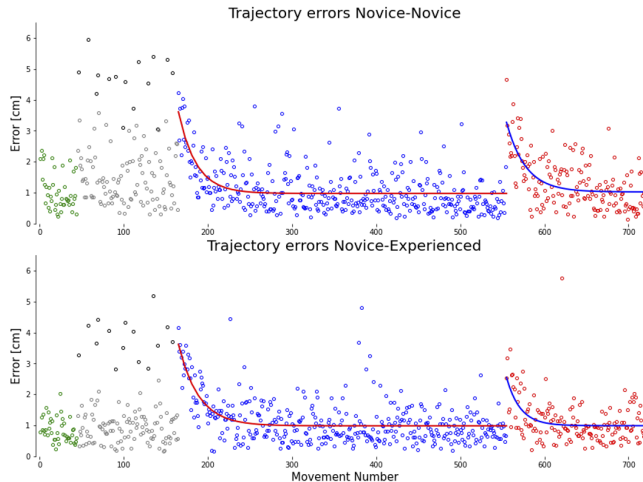TABLE I

ERROR VALUES AND THEIR VARIANCE



Fig. 5. **Representative trajectory errors during the entire experiment of representative dyad**: the green and the gray dots represent the trajectory errors during the Baseline phase,while the blue and the red dots stand for the trajectory errors during the Training and the Washout phases, respectively. On the other hand, the red and blue curves represent the fitting curves respectively. The top image illustrates the trend of the errors for each target in the novice-novice group, whereas trajectory errors for the novice-experienced category are shown in the bottom image. As described before, errors in the Training and Washout phases are very large and then decrease as exponential decay.

that mechanically connects the dominant upper limbs of two people working together, defined dyad, while performing a targeted reaching task in a planar environment. The system has some features that allows to have an haptic feedback between the dyad, in particular providing a mechanical connection between the two subjects.

Since our work is a preliminary study, we had available a small sample size and to test our second hypothesis (two novices working together learn faster than a novice coupled with an experienced), hence only a large difference between the two groups would have been detectable. We did not find the strong difference that Ganesh et al. did in their study [1]: first, it might be that the sample size is too small to show any difference (retrospectively our power was only 3 percent), and if there is an effect from switching from one group to another is not apparent is this pilot study. Second, the different experimental setup might have influenced the learning rate of dyads, since our work is based on a targeted reaching task, while the other consists in a movement tracking. We need to be careful about thinking that all dyads experiment do better with novice-novice, because this is not the case. When subjects have to reach a target, many challenges are associated with this task: healthy subjects

are expected to move in a straight line, which requires an elevated neurocomputational effort, then subjects have to start moving, maintaining that trajectory and then stop on the target. All of these tasks need to be done at the same time to successfully reach a target, while movement tracking does not involve all these challenges.

Even if our results show that dyads adapted their motor behaviour, a series of limitations could have reduced the outcomes of this preliminary investigation. The first constraint is related to the realization of the device: low-cost components, both mechanical and electronics, and the techniques used to build the device could have influenced the experiment.

There are also some limitations that are strictly related to the experiment: the task to be done in the study is not really engaging, which could have influenced the active participation of the users. Developing a more interactive and more challenging environment could be a possible solution, even if the experiment should remain a targeted reaching task. Besides, in the state of the art all the studies regarding users reaching a target are usually as simple as possible, thus implementing an experiment with many additional features could make difficult the comparison with previous works.

Finally, a larger number of dyads are required to evaluate if the results could be generalized and if there is any difference between dyads composed by two novices and dyads made up of a novice and an experienced in terms of amount of learning, rate of learning and residual error.

Even though results did not show any statistical difference between the two groups, this investigation seems to show promising outcomes, since motor skill learning was enhanced. Exponential decay curves show that the dyads adapted to the imposed visuomotor rotation when implemented, and users re-adapted their movements when the visual distortion was turned off. Thus, dyads in the novice-novice and novice-experienced groups developed their own strategies to reduce error. Our results show that visually distorting feedback had advantages because it led to practical improvements in the extent and rate of learning. Influencing and modifying visual feedback to promote motor adaptation has been already done in the literature, and many studies have demonstrated how manipulating visual feedback could lead to perceive an higher stiffness than actually felt [21] and modify vestibular-ocular reflex gains.

## ACKNOWLEDGMENT

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