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Human-Human connected dyads learning a visuomotor rotation in a movement tracking task*

Adriano Gendy[1, 2, 3], Mattia Demasi[1, 2, 3], and James Patton[1, 2]

Abstract—**Dyads are couples of collaborative humans that perform a task together while mechanically connected by a robot. As shown in different studies [1] [2], haptic interaction can be beneficial for motor performance so that the dyad outperforms the subject executing the task alone. These achievements are hypothesized to be the result of the haptic communication engaged between the subjects that triggers internal forward models. In this way the dyad's components can attain additional information about the task, hence improving their performance. Here we show a novel dual robotic system, called Pantograph, used in a pilot study to understand the influence that the nature of the partner has on the learning process. The main hypothesis that we claim is that a Novice-Novice type of interaction is more beneficial, in terms of speed of learning, with respect to an Expert-Novice type of interaction. The results show time constants equal to 5.53 ± 2.79 and 8.45 ± 3.78 for the Novice-Novice and Expert-Novice group, respectively. However, the p-value obtained was *p* = 7.54%. Hence, we can not generalize our results, but this research study shows how haptic communication between interacting humans allows for motor learning and how the nature of the subjects could be an important factor of the learning process.**

I. INTRODUCTION

Little is known on humans interacting and learning together, and yet interaction with other subjects and learning is common in everyday life. The study of dyads, a couple of interacting humans, has been of large interest over the years. These processes can lead to different types of responses that can also affect the motor behavior of the subjects. These responses can be the result of two types of signals:

- Cognitive signals, that is the recognition of the individual with which an interaction is occurring.
- Sensory feedback, such as visual, haptic and auditory signals.

This study mainly focuses on the second type of feedback, particularly on haptic signals that are exchanged between two subjects coupled with a passive dual robotic system called Pantograph. A lot of studies have been done on human-human interaction and more of them are focusing on dual robotic systems. Some of these have the aim of studying the human-human interaction principles to use them in the design of control systems of robots [3] [4] [5] that are used, for example, in the rehabilitation process in which is important to obtain an interaction, between the robot and the user, that allows variability of movements and that is intuitive and natural [6]. So, even if motor learning has been largely studied through different methods, in a lot of fields (particularly in rehabilitation) there is need for more effective motor learning technologies. Exploiting the precision and speed of a robot with the intelligence of a human could provide those results that individual tasks have not been able to give.

However, how our motor behavior is influenced by another interacting subject is still largely unknown. Thus, our study wants to be a first step for future research in which the type of paradigm we evaluated will be studied and used in different fields such as rehabilitation, sports and surgeon training. Our investigation will mainly focus on a preliminary experiment done on healthy dyads, connected through the Pantograph, that were asked to perform collaboratively a target tracking task with a visuomotor rotation of 80°. We defined two different groups: the Novice-Novice group, where both participants do not have any a priori information about the task, and the Expert-Novice group, in which one of the components has been exposed to the task beforehand. Our hypothesis is that a Novice-Novice type of interaction is more beneficial, in terms of speed of learning, than an Expert-Novice type of interaction.

II. RELATED STUDIES

A. Human-Human Interaction Taxonomy

When talking about physical human-human interaction, one of the first elements that has been defined is how the subjects deal with each other. This taxonomy allows to understand the mechanisms that are present in these interactions, hence permitting a better understanding of the agents' behavior. The classification presented here has been defined by Jarrassé [7] and it is based on minimizing effort and error of each individual and on role assignment:

- Competition: in this type of interaction every component minimizes its own error and effort without considering the ones of the partner (or partners). This type of interaction generally occurs in antagonist tasks.
- Collaborative: in this case each component also considers the error and effort of the other components so that the task is completed in a way that benefits each component. In this case, there is not any role assignment prior to the beginning of the task. So, roles are defined during the execution of the task and there is an equal distribution of effort between the participants [3].

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[1] Department of Bioengineering, University of Illinois at Chicago, Chicago, IL, USA.

[2] Robotics Lab, Shirley Ryan AbilityLab, Chicago, IL, USA.

[3] Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB), Politecnico di Milano, Milan, Italy

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- Cooperative: as in the collaborative case the subjects work together to minimize effort and error but in this case the roles of each subject are defined before the beginning of the task and do not change during the execution of the task. In this case there is an uneven distribution of effort since, even if every participant is working to reach the same goal, each component is performing a different part of the same task. This type of interaction can be divided in other two subtypes: assistance, where the effort and error that are being minimized are the one of the person that is receiving assistance (in human-human interaction paradigms the haptic signals exchanged between the subjects can be used as a measure to understand the assistance that the other subject needs), and education, where there is a teacher-student role assignment where the teacher tries to minimize the error of the student so that they can then perform the task alone (this type of interaction represents more the therapist-patient interaction).

B. *Cooperative Dyads*

The research study by Patton and Reed [2] has the aim of understating how human-human physical interaction occurs and if two motor control systems are better than one. They developed a crank that connected two different individuals through two spinning handles. The task that the individuals were asked to perform was to move the handle to the target that was displayed on the screen and to hold the handle until a new target would appear. This task was done by dyads and by individuals alone. What they measured is the completion time of the task and what they found is that, except for two cases, the completion times for dyads were lower than the ones found for the solo tasks. This means that human-human interaction is indeed beneficial to motor performance and since the only way for the two subjects to communicate was through the device (during the task they could not see or talk to each other), this supports the hypothesis for which the haptic communication that was engaged between the participants allowed them to attain more information about the task, hence improving the performance. The force profiles that were recorded showed how dyads develop a new cooperative strategy to complete the task [2] [8].

Even if the presence of another interacting human can be felt as hindering the motor performance, a lot of other studies showed how this interaction is instead beneficial. Not only the cooperation brings to an enhancement of performance, but at the same time it minimizes the effort of the dyad's components [9] [10].

However, the combination of different types of information is not always more effective than a single information channel. Indeed this is dependent on the task [11] [12], the type of information provided [13], and on how the two people in the dyad perceive each other [14] [15].

C. *Dual robotic systems and dyadic tasks*

One of the main research studies that has been done on dyads, and with which we compare our results, is the one made by Ganesh [1]. This work has the aim of investigating motor responses that are given by the sensory feedback through haptic signals when human-human interaction occurs. To quantitatively study the haptic signals' effect on dyads movement, a cyber human system was developed so that there was a connection between the individuals through a virtual elastic band which compliance could be changed. Hence, the compliance could be set to 0 so that each component of the dyad could perform the task individually. The task that was required to be performed was to track a target with a cursor controlled with the dual robotic system with a visuomotor rotation of 80°. This task was performed both by dyads and by individuals alone.

This study shows that the human-human interaction improves motor performance. Moreover, the benefits were higher than the ones registered when the task was performed individually. This means that the haptic communication between the two subjects allowed the participants to improve the performance. Another important result that has been obtained by [1] (and [16]) demonstrates how actual robotic designs can not replace humans. A trajectory and force playback experiments were performed: the interaction was between a human and a robot, the latter's response was predefined and it emulated the one of a human that previously performed the task. These experiments exhibited a degradation of the performance of the dyad. What arose is that in this type of experiment there is a one-way connection, which means that the subject could feel and respond to the action performed by the virtual partner, but the latter could not change its response based on the one of the other component of the dyad. Hence, the user did not receive any haptic feedback. So, a two-way connection seems to be an essential factor that induces mutual motor benefits. This suggests that humans, during physical interactions, have implicit expectations in terms of the haptic forces from a partner and this allows to gain more information on how to complete the task in a more efficient way [17].

Finally, the influence of the nature of the subjects was studied and what was revealed is that it influences the outcome: more gains in terms of motor performance has been measured when the two subjects were similar to each other (which is in the case of the Novice-Novice experiment).

Even if these results are very promising, the complexity of the device that has been used by [1] may drive away the attention from human-human interaction benefits: are these results a consequence of the dyadic interaction or part of these motor improvements have been given by the device's features? For this reason, we decided to develop a much simpler device, with respect to the one used in Ganesh's study, that is fully controlled by two interacting subjects and not influenced by other aspects. The task performed with the Pantograph will be the same used in [1] so that the results can be then compared between the two research studies.

III. DESIGN AND DEVELOPMENT OF THE PANTOGRAPH

A. *Mechanical Structure*

The Pantograph is a mechanical system that presents two handles that are placed at the extremities of the device and are mechanically connected through six steel-tubes linked one another with seven steel-pins. There are four tubes (three for each handle) that are long 25.5cm and two center tubes that are long 51cm. The last two tubes are connected to each other by a common central pin which can be considered the center of rotation of the whole Pantograph, the shorter six tubes, instead, are connected to each other using three different pins: one is connected to the handle (and it is used also as a support of the handle), while the other two link the tubes to the central ones. All these pins are conceived not only to connect the different structures of the system to each other but also as the joints that allow the movement of the whole and the relative movement between two different links. The connection between the subjects is purely mechanical, this avoids the use of local area networks that bring delays that cause the quality of the haptic interaction to degrade [18]. Hence, a direct mechanical connection is optimal.

To read the position of the handles, two incremental optical encoders are connected to the Pantograph. One of them is linked to the lower central tube and it is blocked on the base on which the pantograph lays. The other one is instead connected to the upper tube and it is kept in place through a bridge made of 80/20 aluminum bars on which the support base of the encoder is attached. This avoids the translation of the encoders while the system is in use, hence providing a proper measurement of the angle of rotation.

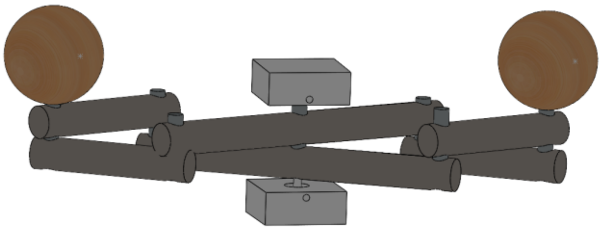

Figure 1 SolidWorks mockup of the pantograph. In this structure the six-steel tubes mechanism, that allows for high compliance between the users, can be seen clearly. The gray boxes represent the structures in which the encoders are inserted and at the extremities of the device the spherical wooden handles are fixed to the device through pins.

B. Data Acquisition System

The data acquisition is made by an Arduino that reads the encoders' signals at an average sampling rate of 50Hz. The incremental optical encoders provide a digital signal that counts how many times the rotational axis rotates. This signal is then sent to Matlab through serial communication and from Matlab the angle of rotation of the central tubes is computed.

Using the angles that are given by the encoders it is then possible to solve the following forward kinematic equations to obtain the position of the cursor:

$$X_c = 2\ a\ cosd(\theta_2)sind(\theta_1 + \theta_2) \quad (1)$$

$$Y_c = 2\ a\ cosd(\theta_2)cosd(\theta_1 + \theta_2) \quad (2)$$

Where X_c and Y_c are the position of the handle in the 2D space, a is the length of the shorter tube and it is equal to 25.5cm, θ_1 is the angle between the lower central pipe and the x-axis and it is computed by multiplying the resolution of the encoder (0.15°) by the digital signal of the lower encoder and θ_2 is half of the angle between the central tubes and it is computed as half of the difference between the digital signals of the two encoders multiplied by the encoder's resolution (0.15°).

IV. METHOD

A. Participants

Twenty participants (10 men, 10 women, all right-handed), age 19-61 (18 of them are younger than 30), from Shirley Ryan Ability Lab participated after giving informed consent. All the experimental procedures presented in this paper and that involve human subjects were approved by the Institutional Review Board of Northwestern University.

B. Experimental Protocol and Task

The experimental protocol has been taken from [1]. This will allow to compare the results and the different devices used in the two research studies.

Participants were randomly assigned to the Novice-Novice or to the Expert-Novice group. From the Expert-Novice group 5 "Experts" were chosen and they performed a training of 10 trials that allowed them to gain knowledge about the task. Also, the composition of the dyads was random within the same group.

The dyads were asked to perform cooperatively a tracking target task in a visuomotor rotation environment of 80° (in a clockwise direction) for 60 different trials of 60 seconds each. "After each trial the target will be switched off and their hand will be passively returned to the center of the screen followed by a 20-30 seconds break" (G. Ganesh, A. Takagi, 2014) [1].

A screen mounted on the Pantograph displayed a cursor, that was controlled through the dyadic interaction, and a target. The participants were asked to follow the target trying to minimize as much as possible the distance between the cursor and the target. The latter moved according to the following multi-sine functions:

$$x_T = 3\sin(1.8t) + 3.4\sin(1.8t) + 2.5\sin(1.8t) + 4.3\sin(2.3t) \quad (3)$$

$$y_T = 3\sin(1.1t) + 3.2\sin(3.6t) + 3.8\sin(2.5t) + 4.8\sin(1.48t) \quad (4)$$

Where x_T and y_T are the target position in the 2D space while t is the time vector defined as:

$$t = [t_i, t_i + 60] \text{ and } 0 < t_i < 20 \quad (5)$$

t_i is chosen randomly for every trial, in this way the target's path is never the same.

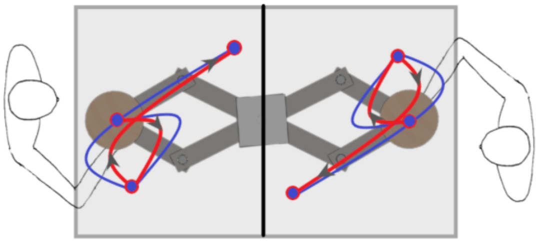

Figure 2 The screen mounted on the top of the device covers the limbs of the subjects so that they are not able to see them while executing the task. On the screen the virtual environment is displayed and the participants are able to see the target (in red) and cursor movements (in blue). The cursor position can be then controlled by moving the wooden spherical handles.

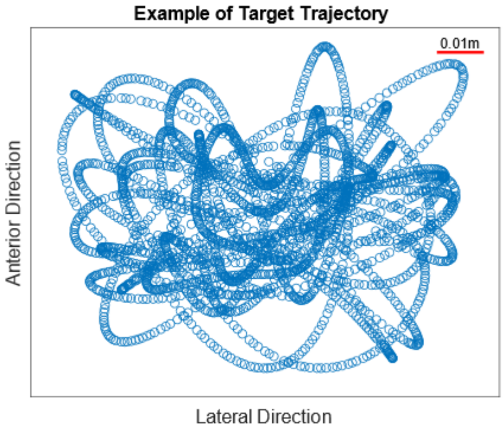
Example of Target Trajectory

Figure 3 Example of a target trajectory during 60 seconds of trial. The hand movements of the subjects had to cover a workspace of 30cm. This is just one of the possible target's trajectory since it changes between different trials.

The 60 trials are then divided in three main phases: the familiarization phase (for the first 10 trials), the visuomotor rotation phase (from trial 11 to trial 50) and a washout phase (for the last 10 trials, in this phase the visuomotor rotation is turned off as in the familiarization phase).

The participants were not allowed to see their own hands, that were covered by the screen mounted on the device, so that they could not develop any strategy different from the one that arises from the dyadic interaction. Moreover, they were not allowed to talk to each other. To avoid the risk that one of the components of the dyad would execute the movement passively, they were told that they had to complete the task as they were performing the task alone. This allowed to have data related to true human-human interaction, and not to a human passively following the movement of the other subject's limb.

V. RESULTS

The performance in each trial was described by the mean distance between target and cursor throughout a single trial. From this data a decaying exponential fitting learning curve was computed as:

$$f = p_1 + p_2 e^{(-x/\tau)} \tag{6}$$

Where p_1 is the initial offset, p_2 it he magnitude of the shift and τ is the time constant that represents the speed of learning.

Out of 10 groups, 9 showed to be able to learn to deal with the visuomotor rotation and with the cooperative interaction. However, one group did not show any learning. In this case, since a decaying exponential fitting curve can not be computed, the time constant for this group was set to 40 trials (which is the maximum number of trials in the visuomotor rotation phase).

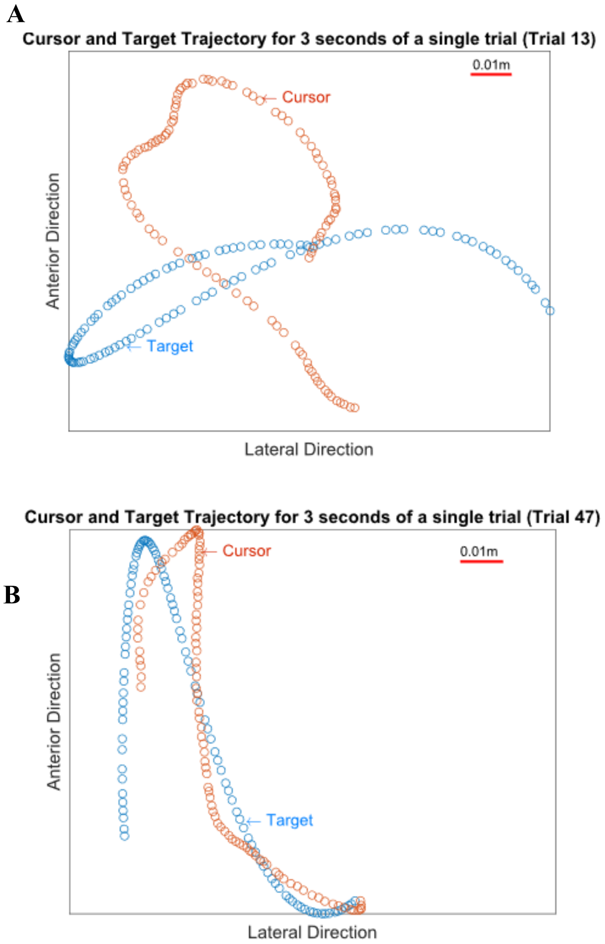

Figure 4 (A) The cursor, controlled by the dyadic interaction, does not follow properly the target path in one of the first trials with the visuomotor rotation. Indeed, the dyad showed a poor performance (error = 7.6 ± 2 cm) with respect to the subsequent trials. (B) In this case the cursor trajectory gets closer to the target path. The mean distance between target and cursor in this trial is equal to 3.4 ± 0.62 cm. Hence, the dyad showed a better performance with respect to the previous trials.

The average time constant for the Novice-Novice group was τ = 5.53 ± 2.79, while the one for the Expert-Novice group was τ = 8.45 ± 3.78. The latter average speed of learning has been computed without considering the outlier.

This happens also in the familiarization phase in which the Novice-Novice group showed an average time constant τ = 2.4 ± 3.17, while the Expert-Novice group had a time constant τ = 6.7 ± 3.33. Instead, in the washout phase the trend is inverted and the Expert-Novice group learns faster with a time constant τ = 2.6 ± 3.58, while the Novice-Novice group's time constant was τ = 4.9 ± 3.09.

The amount of learning in the visuomotor rotation phase for the Novice-Novice group is equal to 4.71 ± 2.99 cm, instead for the Expert-Novice group it is equal to 4.29 ± 1.69 cm.

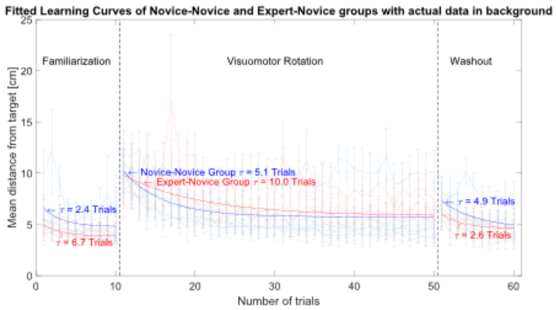

Figure 5 Exponential fitting curves for Novice-Novice (in blue) and Expert-Novice (in red). On the background the real data for each group is plotted. The Novice-Novice exponential curve, decays faster than the Expert-Novice one in every phase except for the washout phase. This means that in the familiarization and in the visuomotor rotation phase, the Novice-Novice group learns faster.

Due to the small sample size and the non-normal distribution of the data, a t-test or a two-way ANOVA test could not be performed. Hence, a Wilcoxon rank sum test was used on the time constants to examine if the difference between the two groups is significant. Five time constants were associated to the Novice-Novice group, while the other five to the Expert-Novice group. The test gave a statistic = 20 and a p-value *p* = 7.5% which indicates that there is not a significant difference between the two groups in terms of speed of learning.

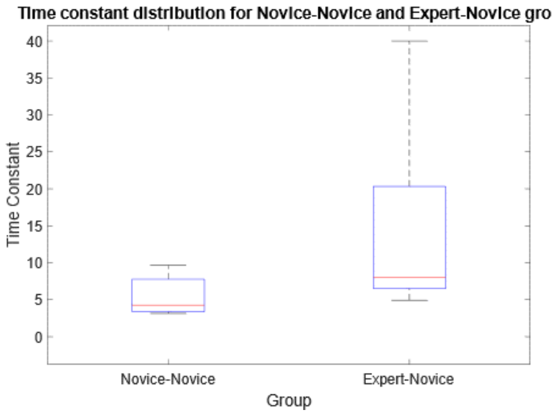

Figure 6 The boxplot shows how the median value (red line) of the time constant for the Novice-Novice group is lower than the one of the Expert-Novice group. Moreover, the Expert-Novice group presents an outlier.

VI. DISCUSSION

So, as shown by the results, a very simple device, as the one we developed, can lead to motor learning by interchanging haptics signals between two subjects. This might be another study that supports the theory for which these haptic signals, trigger internal forward models (as shown in other studies [1][2]) that may benefit motor learning. What is particularly interesting is that, even if the device does not possess complex features (such as a controller, motors or the ability of changing the compliance between the two handles), motor learning still occurs. So just by exploiting human-human interaction we could define a paradigm that triggers the learning process. Also, the same results were obtained by [1] with a much more sophisticated device. This explains how in this type of paradigms the key factor might be the interaction signals between the dyad's components and how the robot features are less significant.

As we hypothesized it is possible to see a difference in the learning speed between the two groups and we can also see how the Novice-Novice group learns faster than the Expert-Novice group. Hence, when the nature of the partners is similar there is an enhancement of the learning process. So, when the implicit expectations of the haptic forces are comparable between the two partners, additional information about the task is retrieved not only with respect to solo tasks [1] [17] but also with respect to the Expert-Novice group.

This is true in the two first phases, but in the washout phase the trend is switched. This means that the Expert-Novice group re-learn how to move without visuomotor rotation faster than the Novice-Novice group. The reason behind this can be found in the role of the Expert, indeed their knowledge about the task could have given the dyad information on how and when to "recover" from the visual distortion.

However, as the statistical test proves, we can not generalize our results. This is probably because the sample size is too small to demonstrate our hypothesis. But these results are promising and more research should be done about it.

In the sample we collected we found one outlier in which one dyad did not show any learning. This might be due to different reasons but the most likely is the lack of attention and of active movements by one of the two subjects during the execution of the task. Indeed, attention is a main component in motor learning [19].

This study can be seen as a first step towards a deeper understanding of how human-human interaction works and can be deployed in actual applications.

VII. LIMITATIONS AND FUTURE WORK

The main limit of this research study is the small sample size that did not allow us to demonstrate the results we presented. So, further studies should be done on this device to understand more consistently if the motor learning benefits that have been found can be generalized.

Even if with the simplicity of our novel device we were able to see motor learning, we still do not know much about how human-human interaction happens. For this reason, it will be important to embed our device with more sensors. Particularly, strain gauges could be added to the center beams to measure the forces applied on them and subsequently to compute the forces applied to the handles. This would bring extra information on how the haptic signals are interchanged and which cooperative strategies are developed between the dyads' components.

Our aim is to continue this study by improving the device first and by using it in experiments that allow to collect more data and more information on how human-human interaction occurs and can be deployed.

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