Bimanual Manipulation of a Complex Object with Internal Dynamics

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***Abstract*— Object manipulation often requires coordination between hands and adaption to the dynamic characteristics of the object. When manipulating the same object, the two hands can have either symmetric or asymmetric impact on the object's trajectory. In this work, we used a bimanual manipulation task of a complex object with internal dynamics to examine how symmetric or scaled-down control of one of the hands affects the coordination between hands. Our result shows that participants are able to quickly adapt to different conditions but the coordination between the two hands changes very little.**

I. INTRODUCTION

The ability of humans to manipulate objects with both hands is often used in everyday tasks. This has been investigated using two types of bimanual object manipulation: 1) The two hands manipulate different objects simultaneously. 2) The two hands cooperatively manipulate the same object. While there are many studies that focused on the independent control of the two hands [1]–[4], relatively fewer have investigated cooperative manipulation [5]–[7].

In many scenarios, the two hands have the same influence in controlling an object, for example in lifting a box and steering a bicycle. However, the control can also be asymmetric for the two hands. Many studies have shown that the two hands are differently specialized. Haaland and Harrington [8] hypothesized that the non-dominant hand plays a greater role in closed-loop control while the dominant hand specializes in open-loop control. Wang and Sainburg [9] hypothesized that, each hemisphere/limb system is specialized for stabilizing different aspects of task performance. Despite the difference, the two hands can readily exchange roles as dominant actor in some bimanual tasks [10].

In this work, we investigated the control of a bimanual manipulation task on a complex object with internal dynamics. Participants controlled a tray with a ball inside and tried to balance the ball within a target area. The two hands controlled the tray via scaling factors, which were either the same or different for the two hands. We hypothesized that when one hand has more control over the tray than the other hand, participants should move more with the more sensitive hand to minimize effort, and vice versa. However, our results showed that the movement ratio between the two hands varied little across the different conditions. Participants tended to coordinate their two hands in a consistent manner even when the scaling factors were very different.

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II. MATERIALS AND METHODS

A. Subjects

Eight neurologically healthy, right-handed participants [11] (23-32 years of age, 4 women) took part in this study. All participants were naive to the purpose of this study and provided written informed consent before participation. The study was approved by the institutional ethics committee at the Technical University of Munich.

B. Experimental apparatus

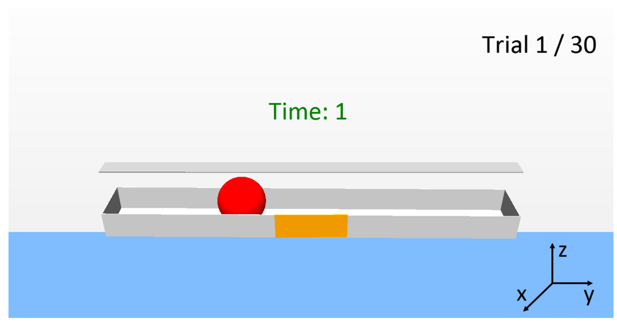

Fig. 1. The virtual environment for the experiment. The goal was to balance the red ball within the orange target. The lower right shows the positive direction of the three axes.

Participants were asked to control a tray in order to move and balance a ball within a target area in virtual reality (VR). The VR environment was rendered by Chai3D [12] and Open Dynamics Engine libraries [13]. Data in the VR environment, for example position of the ball, rotation angle of the tray, and interaction forces, were sampled at 1000 Hz.

The positive directions of the X, Y and Z axes of the virtual environment are shown in Figure 1. The inner dimension of the tray was 400 mm long and 50 mm wide. The radius of the ball was 24 mm. Two haptic devices (Phantom Touch; 3D SYSTEMS) were placed horizontally 360 mm apart in front of the participants. Participants were asked to hold the styluses of the two haptic devices with their two hands. The hand movement was restricted by the program to the vertical direction. The tray was controlled by two control points, which were placed at the two ends of the tray, i.e. 180 mm to the left and right of the center of the tray. The z-coordinates of the control points were controlled by the two hands via the haptic devices and scaling factors. A scaling factor of 100% means the control points moved exactly by the same amount as the hand, while a scaling factor of 30% means that, to make the control point move by 3 cm, the hand had to move by 10 cm. The x coordinates of the control points were fixed to 0 and y coordinates varied in a small range around -180 mm and 180 mm for the left and right control points respectively, due to the physical limits of the tray. The tray could move freely on the z axis and rotate around the x axis, but it could not move on the x, y axes or rotate around y, z axes. The 70 mm-wide target was placed at the midpoint of the tray. A lid was placed over the tray to prevent the ball from falling out, however, the ball always stayed on the bottom of the tray and never touched the lid during our experiments.

C. Experimental paradigm

At the beginning of each trial, the ball was placed with the target area and pushed to the left or right by an external force of 2 N for 0.01 s. The task was to get the ball to roll back to the target area by controlling the tray. The trial ended when the ball stayed inside the target for 1.5 seconds. There was no restriction on the height of the tray for the completion of the task.

We used five conditions with different scaling factors for the hands. The scaling factors were symmetric in three of the conditions, where they are both 100% (SH), 65%(SM) and 30%(SL) for the two hands. In the other two conditions, the scaling factors were asymmetric, namely 100% for the left hand and 30% for the right hand (AL), or 30% for the left hand and 100% for the right hand (AR).

The experiment consisted of a practice session with 20 trials, followed by 10 blocks with 30 trials each (300 trials total). Each block of trials consisted of a single condition. Each participant experienced each condition in two separate blocks (once in the first five blocks and once in the second five blocks), where the order of conditions was pseudo-randomized.

D. Data Analysis

After data collection, the force and kinematic data were low-pass filtered with a tenth-order, zero-phase-lag Butterworth filter with 20 Hz cutoff frequency. The following values were computed: (1) movement length was defined as the length of the path of each hand in one trial; ML_L and ML_R denote the movement length for the left and right hand, respectively. (2) movement ratio (MR) was defined as the ratio of the length of the left hand trajectory to the total length of the left and right hand trajectories in one trial ($MR = ML_L/(ML_L + ML_R)$). (3) velocity correlation coefficient ($Corr_{vel}$) was defined as the correlation coefficient between the inverse left hand velocity and the original right hand velocity. (4) completion time was defined as the time from the beginning of each trial, to the time when the ball stayed in the target area for 1.5s.

III. RESULTS

Participants continued to decrease the completion time over the entire experiment. The mean and standard deviation of the completion time decreased from 5.83±3.66s (mean±std) in the first 10 trials to 3.86±1.29s in the last 10 trials (Fig. 2A). This suggests that participants continued to learn throughout the experiment. When starting a new block, we observed that participants increased the completion time since they needed to adjust the control to a new condition, i.e. to adapt to the scaling factors. This adjustment appeared to be quick and was usually achieved within the first 3 trials of the block. The average completion time was similar across the five conditions (Fig. 2B).

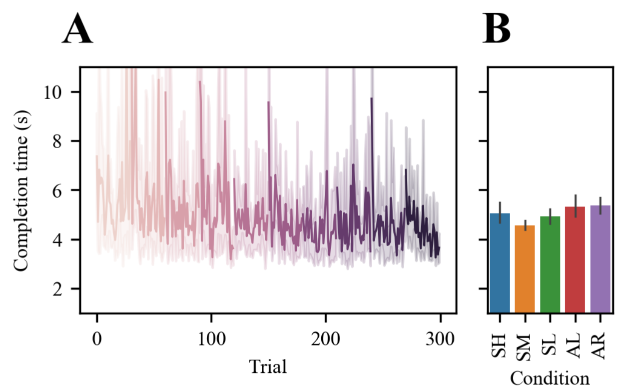

Fig. 2. The mean completion time across all participants. A, The completion time slowly decreased through out the experiment. Darker color shows later blocks. B, Mean completion time across trials and participants. The range of variation in completion time is similar for the five conditions. The shaded region and error bar indicate the 95% confidence interval of the mean.

The correlation between the two hands ($Corr_{vel}$) increased and became more consistent over the course of the experiment, from 0.66±0.35 (mean±std) in the first 10 trials to 0.75±0.14 in the last 10 trials (Fig. 3A). Here, a $Corr_{vel}$ of 1 indicates that the two hands are perfectly coordinated, i.e. the two hands always move opposite to one another with the same or proportional velocity. Figure 3B shows the $Corr_{vel}$ in the different conditions averaged across all participants. There were similar levels of hand correlation across all conditions, both within the symmetric (SH: 0.69±0.27, SM: 0.74±0.24, SH: 0.75±0.29) and asymmetric (AL: 0.71±0.29, AR: 0.72±0.26) conditions. Overall we find stronger hand coordination as the experiment progressed, regardless of the conditions.

There is an increase in movement length when the scaling factor is lower in the symmetric conditions (Fig. 4A). This is expected as participants needed to move their hands further to rotate the tray by the same angle. Similar ranges of movement lengths are also found within the asymmetric conditions. According to our hypothesis, participants would use their more sensitive hand more in asymmetric conditions, to optimize the combined movement length of the two hands and reduce motor cost. In this case, the movement length of the right hand should decrease in the AL condition compared with the length in symmetric condition and based on the same logic the movement length of the left hand should be

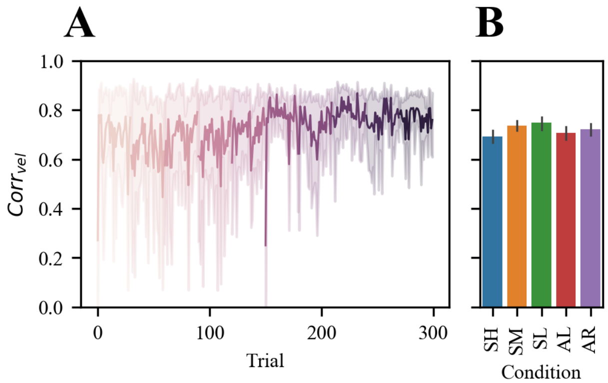

Fig. 3. The correlation between the two hands $Corr_{vel}$ across all participants. A, The $Corr_{vel}$ increased through out the experiment. Darker color shows later blocks. B, Mean $Corr_{vel}$ value for the tested conditions. The shaded region and error bar indicate the 95% confidence interval of the mean.

lower in the AR condition. This can be quantified using the movement ratio, which would show clear differences in the movement ratios for the asymmetric conditions compared with the symmetric conditions. Specifically the movement ratio should be higher in AL and lower in AR conditions. Contrary to these predictions, we found that the movement ratio was similar across all five conditions (Fig. 4B). In order to explain this observation, we initially confirmed that the movement ratio did not change for the symmetric conditions. Individual results confirmed that most participants showed no change in movement ratio across the three symmetric conditions (Fig. 4C), except for participant 6.

We considered three possible strategies to complete this task in the asymmetric conditions: 1) The movement ratio remains the same, regardless of the difference in scaling factors in each condition. 2) The movement ratio changes such that the movement ratio of the control points is the same as in symmetric conditions. 3) The movement ratio changes such that the total movement of the two hands is minimized. We calculated the mean movement ratio (MR) for each participants across the three symmetric conditions (MR_S) and used this to predict the movement ratio in asymmetric conditions. Based on the three strategies, we have three predictions:

$$
\begin{aligned}
&MR_{p1,AL} = MR_{p1,AR} = MR_S \\
&MR_{p2,AL} = \frac{MR_S}{MR_S + (1 - MR_S)/0.3} \\
&MR_{p2,AR} = \frac{MR_S/0.3}{MR_S/0.3 + (1 - MR_S)} \\
&MR_{p3,AL} = 1 \\
&MR_{p3,AR} = 0
\end{aligned}
$$

where p1, p2, p3 denote the three predictions. Regardless of MR_S, we always have $MR_{p3,AL} \geq MR_{p1,AL} \geq MR_{p2,AL}$ and $MR_{p3,AR} \leq MR_{p1,AR} \leq MR_{p2,AR}$. The actual movement ratio in AL and AR conditions always occurred

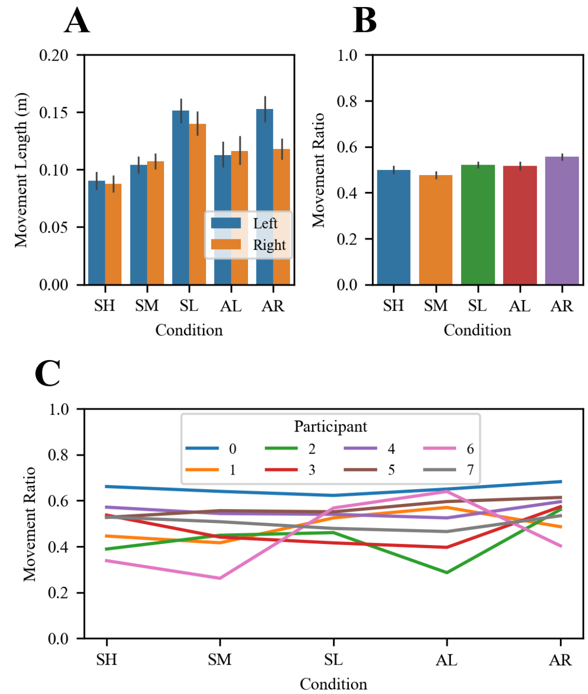

Fig. 4. Comparison of hand movements across conditions. A, Mean movement length of the left and right hand in each condition. B, Mean movement ratio in each condition. C, Mean movement ratio for each participant. Error bars represent the 95% confidence interval of the mean.

within the range of the three predictions (Fig 5). Assuming the actual movement ratio in the asymmetric conditions is a weighted average of either prediction 1 and 2 or prediction 1 and 3, we obtain:

$$
\begin{aligned}
&MR_A = w_1 \cdot MR_{p1} + w_2 \cdot MR_{p2} + w_3 \cdot MR_{p3} \\
&s.t. \quad w_1 + w_2 + w_3 = 1 \\
&\qquad w_2 \cdot w_3 = 0 \\
&\qquad 0 \leq w_1, w_2, w_3 \leq 1
\end{aligned}
$$

where MR_A is the MR in asymmetric condition (either AL or AR), MR_{p1}, MR_{p2}, MR_{p3} are the three predictions for this value and w_1, w_2, w_3 are their respective weights.

As is shown in Fig. 6, w_1 (0.78 ± 0.16) (mean±std) is clearly higher than w_2 (0.18 ± 0.17) and w_3 (0.05 ± 0.11), which shows that strategy 1 had the highest impact on the participants. This is, even if the scaling factor of one hand was decreased by 70% compared with the other hand, most participants still tended to maintain the same movement ratio within the two hands. It is worth noting that participants' strategy in the two asymmetric conditions were slightly different. In AR, all participants combined strategy 1 and 2. This means that the movement of the less sensitive hand increased slightly compared with the symmetric conditions. However, in AL, half of the participants still combined strategy 1 and 2, while the other half combined strategy 1 and 3. The inclusion of strategy 3 indicates that these participants tended to increase the movement of the more sensitive hand,

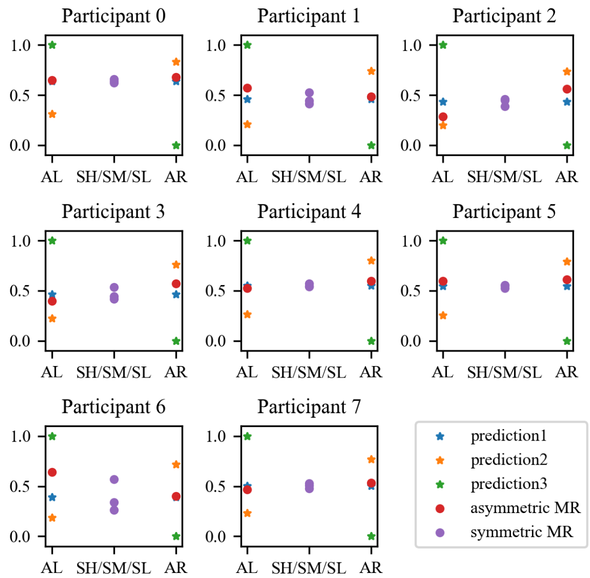

Fig. 5. Movement ratio in each condition and predicted movement ratio for the three strategies in the asymmetric conditions. Circles show the actual movement ratio and stars show the predictions

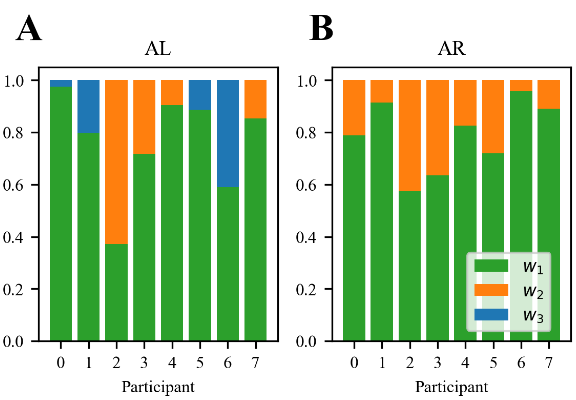

Fig. 6. Weight of the three predictions in AL (A) and AR (B) conditions.

allowing for a reduction of the total movement of the two hands.

IV. DISCUSSION

In this paper, we compared the kinematics of a bimanual complex object manipulation task under symmetric and asymmetric conditions. We found that participants improved their performance across the experiment as evidenced by better coordination between hands and a decrease in completion time. In asymmetric conditions, where the sensitivity of one hand was scaled down by 70% compared with the other hand, the movement ratio between the two hands remained similar to the movement ratio in the symmetric conditions. Despite this, there were slight differences in the strategies in the two asymmetric conditions, and more variability between participants when the left hand was more sensitive than the right hand (AL condition). Previous studies [14] have shown that the non-dominant hand is more variable than the dominant hand. Since all our participants are right-handed, their left hand may be more variable. This might explain why participants had different strategies in the two asymmetric conditions. Our findings could be applied to the field of teleoperated surgical robots, where bimanual operation is often required and scaling is applied to enhance feedback and improve control accuracy.

The task of balancing a ball within the target area on a smooth surface is challenging. Although the sensitivity is reduced on one hand, moving this hand may have still helped the participants have more control of the tray or the ball movement on the tray. The reduced scaling factor might even have been beneficial when participants wanted to do fine movements. This may explain why the movement ratio did not change much across conditions. Further computational approaches will be needed in order to investigate which strategies are actually optimal when considering the overall task.

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