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FULL PAPER

Cooperative Visuomotor Learning Experience with Peer Enhances Adaptability to Others

Kotaro Nishimura[a†], Ozge Ozlem Saracbasi[b†], Yoshikatsu Hayashi[b], and Toshiyuki Kondo[a*]
[a]Department of Computer and Information Sciences, Graduate School of Engineering, Tokyo University of Agriculture and Technology, Koganei, Tokyo, Japan; [b]Biomedical Sciences & Biomedical Engineering, School of Biological Sciences, University of Reading, Whiteknights, Reading, RG6 6AY, UK
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Skilled musicians can improvise with first-time partners. Thus, the question arises how the adaptability to others can emerge through the mutual motor learning experience. We developed a two-person cooperative visuomotor task; an object was connected through virtual springs with the cursors controlled by the subjects. We instructed paired subjects to jointly control the object toward a specified target under a virtual force field. Experimental results suggest that a novice subject who was trained with a skill-level matched peer in the Learning phase showed significantly better adaptability to others in the successive Evaluation phase. Variety of the cooperative experience with others in the visuomotor task probably gave rise to high adaptability in the novice-to-novice group subjects, while the learning experience with an expert did not. We conclude that the motor skills acquired during mutual interactions with peers can lead to have an ability to tune the motor commands subject to the dynamics of the external environment and the behavior of the partners.

Keywords: cooperative visuomotor task; cooperative motor learning; adaptability to others;

1. Introduction

For social animals, moving bodies together in harmony plays an important role in facilitating social interactions. In humans, such coordinated actions are common from mutual interactions to group activities such as playing music and dancing [1–4]. To coordinate one's own motion in harmony with a partner's motion, anticipating the partner's motion at the next moment is crucial to overcome a substantial time delay between the perception and the actuation of the coordinated body motion [5–7].

Since birth, we learn ways to control our body, using motor skills and embodying tools as if there were a part of our body. Motor learning is defined as a set of internal processes within the brain, leading to relatively permanent changes in the capability for new motor skills. Motor learning has been studied mostly through adaptation in motor tasks by introducing perturbation such as visuomotor transformations or virtual force fields in reaching tasks [8–11].

In the human motor learning context, transfer of a motor skill from an expert to a naïve person plays an important role, for example, in teaching how to dance, much of knowledge transfer is done implicitly through visual and haptic interactions rather than verbally. With the focus on the ability of physically coupled subjects to adapt to cooperative visuomotor task, Mireles *et al.* [12] investigated how training in pairs for a cooperative task (arm reaching task with left or right hand) and their skill-level matching (novice-to-novice or novice-to-expert) affect the

†Equal contribution
*Corresponding author. Email: t_kondo@cc.tuat.ac.jp

development of individual motor skills (bimanual reaching task) for unknown environments, and reported that the skill transfer from expert to novice is possible only when the novices have a chance to perform the task first on their own. It suggests that solving the dual instability problem, i.e., discriminating the unknown environmental dynamics [13] and the dynamics of partner is important. Moreover, they suggests that cooperative motor learning with a novice rather than an expert is promising for improving the individual motor performance. Ganesh *et al.* [14] demonstrated that an implicit haptic intervention from the other subject who engaged in the same task simultaneously has a positive effect on the further individual motor performance regardless of the partner's skill level.

According to the background, the adaptation ability (hereafter *adaptability*) to others can be considered as a key skill for improvising with others. In most motor learning literature, however, the adaptability to others has not been investigated, because the validation of the motor skill was evaluated with the learning partner or individual [12, 14], thus it is an open question what kind of motor experience facilitates the adaptability. To study the problem, we executed a motor learning experiment [15], where a participant executed a cooperative visuomotor task with a human partner with different skill levels (novice or expert), and found that the motor experience with a noivce partner (a peer of the participants) is superior to the experience with an human expert (an experimenter who well understood the task) even in the cooperation with a first-time partner. Our previous result suggested that variety of motor execution in cooperation with novices is a significant factor for facilitating the adaptability to others, however, there still remains the problems: the validity of the human expert, i.e., whether the experimenter (human expert) has been a true expert of the task, and whether the expert had always been able to interact with the participant in the same way, because human operation would have variability in motor coordination. Due to this, we hypothesized that variety of motor execution in cooperative motor learning promotes the adaptability to others. The aim of the present study is to develop an artificial agent model which represents the guidance of a human expert and to clarify the validity of the hypothesis.

In this study, we developed a cooperative visuomotor task only using visual feedback based on the referenced paper by Mireles et al. [12], and investigate the adaptability of novice subjects to unfamiliar partner after they experienced cooperative motor learning with a different skill level partner.

2. Materials and Methods

2.1 *Subjects*

Thirty-two human subjects (25 male and 7 female, average age 21.97$\pm$4.03 years) participated in the experiment and provided written informed consent. Two male and one female were left-handed and the rest were right-handed according to the Edinburgh Handedness Inventory [16]. All subjects used their dominant hand in this study. This experiment was approved by the ethical committee of the Tokyo University of Agriculture and Technology (No.28-33).

2.2 *Experimental paradigm*

We developed a cooperative visuomotor task shown in Figure 1A, in which each of the paired subjects was asked to operate the left cursor (yellow filled circle) or right cursor (red circle) individually in order to bring a joint cursor (blue circle, hereafter dubbed as virtual object) to a target (white circle). The virtual object was connected to both cursors with virtual elastic springs. This figure indicates the initial configuration of the task. As shown in the figure, each cursor was controlled by each subject via analogue joystick (TUFB-A01-1, Technotools Co., Japan). The roll and pitch angles of the joystick were linearly corresponded with the Cartesian coordinates of the cursor position on the display, allowing the cursor to travel within a circular region, and to return to the central start position when the joystick was released. Note that these joysticks have no mechanism for force feedback, thus there is no task-related haptic feedback while the subjects are interacting with each other through the virtual springs. The platform of the cooperative task was developed using MATLAB software (The MathWorks Inc., MA, USA).

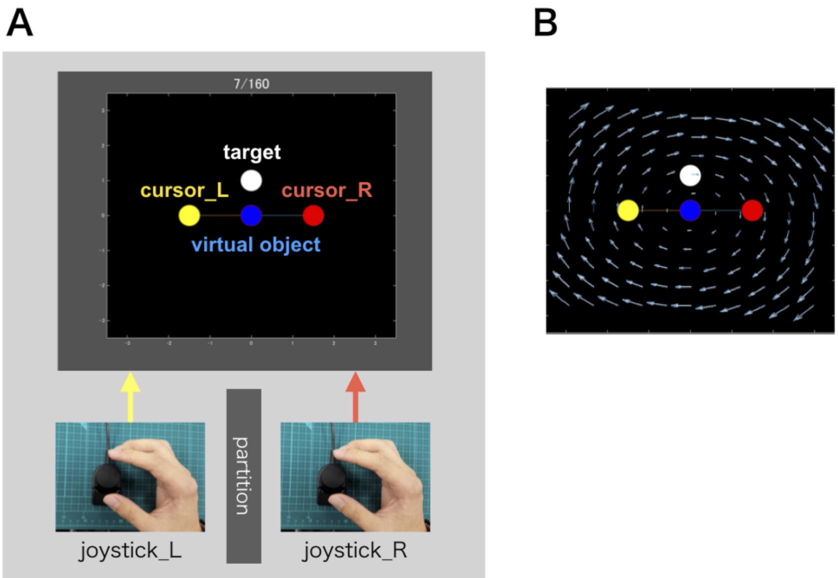

Figure 1. (A) Appearance of a cooperative visuomotor task. Virtual object (blue filled circle) was connected to both left and right cursors (yellow and red filled circles) with virtual elastic springs. The subjects were instructed to jointly move the virtual object toward randomly emerging target (white filled circle) by operating their analogue joystick. (B) Virtual force field assumed in the learning task condition. The virtual object receives an unfamiliar external force from the environment. The virtual force can be visually perceived as the motion of the virtual object.

In the experiment, the target was randomly appeared at one of eight candidate locations which were equally spaced at 45 degrees on a circumference around the start position, and also the initial task configuration was rotated accordingly. The subjects were instructed to move the virtual object to the target as fast as possible when the target appeared.

Additionally, to make it a motor learning task, we assumed a position-dependent force field in the environment (Figure 1B), and that the unfamiliar external force affects the motion of the virtual object. The equation of the force field is as follows:

$$\vec{F}_e = \begin{bmatrix} 0 & K_e \\ -K_e & 0 \end{bmatrix} \vec{P}, \tag{1}$$

where $\vec{P} = [x, y]^T$ corresponds to the position vector of the virtual object in the Cartesian coordinates, $\vec{F}_e = [f_x, f_y]^T$ is the external force vector applied to the virtual object, and K_e is a stiffness constant. It was designed to generate a clockwise rotated elastic force field. As there was no task-related haptic feedback, the subjects had to perceive and compensate for the disturbing force based on the visual feedback through the relative motions between the virtual object and two cursors on the display.

The dynamics of the virtual object can be described using the following equations of motion:

$$M \frac{d^2}{dt^2} \vec{P} + B \frac{d}{dt} \vec{P} = \vec{F}_{\mathrm{L}} + \vec{F}_{\mathrm{R}} + \lambda \vec{F}_e, \tag{2}$$

where M and B are the inertia and viscosity constants. $\vec{F}_L$ and $\vec{F}_R$ correspond to the acting forces from the cursors calculated as,

$$\vec{F}_{\mathrm{L}} = -K_s\left(\vec{P} - \vec{P}_{\mathrm{L}}\right), \tag{3}$$

$$\vec{F}_{\mathrm{R}} = -K_s\left(\vec{P} - \vec{P}_{\mathrm{R}}\right), \tag{4}$$

where $\vec{P}_{\mathrm{L}}$ and $\vec{P}_{\mathrm{R}}$ are the position vectors of the left and right cursors, and K_s is the stiffness parameter of the virtual springs. These task parameters were experimentally determined ($M = 1$, $B = 100$, $K_s = 1000$, and $K_e = 2500$) such that the task cannot be completed through the operation of a single-side cursor alone. Moreover, λ is a session mode selector ($\lambda = 0$ in the Familiarization session, while $\lambda = 1$ in the Training session, explained later).

2.3 *Experimental groups and protocols*

To investigate the effect of the skill level of the learning partner on the subsequent performance of cooperative motor task, we designed an experimental protocol, and set up two groups as shown in Table 1.

Groups	**Baseline phase** (6-FS, 1-TS)	**Learning phase** (3-FS, 20-TS)	**Evaluation phase** (3-FS, 6-TS)
NN (n=16)	S_A - S_B S_C - S_D ⋮	S_A - S_D S_C - S_B ⋮	S_A - S_B S_C - S_D ⋮
NE (n=16)	S_I - S_J S_K - S_L ⋮	S_I - A, A - S_J S_K - A, A - S_L ⋮	S_I - S_J S_K - S_L ⋮

Table 1. **Experimental phases and groups.** In both Baseline and Evaluation phase, all the subjects were asked to execute a cooperative visuomotor task with their pre-assigned human partner, while in the Learning phase they had to perform the task with another novice subject in the same group (NN group) or with a programmed expert agent denoted as A (NE group). In this manner of having training sessions with another partner, we could investigate “the adaptability to others” and motor learning process of adapting to a new person with respect to the baseline performance measured in the Baseline phase. For example, subject A (S_A) executed the task with subject B (S_B) in the Baseline and Evaluation phases, but he/she performed the task with another subject, subject D (S_D) in the Learning phase.

All subjects were novice and randomly assigned to one of two experimental groups: NN (Novice and Novice) or NE (Novice and Expert). Throughout the experiment, half of the subjects in each group played the role of the right cursor operator, while the rest were the left cursor operator.

The experiment consisted of three phases: Baseline, Learning, and Evaluation phases, and each phase included two types of sessions: Familiarization session (hereinafter referred to as FS) in which the subjects were familiarized with the experimental protocol without the effect of unknown external force field, and Training session (TS), where the subjects were trained in the environment with the force field. In the Baseline phase, each pair executed 6 sets of FS, and 1 set of TS. The performance measured in the TS of this phase can be considered as the baseline performance of the pair. In the following Learning phase, 3 sets of FS and 20 sets of TS were assigned. During the TS in the Learning phase, subjects in the NN group had to learn the cooperative visuomotor task with another novice in the same group, while the subjects in the NE group executed the task with a programmed expert agent. To investigate the adaptability of the subjects, they performed 3 sets of FS and 6 sets of TS in the Evaluation phase.

Note that the paired partners were swapped within the same experimental group during the Learning phase, to evaluate individual adaptability in the Evaluation phase appropriately. For example, subject A executed the cooperative task with subject D, instead of subject B in the Learning phase (see Table 1).

2.4 *Expert agent*

In the Learning phase, the subjects in the NE group trained the cooperative visuomotor task with a programmed expert agent. The agent was designed to behave optimally like a human expert in [15], who well understood the dynamics of virtual force field. The following algorithm was implemented.

The algorithm consists of two parts, update of the desired position for the agent's cursor and proportional control to update the current position. First, the desired position along the x-axis for the agent cursor, $\hat{A}_x$ is given by $(\hat{A}_x + P_x)/2 = T_x - \alpha F_x$ where P_x is a x component of the partner's cursor, T_x is a x component of the target position in the reaching task, and αF_x is a x component of the displacement caused by the force field at the current position of the virtual object, i.e., α is a parameter for dimensional adjustment, which was set to 1.0 in the experiment. The identical algorithm was applied for the y component of the agent cursor. Thus, the desired position for the agent cursor was determined to jointly move the virtual object to the target, compensating the current force field.

Second, the proportional control was applied to minimize the relative distance between the desired and current positions of the agent cursor, $A_x = A_x + \beta(\hat{A}_x - A_x)$, with the gain parameter $\beta = 0.125$. Note that when updating the desired position of the agent cursor, the time delay of 400 ms was introduced to simulate the visuomotor delay of humans, which was experimentally determined based on the results of our previous study [15]. Therefore, the update of the current position was based on the kinematic data of the partner's motion at 400 ms in the past. Moreover, a small Gaussian noise was added to the desired position of the expert agent, thus, avoiding the possibility of the agent cursor's movement being perceived as mechanical.

2.5 *Performance index*

As the criterion for evaluating the performance of cooperative motor task, we defined the combined index (CI), which is the product of the total time required to achieve the task (time-to-target index) and the total traveling distance of the virtual object (distance index). Analysis of the result from a pilot study indicated that the CI immediately decreases across the trials, revealing that it forms a log-normal distribution. Thus we decided to use the logarithm of CI (i.e., $\log CI$) in the statistical analysis.

3. Results

Figure 2 demonstrates the transitions of combined index ($\log CI$) averaged within each group, measured in TS of the Baseline, Learning, and Evaluation phases. Note that each pair in both Baseline and Evaluation phases is identical, but the pairs during the Learning phase were swapped within the same group (see Table 1).

As shown in the Baseline phase of the figure, both groups showed almost same performance in average, however we can see that the pairs in the NN group indicated better averaged performance compared with the NE group in the Evaluation phase. On the other hand, we can confirm that the pairs in the NE group demonstrated superior performance in the Learning phase.

In order to investigate the effect of skill-level matching during cooperative visuomotor learning in the Learning phase, we statistically evaluated the performance of the cooperative visuomotor task at two distinct ROI (region of interest) time-points: i.e., TS in the Baseline phase and

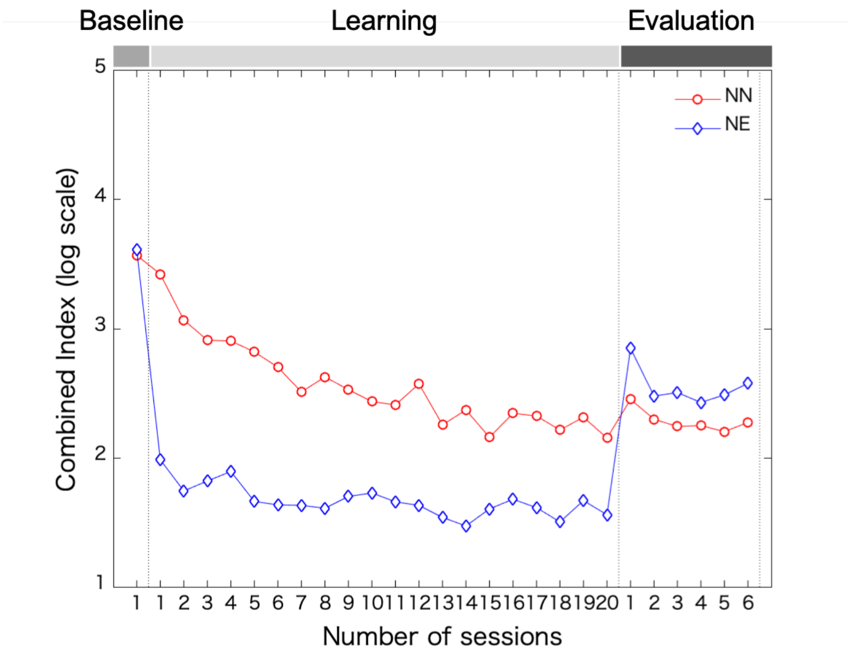

Figure 2. Transitions of combined index ($\log CI$) measured in the Training Session of the Baseline, Learning, and Evaluation phases. Each marker represents the median within the group.

the first TS in the Evaluation phase. A 2×2 repeated-measures ANOVA (groups $\times$ phases) was applied to the $\log CI$, and significant interaction effect ($F(1, 14) = 8.89$, $p < 0.01$) was confirmed. Thus, we firstly tested simple main effect on phases in each group using paired t-test, and confirmed significant differences in both groups ($p < 0.01$ for both). In addition, we performed further analysis on the difference of experimental groups regarding each phase using Weltch's t-test.

As shown in Figure 3, no significant difference between the groups was confirmed in the Baseline phase ($p = 0.355$). This indicates that the task performance of the individual pairs in both NN and NE groups was more or less at the same level in the first encounter. In the first TS of the Evaluation phase, on the other hand, each subject was paired with the partner in the Baseline phase, who can be considered as a different partner of cooperative visuomotor learning, we found a significant difference between the NN and NE groups ($p < 0.01$). This result indicates that the subjects in the NN group showed superior performance with a novel partner in the cooperative task rather than the those in the NE group.

Moreover, to be clear the effect of training group on the Evaluation phase, we executed additional 2×6 repeated-measures ANOVA (groups $\times$ trials) with respect to the performance indexes in the phase. It revealed no interaction effect ($F(5, 70) = 1.067$, $p = 0.386$), but main effects for groups ($F(1, 14) = 7.384$, $p = 0.0167$) and trials ($F(5, 70) = 5.873$, $p = 0.000138$). This implies that the experience in the Learning phase has different effect among the groups, i.e., cooperative motor learning experience with novice peer is superior to the experience with the expert agent, in the future adaptability. Thus, we could verify our hypothesis that training with the novice subject helped to demonstrate adaptability to others, whereas pairing with the expert agent did not have the skill transfer effect.

4. Discussion

In the case of physical human–human interaction, the sensory feedback exchanged among one another can become a channel for the mutual sharing of intentions, and plays a primary role in the construction of a shared motor plan in order to achieve a task together. A recent study showed

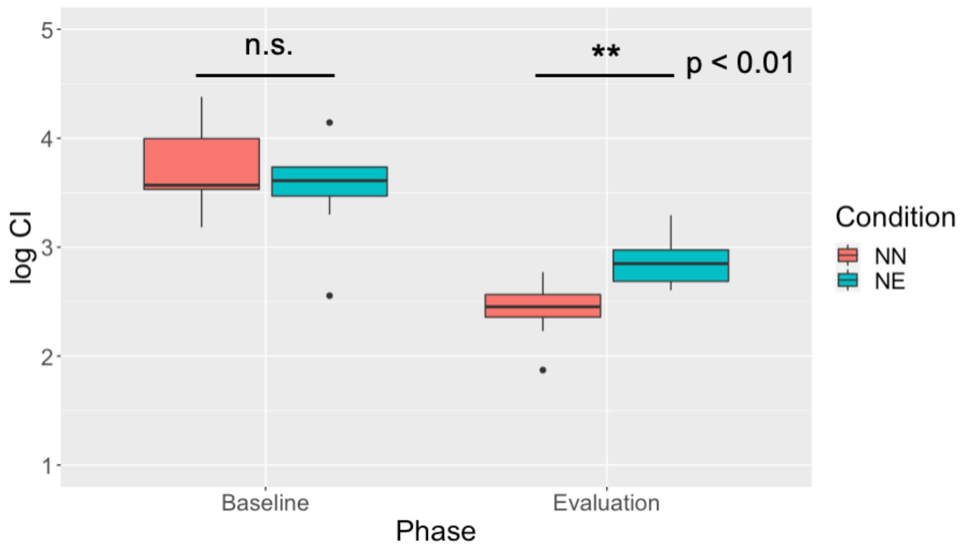

Figure 3. Statistical comparison of $\log CI$ between the Training Session of the Baseline phase and the first Training Session of the Evaluation phase.

that the skill transfer from the expert to novice subject through visual and haptic interactions is possible [12]. However, the focus has been only on the improved performance of the individual, i.e., the nature of the mutual interactions between the expert and novice, e.g., adaptability to others, has not been explored.

When cooperating with others, predicting the motion of the partner at the next step is critical as feedback control adjusting motion is subject to the time delay [17]. Here, for such prediction, an internal model of the partner is necessary to simulate the motion of the partner in response to which one can perform an action.

Through iterative active-perception of how the other partner moves in response to one's own motion, we consider that one can develop the plastic internal model, which can be used to predict the next motion of the partner. If one can build up the plastic internal model that can simulate the dynamics of others, one can adapt to a new partner and cooperate with him/her quickly to achieve a cooperative task. On the other hand, interacting with the expert would prevent the development of the plastic internal model of the partner as the interaction with the expert tends to be one directional, given the lack of real-time action-perception loops, though the subjects could learn the integrated dynamics of the expert agent and environment.

Now, let us take a close look at the internal model developed in the Learning phase. As shown in Figure 2, the novice participants in the NE group showed a better motor performance than those in the NN group in the Learning phase. Thus, the programmed expert agent could play a certain role in guiding the participants through the unknown environmental dynamics.

From the motor performance of the novice participants in the Learning phase, we can assume that they could acquire the integrated internal model to cope with the dual instability, i.e., the partner dynamics and environmental dynamics. However, if the partner is the expert agent, the integrated internal model cannot produce appropriate motor commands to immediately cooperate with another new partner, thus, 'adaptability' to a new partner should be realized by immediate tuning of the motor commands would play a critical role for immediate cooperation, and it is needless to say that the real-time adaptation should be based on the real-time feedback loops and sensory input.

On contrary, as shown in Figure 3, we found that the novice participants who were trained with another novice in the Learning phase could gain this adaptability for the immediate tuning. This is because the participants in the NN group can experience a wide range of motor coordination together while exploring the unknown external force field, leading to higher adaptability to a new partner in the Evaluation phase.

Note here that in this study, motor learning paradigm is limited to the visual feedback for investigating the sensory feedback effect independently, in order to clarify if somatosensory feedback is absolutely necessary for learning the cooperative task in the similar paradigm. As a result, we could show that participants can learn the cooperative task only through the visual feedback loops.

This study has some potential limitations. The results reported here might be linked to the specificity of the cooperative motor task used in this study. And the adaptability we considered here is limited to the other partners, not to other tasks. Most significant limitation is that we adopted a human partner in the Learning phase of the NN group as opposed to the expert agent in the NE group. Although we consider that the adaptability to others is endowed by the variety of interaction, we cannot discard the possibility that it depends on human intervention. In addition, there is another possibility regarding the skill level of the partner, i.e., mutual learning on the peer-to-peer basis, rather than just facing a variety of motor coordination patterns. This point will be persuaded in the future study by developing the novice agent.

Our results are informative for training in team sports. We suggest that having the novice-to-novice sessions in the team sports would promote the adaptability to other players and reform their actions [18]. This finding would be useful for motor learning not only through human–human interaction [19], but also human–robot interaction such as robot-assisted human motor learning [11, 20] and physical therapy [21].

5. Conclusion

In this study, we investigated the hypothesis that the cooperative motor experience with novices is superior to the experience with an expert agent algorithm in terms of promoting adaptability to others. The experimental result suggests that poor adaptability of the participants who were trained with an expert agent is not due to a particular human experimenter and less variability, but a fixed strategy designed to behave optimally.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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