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Parallel Adaptation: Switching between Two Virtual Bodies with Different Perspectives Enables Dual Motor Adaptation

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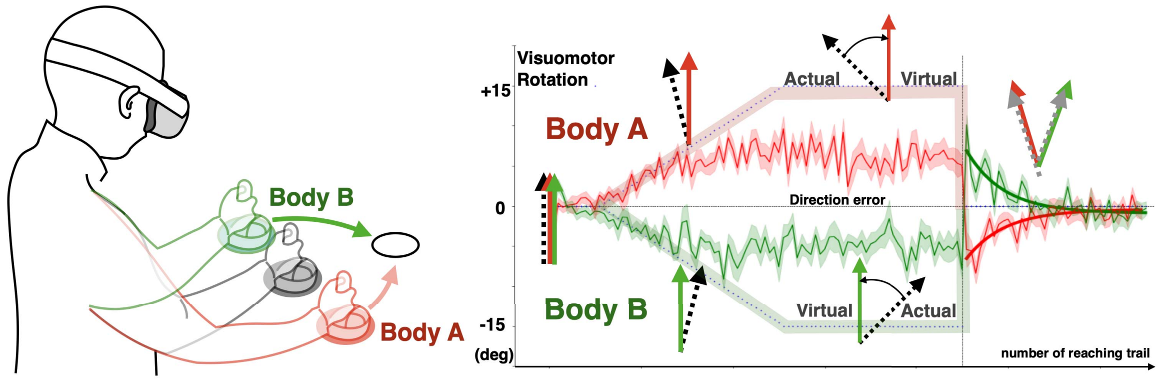

Figure 1: Dual motor adaptation over two bodies as a way to explore parallel embodiment over multiple bodies. We found that switching between two virtual bodies with different perspectives allows human to adapt implicitly opposite visuomotor rotation.

Abstract

Virtual Reality (VR) lets us experiment embodiment. Here we investigate dual embodiment under the prism of dual motor adaptation. We asked participants (N=21) to perform reaching motions in VR with opposite gradual visuomotor perturbations. The participants sequentially switched between 2 VR bodies and had to adapt to the VR body's perturbation (up to +15° for the VR body_A, and -15° for the VR body_B). We then designed a 2x2 within-subject study: 1 factor being the perspective (1^{st} person or 3^{rd} person), and 1 factor being the head rotation (without head rotation before the reaching motion or with head rotation before the reaching motion). We found that by providing strong visual cues between bodies (alternating symmetric perspective and/or symmetric head rotation), participants had little awareness of the perturbations, good adaptation, and large aftereffects in both VR bodies. Those elements are consistent with implicit dual adaptation. In contrast, a naive 1^{st} person perspective resulted in little to no adaptation with a high cognitive load and no aftereffects.

Keywords: multiple embodiment, motor adaptation, virtual bodies

Index Terms: Human-centered computing—HCI theory, concepts and models; Human-centered computing—User studies

1 Introduction

In Virtual Reality (VR), embodying a VR body delivers contextual cues associated to the VR body. For example, I am in a taller or stronger body. If our VR body's contextual cues are very different from our real body's, we need to change how we do our movements. For example, if my body is taller, I need to lower myself to reach a target, or if my body looks stronger, I need to adapt my grip to grab a target. But if our contextual cues change too much, we will likely do a "wrong" movement. To correct it we will need to adapt or switch our internal model [16] (the internal model of an object [e.g., a limb] is a neural network modeling the object's movement by relying on the object's sensory-motor state [22, 47]).

In VR, it is possible to embody 2 VR bodies at the same time, that is, *dual-embodiment* or *parallel-embodiment*. Similar to "single embodiment", in dual embodiment we can theoretically change our VR body model and VR body representation all while adapting our motor control to the VR bodies. Indeed dual embodiment should let us intuitively use the motor control associated with the body we control without impacting our cognitive load. For example, being in a small VR body, looking up to see an object placed slightly above us, then switching to a tall VR body, and intuitively looking down to see the same object. Now from a motor control context, embodying 2 VR bodies should let us (α) maintain 2 internal models for the same movement, one for each VR body, and (β) switch to the internal model associated with the VR body we currently control (or currently delivering the sensory cues) [46]. Yet whether we can maintain multiple internal models for the same movement remains controversial [13]. Meaning that (α) and (β) remain theoretical and questionable.

In this work, we investigate dual embodiment under the prism of motor adaptation. We do a reaching task with 2 VR bodies and add an opposite, gradual visuomotor rotation (VMR) on the VR body's reaching motion (here, one clockwise (CW) and the other counterclockwise (CCW)). With this approach, we can analyze our motor control within the framework of well-known visuomotor adaptation standardized procedures [1, 3, 28, 41].

What we want to know is if adapting to an opposite perturbation when controlling and frequently switching between 2 VR bodies is driven by explicit processes (meaning relying on a cognitive strat-

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egy) or driven by implicit processes (meaning relying on sensory-prediction errors) [16]. If implicit processes drive it, then the adaptation is intuitively associated with the body we control and brings us closer to a proof of dual embodiment.

At last, studying dual embodiment might seem a bit far stretched. But dual embodiment is also another way to study "single embodiment". Indeed, the processes used to switch between 2 VR bodies, or to change from our real body to 1 VR body, might be very similar.

1.1 About motor adaptation

Many VR research already uses motor adaptation, such as redirected walking [36] and redirected haptic [33]. They typically introduce a visuomotor shift that decouples the real body position from the VR body position. The user then adapts their motions implicitly to the visuomotor shift. We are relying on the same principle.

In visuomotor adaptation studies, the participant typically reaches a target point without seeing their hand [27]. They instead look at a cursor that follows their hand position. Then during the study, we add an offset (the perturbation) between the participant's hand position and the cursor. There are many different perturbations and ways to introduce them. Here we use a VMR perturbation.

About visuomotor rotation A VMR is a visuomotor perturbation where we add a rotation offset angle (here of max. $\sim 15°$) between an effector (here, the real right hand) and its visual feedback (here, the VR right hand) [27]. The VMR is about the start position of the motion.

About explicit and implicit motor adaptation We assume that we have explicit adaptation if we have the knowledge and awareness about the intention/strategy to adapt our motor behavior to a perturbation and implicit adaptation if we do not. Because there is not yet a conclusive, definitive metric to say whether an adaptation is explicit or implicit [32], we rely on several key metrics, such as the direction error changing side/sign after removing the perturbation (i.e., the aftereffects), the direction error decay speed after removing the perturbation (c.f., Sec 4.2).

1.2 Hypothesis and findings

First, we want to validate whether under "single embodiment" the adaptation is driven by implicit process. It is well validated outside of VR [35] but we still need to verify it with a VR body.

H1 Implicit motor adaptation is possible under VR embodiment;

Second, we want the 2 VR bodies to have different context cues, so the user can easily associate an internal model with a VR body. We decided to rely on a change of visual workspace [48]: (1) with a change of perspective and/or (2) with a change of head rotation (i.e., the user has to look on their left/right to see the target, c.f., Fig. 5). We believe those visual cues are different enough to facilitate the association between a specific internal model and a VR body and therefore facilitate implicit dual adaptation.

H2 Switching between head rotation facilitates dual implicit adaptation;

H3 Switching perspective facilitates dual implicit adaptation;

Also, implicit adaptation is less cognitively demanding than explicit adaptation (as explicit adaptation relies on cognitive strategies [32]). Therefore we believe that adapting while changing the visual workspace (admittedly leading to implicit dual adaptation) is less cognitively demanding than not changing the visual workspace.

H4 Both switching between head rotations and perspectives alleviates the cognitive load in dual adaptation;

Throughout our study, we found that without a change of visual workspace, the participants are aware of the perturbation and do not manage to adapt to the perturbation with success. But when there is a change of visual workspace (with a change of perspective and/or a change of head rotation), the participants can adapt to the perturbation, and we observe aftereffects. This is consistent with an implicit adaptation. Our results imply that when the 2 VR bodies have different perspectives and/or head rotations, we develop 2 internal models when adapting their movements.

2 Related Works

2.1 Parallel Embodiment

Beyond our original single body, VR brings out capabilities of embodying multiple bodies [6, 10]. There have already been numerous physiological and psychological experiments investigating supernumerary body parts, e.g., 3rd arm [6, 10] and 6th finger [14]. They systematically showed that participants experience some degree of embodiment toward the supernumerary body parts. It indicates that it is possible to update our body's model to add additional body parts. Recent research then investigated multiplied embodiment, such as developing a view sharing system for up to 4 persons [19], synchronizing 4 virtual avatars [34], and controlling 2 robot arms in parallel for ping-pong [40]. In the context of cognitive neuroscience, research showed that we could distribute ourselves at 2 places at a time [45] and self-locate at 2 places at a time [7]. Guterstam et al. reported that multisensory perceptual integration might induce the experience of dual body ownership and dual self-location [9].

2.2 Parallel Motor Adaptation

We are surprisingly skillful in multiple tools simultaneously. We are capable of using them in variable environment [21], and capable of using them as an extension of our body [31]. This indicates that it is possible to adapt and learn multiple motor control models in parallel [15, 21, 46] Adapting and learning bodily motion models in parallel has been investigated with various paradigms, including prism exposure [43], robotic manipulandum [11] or cursor and display system. In general, simultaneous learning of 2 or more conflicting motor movements has been reported to be difficult. When subjects are required to adapt to opposite visuomotor rotations [26] or velocity-dependent force [5] in quick succession, the interference prevents the dual learning from consolidating.

Dual adaptation becomes even more difficult when the motion trajectories and targets are identical. Especially when the user does not have any cues on when to adapt to the perturbation [18]. Indeed series of research suggests that the central nervous system has a strong tendency to employ a single internal model when dealing with a sequence of perturbations [18]. Furthermore, when participants try dual adaptation in close temporal proximity, participants cannot simultaneously learn opposing force fields or opposing visuomotor rotations even when provided with contextual information, suggesting that multiple visuomotor rotations compete for common working memory resources [44]

In contrast, Osu et al. reported that participants could adapt to 2 opposing force fields with contextual cues if random and frequent switching occurs [37]. In addition, dual adaptation has been reported as possible by varying hand and body postures as contextual cues, even when the cursor movements are identical. This research shows that participants can update their movement to the target in static opposing visuomotor rotations with different hand and body postures [2, 4] Hirashima et al. also demonstrated that multiple motor memories could be learned and flexibly retrieved, even for physically identical movements, according to distinct motor plans in a visual space [13]. These reports of the ability to select an appropriate internal model for a given environment and learning the multiple models simultaneously [46] might also apply to multiple bodies.

However, another significant factor in dual adaptation would be whether it is explicit or implicit. Schween et al. reported that visual workspace separation as a contextual cue enables the compensation of opposing cursor rotations by combining explicit and implicit processes [38]. Nevertheless, despite strategizing an explicit adaptation from contextual cues, the cognitive load of dual adaptation remains high [12]. If dual adaptation requires a high cognitive load, it would be very challenging to embody multiple virtual bodies concurrently. In other words, we wonder if it would be possible to provide a context or a cue to adapt to multiple bodies in parallel without requiring a high cognitive load.

2.3 Motor Adaptation in Virtual Reality

With the incorporation of motor control and motor learning principles, the potential of VR for motor rehabilitation has been heavily researched [29]. For instance, Ballester et al. reported that visual feedback modulation in VR enables the acceleration of motor adaptation in rehabilitation scenarios [3]. VR is capable of adaptive and real-time manipulation of the visual feedback, such as for a gradual visual perturbation [20], which requires a particular setup in reality. In VR we can also investigate precise control of bodily behavior and manipulate the context and feedback while preserving a sense of embodiment in the Virtual Environment (VE) [23]. For instance, in VR, participants can feel that they have augmented and manipulated body images such as longer arms [24], a 6th finger [14], or being of smaller size [42]. The ability to acquire novel embodiment in a VE is an important research question in designing a new bodily experience in VR [23,28]. Futhermore visuomotor adaptation in VR provide the wide range of opportunities to investigate how various factors will impact the sensorimotor learning [25].

From those aspects, motor learning in VEs has been gaining attention [1,3,28]. Researchers found similar and dissimilar factors across virtual and conventional motor learning paradigms [1,3,8]. For instance, Just et al. compared upper limb movement profiles of reaching motor tasks in virtual and real environments [17]. Anglin et al. reported motor adaptation in tern of implicit and a more cognitive/explicit strategy [1] Here, We aim to investigate how multiple embodiments can be achieved under the prism of motor adaptation. We will use VR bodies as a research tool to investigate whether humans can learn and master multiple bodies in parallel.

3 STUDY METHOD

3.1 Experiment Apparatus

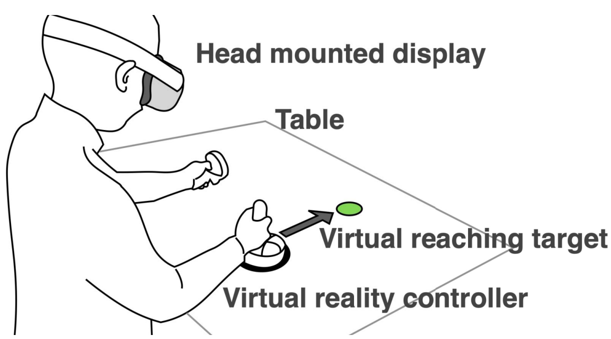

Figure 2: The experiment setup. The participant wears the HMD, holds the right VR controller up-side-down and slides it on the table.

The system consists of a Head Mounted Display (HMD) with 2 VR controllers, and is implemented in an Unity 2020[1] VR application. The right hand motion data is recorded from the right controller with a ∼75Hz sampling rate.

3.1.1 Hardware

We use a *Meta Quest 2* HMD and its 2 controllers[2]. We connect the HMD with the Meta Quest Link to a VR-able laptop.

[1]https://unity.com/
[2]https://store.facebook.com/jp/en/quest/products/quest-2/

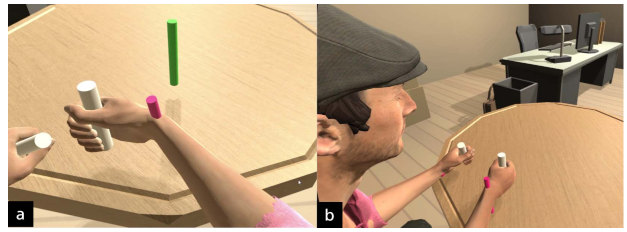

Figure 3: The task from the participant's point of view. From left to right: (a) in 1pp conditions; (b) in 3pp conditions. The pink cylinder represents the cursor, and is attached to the participant's right wrist. The green cylinder is the target area. The white cylinders represent the controllers; they are not part of the task and are solely here for visuo-haptic congruency.

Meta does not publicly document the Meta Quest 2 controllers' accuracy and precision. Yet: (1) a German institute [30] measured the Meta Quest 2 controller offset after a displacement of 500mm on the $X-Y$ axis and reported a sub-milliliter offset (in mm, $\overline{X} = 0.184$, $\sigma_X = 0.160$, $\overline{Y} = 0.096$, $\sigma_Y = 0.093$); and (2) Shum et al. [39] determined that the "Oculus Touch controllers [3] [are] within an agreeable range for measuring human kinematics in rehabilitative upper-limb exercise", even though their reported accuracy is worst than the more recent Meta Quest 2 controllers. Therefore, the Meta Quest 2 controllers seem to meet the requirements of our motor task.

Because we asked the participants to hold the right controller up-side-down and slide it on the table (c.f., Fig. 2), we added thin foam strips along its ring to let it slide with little resistance.

3.1.2 Virtual Environment

We prepared 2 visually different avatars and 2 visually and spatially different Virtual Environments (VEs). The avatars stay in their respective VE in front of a VR wooden table congruent with a physical wooden table (c.f., Fig. 3). The 2 VEs are "aligned" between each other, meaning that the 2 bodies, the 2 tables, and the 2 start points and end points of the VMR task all share the same local position within their VE (e.g., if the participant touches the start point in one VE, they will also touch it in the other VE).

We represent the *start*, *end*, and *cursor* points as 20mm ⌀ cylinders. Therefore, when the system detects a collision between the start/cursor points or the end/cursor points, there is a ∼10mm offset between the collision point and the cylinders' base area centers points. We will refer to *point* when we mean the cylinder's base area's center point and to *area* when we mean the cylinder's base area.

During the task, the participant sits in front of the table at about 20cm from the start point and 40cm from the end point. The cursor point follows the right controller and is positioned on the participant's right wrist instead of on the participant's right palm to limit the differences in position if the participant changes their hand posture.

3.2 Experiment Design

3.2.1 The Visual-Motor Rotation Task

We designed the VMR following standardized procedures in motor adaptation studies [1,3,28,41]. Since we aim to investigate a quick switch between 2 bodies, we rely on a task without any verbal/aiming report to limit the interruption between 2 switches. During the task, the participant holds a right controller upside-down and makes back and forth movements between a start point and end point by sliding the right controller on a table. We asked the participant not to rest

[3]The Oculus Touch controllers (2016) are an older generation of controllers from the same company than the Meta Quest 2 controllers (2020)

their right arm on the table to avoid too much sensory feedback when moving.

At the start of every trial, the end cylinder is hidden. The participant starts the trial by entering the start area with the cursor area. Then they wait for 1s without leaving the start area. After 1s, the start cylinder disappears, the end cylinder appears, and an audio cue plays to let the participant know they can reach the end point. The participant reaches the end point and stops the trial by entering the end area with the cursor area. Then the end cylinder disappears, the start cylinder appears, and an audio cue plays to let the participant know they reached the end point (a message "too slow" appears briefly if the trial took more than 700ms). Then the participant goes back to the start point.

3.2.2 The blocks design

As often in adaptation studies, the experiment is organized into block [4]. We present them in order as follows. **Familiarization block - Trial 1 to 10**: The VMR stays at 0° (= no perturbation). **Gradual perturbation block - Trial 11 to 50**: The VMR gradually increases (±0.375° by trial). The rotation is at its maximum (±15°) at the 50th trial. **Full perturbation block - Trial 51 to 90**: The VMR stays at ±15°. **Washout block - Trial 91 to 130**: The VMR goes back to 0° (= no perturbation).

Note that the total number of trials is 260 (130×2) since the participant performs the VMR task with the 2 bodies (except in the pre-study since there is only 1 body). In every trial, there is a ∼50% chance to switch to the other body (except in the pre-study since there is only 1 body). The switch sequence order is randomly pre-generated and is the same for all the participants (c.f., Fig. 6-c). Also, the participant spends as many trials in the $body_A$ than the $body_B$.

3.2.3 Procedure

We divided the experiment into 2 studies, a pre-study with only 1 VR body and a main study with 2 VR bodies. The participant performs the pre-study and then the main study. In the pre-study, the participant is embodied in only 1 VR body. In the main study, the participant is embodied in 2 VR bodies.

Whether it is for the pre-study or the main study, for every condition: the participant first does a few VMR task trials (without perturbation) for 2 minutes; then, they answer an embodiment questionnaire (c.f., Tab. 1) and a NASA-TLX questionnaire and take a short break; then the participant performs the entire VMR task (with perturbation); then they answer the same questionnaires (c.f., Fig. 4). We call the first VMR and questionnaires the baseline step and the second VMR and questionnaires the adaptation step.

We inform the participant that they will hear a 'bell' sound during the full perturbation block at the 75th trial (as depicted in Fig. 6 - b) and are requested to answer the embodiment questionnaire based on how they felt at that moment. In addition, only for the pre-study, we ask the participant about their awareness of the VMR perturbation at (1) the 'Bell' in the full perturbation block and (2) in the washout block.

Table 1: BO stands for Body Ownership; AG stands for Agency; and PE stands for perception. We ask those questions one time for the $body_A$, then one time for the $body_B$.

ID	Question	scale
BO1	I felt as if the virtual body was my own	Likert (0-6)
BO2	It felt as if the virtual body I saw belong to someone else	Likert (0-6)
AG1	It felt I could control the virtual body as if it was my own body	Likert (0-6)
AG2	The movements of the virtual body were caused by my movements	Likert (0-6)
PE1	It was difficult to see my right hand and/or the target	Likert (0-6)

[4] A block is a set of trials usually associated to a specific perturbation state.

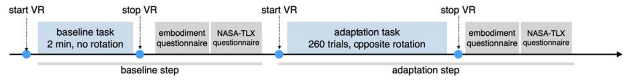

Figure 4: Experiment procedure of a condition.

3.3 Study Conditions

In the pre-study there is only condition: 1pp-fix (c.f., the next paragraph); meaning both views are in first person perspective (1pp), without the need to rotate the head to see the end point. In the main study the participant we use a 2x2 factor design, with the following IVs and levels:

- **perspective**. *1pp* (1st person perspective) and *3pp* (3rd person perspective). In 3pp the VR views are symmetric to each others, along the body center point.
- **head rotation**. **fix** and **move**. In fix, there is no need to rotate the head to see the end point; and in move, a head rotation is needed to see the end point, since at the start of trial the end point is not in view.

In the main study, the participant therefore performs 4 conditions: 1pp-fix; 1pp-move; 3pp-fix; and 3pp-move (c.f., Fig 5). Compared to 1pp conditions, the VR view position in 3pp conditions is 0.35m to the left for $body_A$, 0.35m to the right for $body_B$, then 0.15m above for both bodies and 0.1m behind for both bodies. In 3pp-fix and 1pp-move, the VR views are rotated ±40° on the yawn axis.

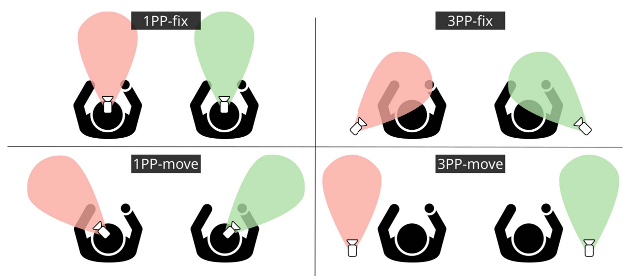

Figure 5: The 4 conditions. Each cell display one condition. The shaded persons represent the bodies (the $body_A$ is associated with the red color, and the $body_B$ is associated with the green color). The camera represents the view's position/rotation (note that even if in the figure the bodies are close to each other, in the experiment the bodies are in different rooms and cannot see each other). **1pp-fix**, the views are at their natural position/rotation. **1pp-move**, the views are at their natural position but have a 40° angle from their normal rotation (therefore, if the participant wants to look at the end point, they need to rotate their head). **3pp-fix**, the views are in 3pp and have a 40° rotation so the participant can see the end point. **3pp-move**, the views are in 3pp but are at their natural rotation (therefore, if the participant wants to look at the end point, they need to rotate their head).

4 Study

4.1 Participants

21 participants (14 men, age: M = 26.5, Standard Deviation (SD) = 4.18) were recruited from Keio University (Japan) and from the University of Tsukuba (Japan). The experiment mostly took place at Sony CSL (May 2022). Except for 1 participant, all were students. 1 (∼5%) had no previous experience with VR, 8 (∼38%) had some experience with VR and 12 (∼57%) had extensive experience with VR. All participants were right-handed. The participants provided written informed consent to participate in the experiment. The protocol is approved by Sony Group Corporation ethics committee (Sony

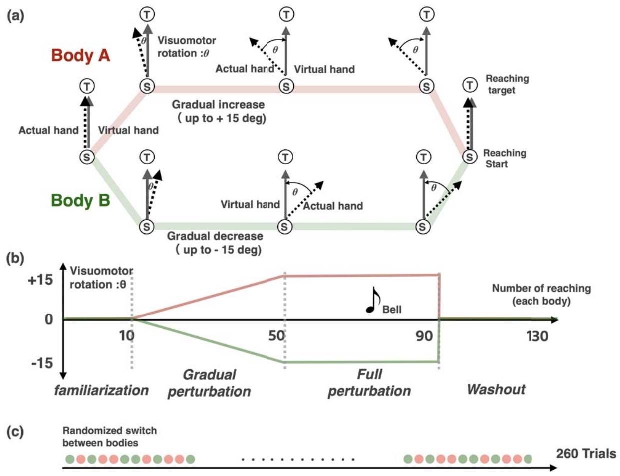

Figure 6: Experiment paradigm with gradual visuomotor rotation with opposite direction.

Group Corporation, Application 21-F-0040), and is conformed to the Declaration of Helsinki.

4.2 Analysis

4.2.1 Direction error and the difference error

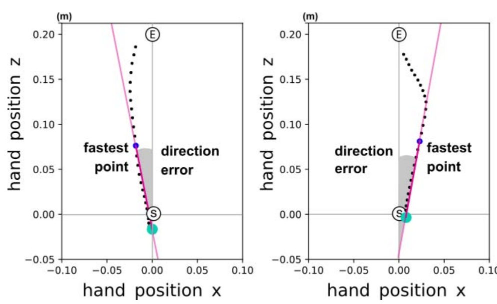

Figure 7: 2 opposite visuomotor rotations. The gray angular area represents the direction error. The direction error is defined as the angle difference between the cursor direction (the magenta colored line) and the target direction (from the S circle to the E circle, respectively representing the start point and end point). The cyan colored point is the cursor point at the start of the trial. The blue colored point is the peak velocity of the cursor motion.

The direction error. To quantify the adaptation between conditions, we rely on the *direction error*. The direction error is the angle difference between the cursor direction (the start position of the cursor motion minus the point of peak velocity of the cursor motion) and the target direction (the start point minus the end point) as depicted in Fig. 7. We use the direction error since it reflects the feed-forward motion elicited from the internal model of the right arm [37]. We labeled trials with an absolute direction error $> 45°$ as outliers and excluded them (proportion of trials discarded: 0.23%).

To visualize the general trend of the motor adaptation, the direction error is averaged by conditions and bodies and trials across participants (c.f., Fig 10).

The direction error offset. In the statistical analysis, we add an offset to the direction error by conditions and bodies for each participant. The offset is defined as the average direction error in the last half of the familiarization block (trials 5 to 10). We need to add an offset because our experiment factors (view perspective and view rotation) seem to shift the direction baseline. The shift seems to occur because of a combination of 2 artifacts in our experiment design. Indeed because the user feels out of position (in 3pp condition and/or in move condition): (1) their motion can be more natural to do on one side than on the other; (2) the user does not notice as well the sensory error and task error and integrates them in their motion.

The difference error. To statistically quantify the adaptation between bodies, we rely on the *difference error*. The difference error is the absolute difference in absolute direction errors between the $body_0$ and the $body_1$. The difference error is averaged by conditions across participants.

4.2.2 De-adaptation speed

To compare the speed of de-adaptation between conditions in the washout block (Fig. 6-b), we fitted an exponential decay function (see below) to the average direction error by conditions and bodies across participants. We calculate it in the washout block (trials 91 from 130), with $y(k)$ the direction error in the $k-th$ trial; and A, B, and λ are the estimated parameters: $y(k) = A * e^{-\lambda k} + B$

4.2.3 Questionnaire

Since we have a relatively small sample size of participants, we run a Shapiro-Wilk on the data. If the data follow normality, we run an ANOVA test. If $p < 0.05$ we follow it by post hoc pairwise t-tests with Benjamini-Hochberg correction. If the data do not follow normality, we run a Friedman test. If $p < 0.05$ we follow it by post hoc Wilcoxon signed-rank tests with a Bonferroni correction.

4.3 Pre-study

The pre-study aims to validate **H1: Implicit motor adaptation is possible under VR embodiment** when a participant is embodied in a single VR body.

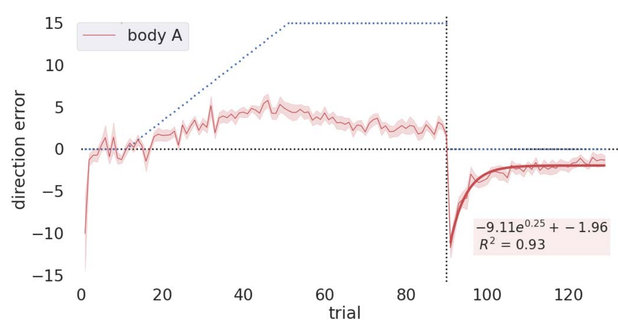

Figure 8: The direction error averaged by trials across participants. The thin red line is the averaged direction error. The red shading is the standard error of the averaged direction error. The blue dotted line is the perturbation angle. The vertical black dotted line shows the moment when the washout block begins. The thick line is the exponential decay equation fitted against the average direction errors. We also display the equation parameters and the R^2.

Motion analysis. We show in Fig. 8 the averaged direction error over trials. In the gradual perturbation block, the direction error increases more slowly than the perturbation. In the full perturbation block, the direction error slowly decreases and reaches a plateau around its last 20 trials at $\sim 2.5°$. In the washout block, the direction error slowly decreases toward baseline. Those patterns are consistent with the general trend of implicit adaptation. First, the direction error has a slow gradual adaptation. Second, the direction error slowly decays after the aftereffect. The trials following the aftereffect fit very well ($R^2 = 0.93$) the exponential decay function.

Body ownership and agency The body ownership ($M = 9.86; SD = 1.49$) and the agency ($M = 8.52; SD = 2.31$) are highly rated in the adaptation step. This is in line with usual VR embodiment ratings. There is no statistically significant difference in body ownership (ANOVA: $F(1,19) = 0.68; p = 0.42$) and agency (ANOVA: $F(1,20) = 0.07; p = 0.80$) between the baseline step and the perturbation step. Therefore the perturbation has no significant impact of the feeling of body ownership and agency.

Self reported perturbation The perturbation felt before the aftereffect is weakly rated ($M = 2.8; SD = 2.17$). It is barely above the perturbation felt after the aftereffect ($M = 1.70; SD = 2.0$). The perturbation after the aftereffect is excepted to be reported at 0 but has an average of 1.70. Seven (33%) participants reported the perturbation. Yet, when analyzing their motion adaptation, they did not seem to adapt with an explicit strategy (the adaptation rate was similar to the other participants). We believe they only had a declarative knowledge of the perturbation [32].

Workload The NASA-TLX score is rated very low ($M = 6.55; SD = 3.68$) in the adaptation step. It therefore required minimal workload from the participants. There is no statistically significant difference in the NASA-TLX score (ANOVA: $F(1,19) = 1.5; p = 0.23$) between the baseline task and the adaptation step. Therefore the perturbation has no significant impact on the workload.

Taken together, the pre-study shows that motor adaptation is implicit when embodied in a single VR body; thus validating H1. Even if some participants were aware of the perturbation, they did not seem to adapt with an explicit strategy. The body ownership and agency remain high despite the perturbation. Also, the task requires little workload despite the perturbation.

4.4 Main Study

The main study aims to validate **H2 and H3: Switching between head rotation and perspective facilitates dual implicit adaptation** when a participant is embodied in 2 VR bodies with different motion profiles, also to validate our **H4: Both switching between head rotations and perspectives alleviates the cognitive load in dual adaptation**.

4.4.1 Motion Behaviour

Direction error between conditions We compare the direction error for the bodies$_A$ and the bodies$_B$ between conditions. We do it for the last 10 trials of the full perturbation block (C_{FP} [5], trials 80 to 90); and for the first 10 of the washout block (C_W, trials 91 to 101) (c.f., Fig. 9).

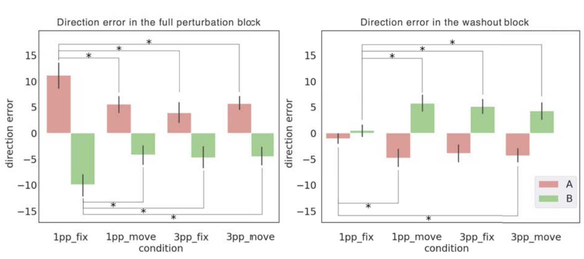

Figure 9: From left to right: (1) the direction error for C_{FP} (full perturbation); and (2) the direction error for C_W (washout). The error bars are the confidence intervals.

For the cycle C_{FP}, there is statistically significant differences in direction error between the bodies$_A$ (ANOVA: $F(3,51) = 9.52, p < 0.001$) and between the bodies$_B$ (ANOVA: $F(3,51) = 10.1, p < 0.001$). Then the posthoc pairwise t-tests with Benjamini-Hochberg correction show significant differences in direction error between the bodies$_A$ and between the bodies$_B$, c.f., Tab. 2. In absolute values, the direction error for 1pp-fix is significantly higher than the one for 1pp-move, 3pp-fix and 3pp-move.

For the cycle C_W, we also have statistically significant differences in direction error between the bodies$_A$ (ANOVA: $F(3,51) = 3.57, p < 0.020$) and between the bodies$_B$ ($F(3,51) = 13.5, p < 0.001$). Then the posthoc pairwise t-tests with Benjamini-Hochberg correction also show significant differences in direction error between the bodies$_A$ and between the bodies$_B$, c.f., Tab. 2. In absolute values, the direction error for 1pp-fix is significantly lower than the ones for 1pp-move, 3pp-fix and 3pp-move.

Overall, 1pp-fix shows for both body$_A$ and body$_B$ significantly more direction error when adapting to a perturbation (see the full perturbation block in Fig. 10); and significantly less direction error when de-adaptating (see the washout block in Fig. 10). It hints that 1pp-fix adaptation relies on an explicit strategy, and that this strategy is likely different that the one in the other conditions.

Difference error between conditions Similarly, we compare the difference error between conditions for the cycle C_{FP} and the cycle C_W. For the cycle C_{FP}, there is no significant difference between the conditions (ANOVA: $F(3,51) = 0.45, p = 0.720$). For the cycle C_W, there is a statistically significant difference in difference error between conditions (ANOVA: $F(3,51) = 3.69, p < 0.018$). Then the posthoc pairwise t-tests with Benjamini-Hochberg correction show significant differences in difference error between: 1pp-fix ($M = 1.51, SD = 1.24$) and 1pp-move ($M = 4.04, SD = 3.05$): $t(17) = -3.87$, $p = 0.007$; as well as between 1pp-fix and 3pp-fix ($M = 3.75, SD = 2.43$): $t(17) = -2.88$, $p = 0.031$. Overall, 1pp-fix shows significant less difference error when de-adaptating (see the washout block in Fig. 10). It hints that 1pp-fix lead to a very similar de-adaptation between bodies, unlike 1pp-move and 3pp-fix.

De-adaptation speed We observe in the direction error plots (c.f., Fig. 10) that the de-adaptation speed is much faster for 1pp-fix than the other conditions. Also, 1pp-fix does not fit well with the exponential decay function (body$_A$: $R^2 = 0.21$; body$_B$: $R^2 = 0.30$). In contrast, we observe gradual de-adaptation process along with the exponential decay function in 1pp-move ($R^2 = 0.54$ in body$_B$) , 3pp-fix ($R^2 > 0.55$ in both bodies) and 3pp-move ($R^2 > 0.68$ in both bodies) conditions. Note that the trend of 1pp-move partially fits with the exponential decay model (body$_A$: $R^2 = 0.32$). The de-adaptation speed is noticeably faster for 3pp-fix (body$_A$: $= 0.22$; body$_B$: $= 0.20$) than for 1pp-move (body$_A$: $= 0.06$; body$_B$: $= 0.16$) and 3pp-move (body$_A$: $= 0.12$; body$_B$: $= 0.12$).

Together with the analysis of motion behavior, the general trend of 3pp-fix and 3pp-move is consistent with implicit adaptation; thus validating H3. However, 1pp-move is only partially consistent with implicit adaptation; therefore H2 remains controversial.

Overall 3pp fits much better the exponential decay function than 1pp. Moreover, it seems that the fix rotation allows for a faster adaptation than the move rotation. Yet there is a 2 unique elements for 1pp-move. First the offset value B is noticeably larger ($B = 5.83$ between bodies) than for the other conditions, probably because of its

Table 2: The direction error posthoc pairwise t-tests (we only report the significant differences)

cycle	body	condition$_x$	M	SD	condition$_y$	M	SD	t(17)	p-value
C_{FP}	A	1pp-fix	11.1	5.76	1pp-move	5.54	3.80	4.42	0.002
C_{FP}	A	1pp-fix	11.1	5.76	3pp-fix	3.89	4.45	3.27	0.003
C_{FP}	A	1pp-fix	11.1	5.76	3pp-move	5.65	2.87	3.42	0.003
C_{FP}	B	1pp-fix	-9.94	5.03	1pp-move	-4.15	4.26	-4.58	0.015
C_{FP}	B	1pp-fix	-9.94	5.03	3pp-fix	-4.70	4.70	-2.78	0.037
C_{FP}	B	1pp-fix	-9.94	5.03	3pp-move	-4.47	3.73	3.81	0.015
C_W	A	1pp-fix	-1.05	2.22	1pp-move	-4.73	4.22	4.01	0.024
C_W	A	1pp-fix	-1.05	2.22	3pp-move	-4.28	3.17	2.87	0.024
C_W	B	1pp-fix	0.52	2.52	1pp-move	5.70	3.56	-6.91	<0.001
C_W	B	1pp-fix	0.52	2.52	3pp-fix	3.20	3.20	-4.59	<0.001
C_W	B	1pp-fix	0.52	2.52	3pp-move	3.62	3.62	-4.16	0.001

[5] C stands for cycle

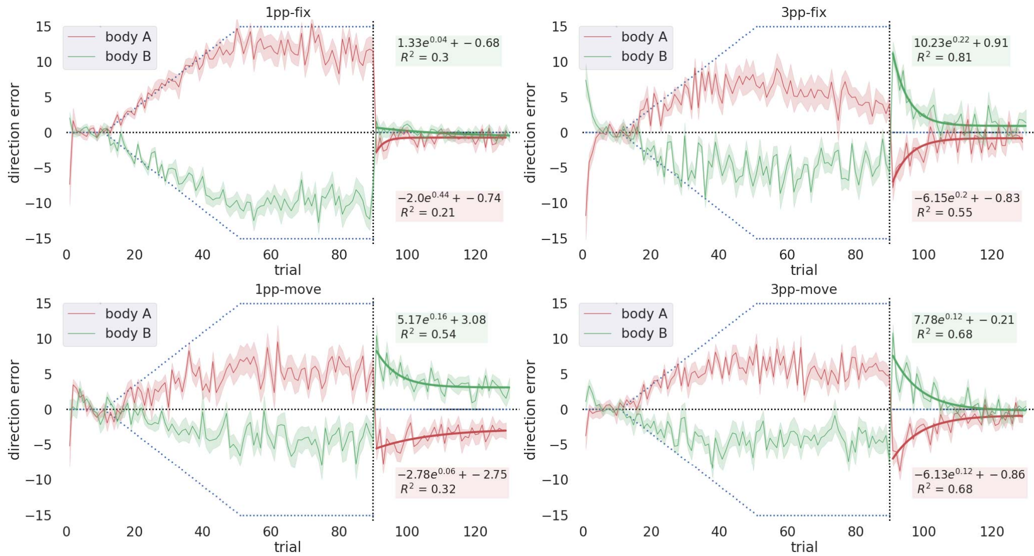

Figure 10: The direction error, with offset, averaged by conditions and bodies across participants. The conditions are from left to right and top to bottom: (1) 1pp-fix body; (2) 3pp-fix body; (3) 1pp-move; and (4) 3pp-move body.

much slower decaying speed. Second, there is a large de-adaptation speed difference between the bodies ($\text{body}_\text{A}: = 0.06$; $\text{body}_\text{B}: = 0.16$). It hints that 1pp-move adaptation strategy is different between body_A and body_B (despite not having a difference error significantly different than 3pp-fix and 3pp-move).

4.4.2 Body Ownership and Agency

In the adaptation step, there is statistically significant differences in the body ownership between the bodies_A (Friedman: $X^2 = 11.1, p = 0.011$) and the bodies_B (Friedman: $X^2 = 10.2, p = 0.016$), but not in agency between the bodies_A (Friedman: $X^2 = 7.07, p = 0.070$) and the bodies_B (Friedman: $X^2 = 2.09, p = 0.554$). Then the posthoc Wilcoxon signed-rank tests with Bonferroni correction show significant differences in body ownership between: 1pp-fix / 3pp-move (for bodies A and B), and 1pp-move / 3pp-move (for bodies A and B) (c.f., Fig. 11).

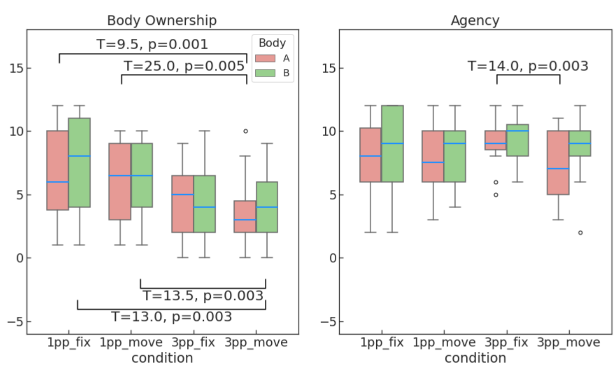

Figure 11: From left to right: (1) the body ownership rating for the bodies_A and the bodies_B between conditions in the adaptation step; (2) the same, for the agency rating.

The condition 3pp-move is significantly worst on body ownership than 1pp-fix and 1pp-move for both bodies. Moreover: (1) the average score of body ownership is relatively high for 1pp-fix and 1pp-move, and relatively low for 3pp-fix and 3pp-move; and (2) the average score of agency is high for all conditions. We verified for each condition if there are statistically significant difference between the baseline step and the adaptation step by bodies in body ownership and agency. There is one for: 1pp-fix in body ownership (paired t-test:$T(19) = 3.00, p = 0.007$) and agency (paired t-test:$T(19) = 3.44, p = 0.003$); 1pp-move in body ownership (paired t-test:$T(19) = -2.96, p = 0.008$); and 3pp-fix in body ownership (paired t-test:$T(19) = -2.74, p = 0.01$). Therefore the perturbation in 1pp-fix leads to a significantly worst feeling of body ownership and agency; while the perturbation in 1pp-move and 3pp-fix leads to a significantly better feeling of body ownership.

4.4.3 NASA-TLX

In the adaptation step, there is statistically significant differences in the NASA-TLX score between conditions (Friedman: $X^2 = 8.83, p = 0.031$) (c.f., Fig. 12). Then the posthoc Wilcoxon signed-rank tests with Bonferroni correction show significant differences between: 3pp-fix ($M = 8.18; SD = 4.22$) / 3pp-move ($M = 10.7; SD = 4.25$): $T = 10.0, p = 0.002$.

There is also a statistically significant difference between the baseline step and the adaptation step in NASA-TLX (Friedman: $X^2 = 15.1, p = 0.002$) (c.f., Fig. 12). Then the posthoc Wilcoxon signed-rank tests with Bonferroni correction show significant differences between: 1pp-fix ($M = 5.15; SD = 4.55$) / 1pp-move ($M = 0.72; SD = 3.09$): ($T = 13.0, p = 0.003$); 1pp-fix / 3pp-fix ($M = -1.26; SD = 2.13$): $T = 3.0, p = 0.003$); and 1pp-fix / 3pp-move ($M = 1.62; SD = 3.49$): $T = 11.0, p = 0.001$).

We observe that the pre study seems to cause less workload than the dual body conditions. Then, for the dual conditions, 3pp-fix requires significantly less workload than 3pp-move, and the perturbation has a significantly worst effect on 1pp-fix than on the other conditions; this validates our H4.

5 Discussion

5.1 Dual adaptation with implicit or explicit adaptation

Our result showed a pattern of dual implicit adaptation over 2 VR bodies with opposite VMR perturbations in 3pp-fix, 3pp-move, and partially in the 1pp-move condition. We discuss in detail the implicit

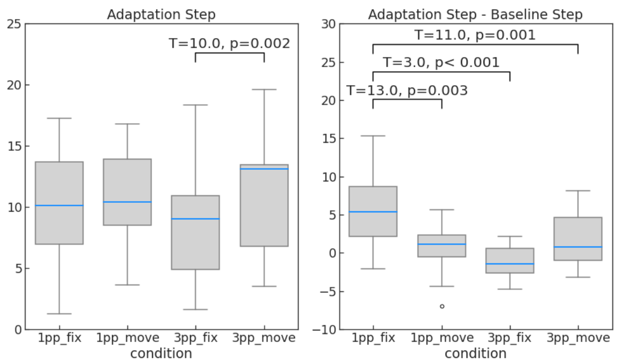

Figure 12: From left to right: (1) the NASA-TLX score in the adaptation step; (2) the NASA-TLX score after the difference between the adaptation step and the baseline step.

or explicit nature of the different factors. To discuss it, we compare the exponential decay functions fitting of the average direction error in the washout block to highlight the differences in implicit adaptations (c.f., Fig 9). Let us note that the exponential decay function does not fit 1pp-fix. Therefore we do not compare the results of this method with 1pp-fix.

We can observe that 3pp-fix de-adapts faster than the move conditions. Therefore it seems that not rotating the head between switches leads to a faster implicit adaptation. The change of head rotation may cause a lower sensory error sensitivity, which does not allow the user to notice the errors driving implicit adaptation and lead to the difference in de-adaptation speed. Indeed 3pp-move has a workload significantly bigger ($M = 10.7; SD = 4.25$) than 3pp-fix ($M = 8.18; SD = 4.22$).

We also note that 1pp-move, to a degree, also exhibits smaller correlation in fitting into the exponential decay model on body$_A$ ($R^2 = 0.32$), while on body$_B$ it shows a higher value ($R^2 = 0.54$). This suggests that 1pp-move exhibits both implicit and explicit adaptation (such as implicitly adapting to body$_B$ while explicitly adapting to body$_A$). Therefore, there could be a combination of implicit and explicit adaption with dual adaption. For instance, difficulty in quickly rotating the head leads to a higher workload, which causes, in turn, a lower sensory error sensitivity.

5.2 Potential trade-off between benefit of dual adaptation and error sensitivity

We found interesting contradictory results between our pre-study and our main study. We know that for a single body adaptation, 1pp-fix leads to implicit adaptation. Yet, for a dual body adaptation 1pp-fix leads to explicit adaptation. In dual bodies 1pp-fix, the user has a better opportunity to compare the direction error between the 2 bodies since the absolute difference between the perturbation for body$_A$ and body$_B$ is 30°. This allows the participants from the main study in 1pp-fix to have a higher opportunity to detect and understand the sensory prediction error and to see the task error, making them more likely to use their movements. In 3pp, the participants' view shifts to the left or the right. Even if the view direction is preserved in 3pp-fix, participants might require to process the mental rotation to compare the rotation error of body$_A$ with body$_B$. Moreover, the perception in 3pp-move would be significantly harder than in any other conditions since it increases the difficulty of perceiving the errors, which reduces the error sensitivity. In contrast, 1pp-move, like 1pp-fix, has a higher opportunity to detect and understand the sensory prediction error and see the task error. However, the change of rotation likely makes it harder in 1pp-move, and might be the reason why 1pp-move exhibits the characteristics of both explicit (for body$_A$) and implicit adaptation (for body$_B$).

5.3 Implication for designing multiple virtual bodies

When looking at the effect of explicit adaptation on body ownership and agency, we see that the 1pp-fix perturbation leads to a significantly worst feeling of body ownership and agency, despite its natural view. Conversely, for the implicit adaptation, the perturbation in 1pp-move and 3pp-fix lead to a significantly better feeling of body ownership. This does not apply to the 3pp-move condition, likely because of the significantly higher workload and difficulty perceiving their own motion.

Therefore it seems that explicitly adapting to a dual perturbation leads to a decrease in body ownership and agency over both bodies. Thus the ability to detect discrepancies in sensory error prediction, despite understanding and strategizing against it, leads to a decrease in body ownership and agency. Conversely, implicitly adapting and reducing task error lead to a significantly better feeling of body ownership. Thus we believe that for dual adaptation, it is important to limit the ability of the participant to detect either the sensory error prediction or the task error. This could be done by limiting the view perception from the ongoing task. For example, here, we shifted the view perspective in 3pp conditions. But this has to be done within the limit of the task, or else the advantage of implicit adaptation will be eclipsed by the difficulty of completing the task, as seen in 3pp-move. Taken together, our result suggests both advantages and disadvantages in combining the head rotation and the perspective factor.

6 Conclusion

We demonstrated that it is possible that participants implicitly adapt to 2 VR bodies to 2 opposite VMRs in parallel. By providing different visual workspaces for the bodies, participants were less aware of the opposite VMRs yet adapted better and yielded larger after-effect. Those results are consistent with implicit dual adaptation. Moving forward, we expect our findings to shed light on designing multiple embodiments with different body internal models. Ideally, we would like to show that in explicit adaptation, only 1 internal model is updated, while in implicit adaptation 2 internal models (1 for each body) are updated; and then use one's ability to update 2 internal models as proof and key measure of dual embodiment.

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