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Real Time Remapping of a Third Arm in Virtual Reality

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Abstract

We present an initial study investigating the usability of a system for users to use their own limbs (here the left arm, right arm, left leg, right leg and head) to remap and control a virtual third arm. The remapping was done by: pre-selecting the limb by gazing over it, then selecting it by voice activation (here we asked the participants to say "switch"). The system was evaluated in Virtual Reality (VR), where we recorded the performance of participants (N=12, within-group design) in 2 box collection tasks. We found that participants self-reported: (i) significantly less body ownership in switching limbs than in not switching limbs; and (ii) less effort in switching limbs than not switching limbs. In addition, we found that dominant limbs do not significantly affect remap decisions in controlling the third arm.

CCS Concepts

• ***Computer systems organization*** → *Real-time operating systems;* • ***Software and its engineering*** → *Virtual worlds training simulations;*

1. Introduction

In this paper, we present a method to remap human limbs to a virtual third arm (here, a wearable robotic arm) in a Virtual Reality (VR) Environment. We explore its effect on performance, body ownership and workload. We used a VR Environment as it allowed us to easily test out our hypothesis.

1.1. Context

Wearable robotic arms are most commonly used to assist people in physical activities [PCA14]. They have been adopted in several sectors of activities where there is a need to: (i) reduce physical workload; and (ii) use more than 2 arms (e.g. construction [BA14, VH17], healthcare [PCRBJ16]). While some of those systems use 2 robotics arms, here we will focus on a system with *only* 1 robotic arm (whom we will refer to as the **third arm**).

A third arm is usually operated by the user "wearing" it (whom we will refer to as the **operator**) [LAM18]. It is able to move thanks to: (i) a direct mapping of the operator's arm to the robotic arm (e.g. strapped to the operator); and / or (ii) joysticks / buttons.

Use cases for a third arm mostly involve: (i) dual tasks where the user is required to perform 2 different tasks simultaneously [ABB*16, PA16], e.g. pulling luggage while the operator uses his/her phone for direction; as well as (ii) single tasks requiring a third arm, e.g. balancing a large box. These tasks can be challenging, especially in the case of a supernumerary limb (here the third arm), since: (i) the movements of the body directly affect it; (ii) its motions / operations require the use of one of the operator's limb.

Recent works have been addressing this issue by either stopping the mapping (e.g. releasing a joystick on top of the robotic arms), by remapping [ABB*16, SSK*18], by recording / playing commands, and / or by using AI [BA14].

1.2. Hypothesis

Here, we will use a system with real time remapping of a third arm to another limb, i.e. the operator can remap the third arm in real-time to any of his/her limbs (here the left arm, right arm, left leg, right leg, head or *none* [= rest position]).

Remapping has the advantage of "freeing" the operator's arm, and the disadvantages of: (i) "bounding" another one of the operator's limbs; as well as (ii) possibly making the arm more confusing to operate (e.g. if the remapping is done to a leg). A real-time remapping has the added advantage to "free" and "bound" the operator's limb depending of the type of task. For example, the operator

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is sitting with the third arm mapped to his/her left foot. If he/she needs to walk a few meters away, to avoid having unwanted motions of the third arm as he/she is walking, he/she remaps the third to his/her left arm.

Our work is heavily based on the numerous research on body ownership. Unlike previous works on body ownership involving a third arm / hand / finger (and more), here we add the possibility to "switch" the limb operating the supernumerary limb. Based on previous research (c.f. Sec. 2.2), we believe the operator will be able to adapt quickly to "non-natural" mappings [SSS13,WBLL15], and to feel body ownership toward the third arm.

[HH1] Remapping from one limb to another limb will not affect body ownership.

Since the operator has the possibility to switch limbs, it is also an opportunity to verify if he/she actually prefers to use his/her dominant limb over the other to control the third arm.

[HH2] The operator prefers to use their dominant limb to control a third arm.

We also believe that the ability to switch limbs will reduce the overall workload [ABB*16]. The possibility to switch limbs to fit the task might reduce the effort / frustration, but might also have an advert effect on the concentration.

[HH3] Remapping from one limb to another limb will reduce the overall workload.

1.3. Novelties and Plan

The novelties are the following:

1. We developed a system enabling a operator to remap a VR third arm in real time using gaze information and voice activation. We studied its usability and showed it was "below average";
2. We studied the impact of real time remapping regarding performance, body ownership and workload in a VR reaching task. We showed that real time remapping has a significant negative effect on body ownership and a significant positive effect on effort.

In Sec. 2 we explore the related work, then in Sec. 3 we detail the VE alongside the real time remapping system and in Sec. 4 the experiments details. In Sec. 5 we present the results, discuss them in Sec. 6 and conclude in Sec. 7.

2. Related works

2.1. Supernumerary Robotic Limbs

Supernumerary limbs involves the concept of having additional limbs attached to your body that can be used to assist in simple and complex tasks [GPE11].

Parietti and Asada [PA16] explored the use of Supernumerary Robotic Limbs (SRL, here 2 arms) that could support and "anchor" the operator against a wall / on the floor in order to let them perform a task safely and stably.

Abdi et al. [ABB*16] investigated controlling a third hand in VR using their foot, finding that in a demanding task 3 hands performed better than 2 with less physical / mental demand. Saraiji et al. [SSK*18] additionally experimented with SRL that could be controlled with the operator's leg / feet. Body ownership improved over the sessions, instigating that the robotic arms felt more like a limbs from their own body.

Similarly, Sasaki et al. [SSM*16] tracked the operator's arms to use SRL for simple tasks, there was also a strong body ownership toward the limbs.

2.2. Body Ownership

Body ownership is the feeling that the virtual body is the source of sensations [TPH06]. Kilteni et al. [KGS12] stated that it emerges from a combination of visuo-tactile and visuo-proprioceptive interactions [BAPS14] as well as morphological similarities [LLL15b].

Historically, Lambier et al [Lan06] introduced the *Homoncular Flexibility*, i.e. *"the possibility for people to quickly learn to inhabit different bodies and still interact with the VE"*. Won et al. [WBLL15] explored it with the remapping of normal or supernumerary limbs. They showed through 2 studies (N=53 and N=20, both in VR) that people were able: (i) to adapt within 10 minutes to a "non-normal" mapping (e.g. having a normal arm moving 2x faster than it should; having a normal arm mapped to the foot); and (ii) to use a supernumerary limb (here a third arm) to help them perform better. Steptoe et al. [SSS13] had similar results with a virtual tail remapped to the arms and / or legs. They showed in a study (N=32, in VR) that people were able to *"quickly learn how to remap normal degrees of bodily freedom"*.

Guterstam et al. [GPE11] provided insights behind the conditions for body ownership. They conducted 5 separated studies (N=154 in total, not done in VR) around a "Rubber Hand Illusion (RHI) setup", and identified 4 conditions for body ownership to occur: (i) laterality; (ii) limb type (i.e. the illusion does not work with a rubber foot); (iii) anatomical alignment (the rubber hand must be placed in an anatomically congruent position to the real one and the person's body); and (iv) visual stimulation on the rubber hand and the visuo-tactile stimulation on the real hand must be synchronous. In a similar "RHI setup", Hoyet et al. [HANL16] showed in a study (N=24, in VR) that a hand with 6 finger was able to elicit strong body ownership, even if the 6th finger had a "non-normal" mapping (e.g. was not moving at all).

Let us add that: (i) Maselli and Slater [MS13] showed in a study (N=54, in VR) that visuo-tactile stimulation was not actually necessary to elicit body ownership (as long as the avatar was of a "convincing" appearance); and (ii) Lugrin et al. [LLL15a] tested different avatar representation (here male, female, robot, stick man, "2 spheres" [= for both hands]) and shown in a study (N=24, in VR) that all the avatars were able to elicit strong body ownership.

Overall, there has been a large array of work done on body ownership in VR. Among the important points to remember: (i) a third arm can elicit strong body ownership, (ii) people adapt quickly (< 10 minutes) to a "non-normal" mapping, (iii) people adapt quickly (< 10 minutes) to a supernumerary limb. At the best of our knowledge, real time remapping and its impact on body ownership has not been studied yet.

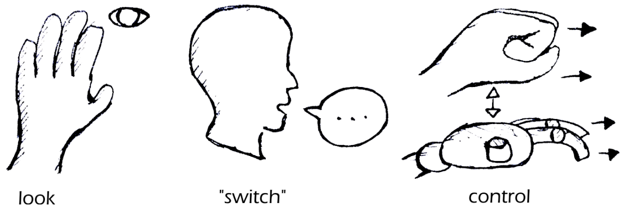

Figure 1: *The remapping of the third arm*

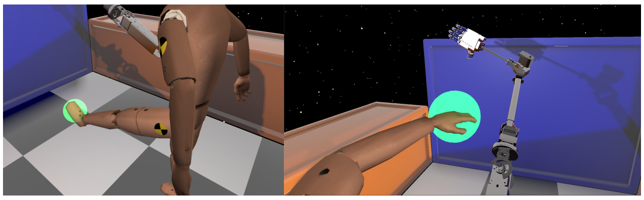

Figure 2: *Left: the operator is going to remap to his/her left leg. Right: the operator is going to remap to his/her left arm.*

3. System Description

As stated in the introduction (c.f. Sec. 1), our real-time remapping system allows the user to remap the third arm to his/her left arm, right arm, left leg, right leg, head and none [= no remapping] in VR.

3.1. Real Time Remapping

To remap the third arm to a limb, the process involves the user looking at a limb on his/her body, followed by saying "switch" which then remaps the third arm to the desired limb (c.f. Fig. 1). Following a successful switch, the user is given audio feedback through a "beep" sound. Additionally, a green sphere is placed at the limb the user is looking at to give them visual feedback of the limb they are about to select (c.f. Fig. 2). If the user wants to control the third arm with their head, he/she simply have to look up above a pitch of 290° and then say "switch".

The third arm is positioned inside the upper centre of the user's chest to avoid influencing his/her decision on remapping to a left or right limb. Its motion are driven by Inverse Kinematics (IK): each limb has 2 invisible transforms near by (target and bend goal), the third arm then tries to reach the mapped limb's target while bending according to the mapped limb's bend goal.

3.2. Setup

Our experimental apparatus consists of a HTC Vive[†] with tracking performed using 3 Vive Trackers[‡] and 2 Vive Controllers[§] in

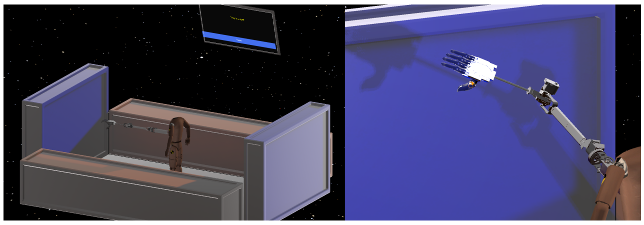

Figure 3: *Left: the "space room", with the avatar and third arm in default position. Right: focus on the third arm.*

a tracking space approximately of $10.3m^2$ ($4.37m \times 2.37m$). We developed the study in Unity 3D (v2018). The participants head, hands, waist and feet were tracked with the Vive products (c.f. above), with the rest of the skeleton being solved with IK using the FinalIK Unity package[¶] (the third arm IK, c.f. Sec. 3.1, was also solved with the FinalIK Unity package). Voice was captured with a microphone embedded in the Vive HMD, with the switch event being registered if the user spoke above a threshold of 0.0001. Microphone levels were obtained by finding the wave peak from the last 128 samples of audio recorded from the microphone at a sample rate of 44.1KHz.

3.3. Virtual Environment

The VE was voluntarily simplistic, as there was no need for realism. It consisted of: (i) a "space room" (c.f. Fig. 3) of about the same size than the tracking area (c.f. Sec. 3.2); and (ii) a TV displaying short messages (e.g. *"Press the Next button"*) and a "Next button" that the user had to select to go to the next step (c.f. Fig. 3).

The avatar had a "puppet like appearance" (c.f. Fig. 3) which had the advantage to "hide" eventual rendering issues (since in practice, the IK was not always accurate[‖]). Additionally we removed the avatar head (the user had no way to know it since there was no mirror in the VE). The third arm had a more complex appearance (c.f. Fig. 3).

3.4. Initial Testing

While developing the remapping system, we tested its functionality through a VR manipulation tasks, to fine-tune and improve it before formal evaluation. The tasks were inspired by previous benchmark tests used in robotics [HQBAC18] and included: (i) a door manipulation task, (ii) a box and block test, and (iii) block touching task:

- **The door manipulation task**, involved the operator picking up a real box with their real hands, opening a virtual door with their third arm, and delivering the box on the other side of the door. The box was a large physical cardboard box (tracked in VR) requiring both hands to be lift. While we did not do any formal

† https://www.vive.com/us/product/vive-virtual-reality-system/
‡ https://www.vive.com/fr/vive-tracker/
§ https://www.vive.com/us/accessory/controller/

¶ http://www.root-motion.com/final-ik.html
‖ The knee and elbow were not always at the correct position, but the simplistic appearance made it hard to notice it

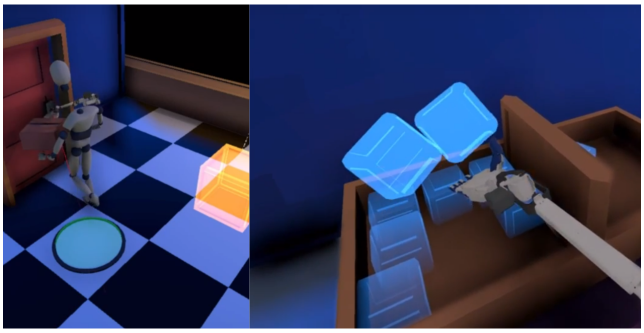

Figure 4: *Left: the door manipulation task, the operator tries to open the door with the third arm. Right: the box and block task, the operator grabbed a block and will drop it into the other bin.*

study, we had a couple of participants informally perform the task successfully (c.f. Fig. 4).

- **The box and block task**, which is commonly used to benchmark in robotics [HSS*17], involved the user using their third arm to pick up virtual boxes from a bin and dropping them into another bin. In addition to the door task, initial informal tries proved successful (c.f. Fig. 4).
- **The block touching task** involved floating blocks appearing in the VE, which the operator had to collect using their third arm. We eventually evolved this concept into our formal user evaluation (c.f. Sec 4.2.2).

4. Experiment

4.1. Participants

The experiment took place in Japan. There were 12 participants (age: M = 24.4, SD = 2.63; 11 males). The participants were all students or faculty members, among which ≈ 20% had little previous experience with VR (< 10 times), and ≈ 80% had extensive experience with VR. Participants were for the most part knowledgeable about the use of exoskeletons.

We used a within-subjects design with 2 groups. The independent variable was the real time remapping condition: remapping is possible and remapping is not possible, respectively called "Remapping" and "Non remapping". To avoid order effect, half the participant started with the Remapping condition and the other half started with the Non remapping condition.

4.2. Experiment Design

Participants were invited one-by-one to join the experiment. Only the participant and the assistant were present in the room. Participants read a description of the controls / tasks with the assistant, then put on the body trackers and the HMD. Throughout the experiment, the assistant provided help if needed. Participants were allowed to stop if there was any sign of discomfort (such as dizziness).

Once in the VE, participants followed a training session (step I, c.f. Sec. 4.2.1). Upon completion, participants performed the experimental tasks "Touch 1 Block" and "Touch 3 Blocks" (step II, c.f. Sec. 4.2.2). After doing those 2 tasks, they answered 2 questionnaires on a computer (step III, c.f. Sec. 4.2.3). They then did again the steps II and III in the other condition. Upon completion, they removed the HMD / trackers and answered 2 post-experimental questionnaires (step IV, c.f. Sec. 4.2.4).

The questionnaires were available in English and Japanese (translated from the English version by a native Japanese speaker).

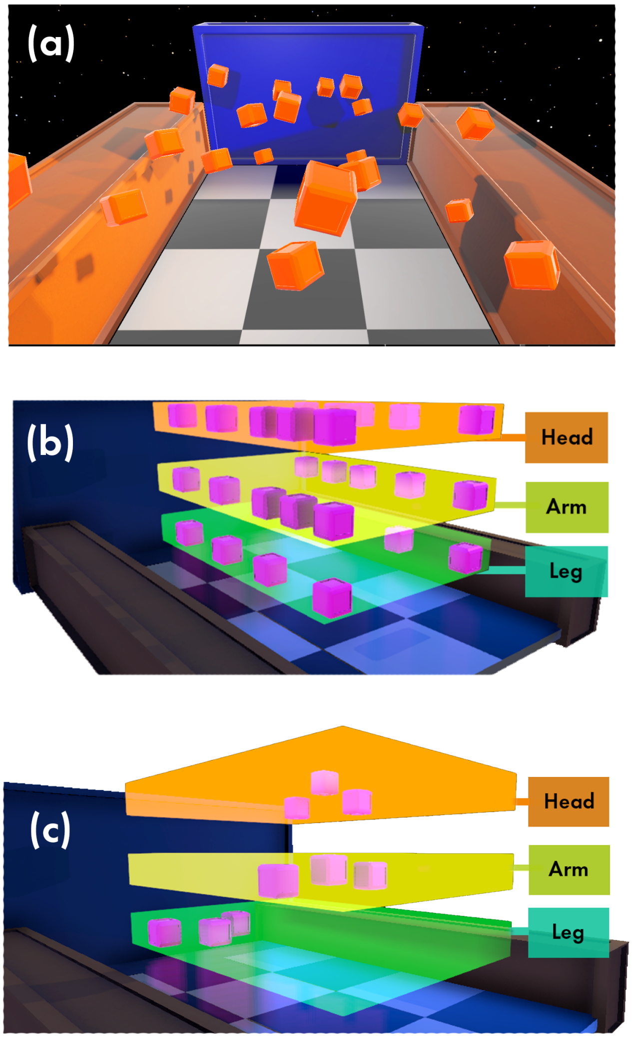

Figure 5: *Top: the training session. Middle: the Touch 1 Block task, here we displayed all the blocks at the same time to get an overview of their position, during the task they appear one by one. Bottom: the Touch 2 Block task, here we displayed 3 groups of blocks at the same time. The "leg", "arm" and "head" annotations give an idea of how we positioned the blocks to favor a remapping.*

4.2.1. Step I - Training Session

The participants touch blocks with their hands or with their third arm in a sand box mode (c.f. Fig. 5). The training gave them the opportunity to get used to their body and to get used to the real time remapping system. After 3 minutes the participants were allowed to pass to the next step (some decided participants to stay longer).

4.2.2. Step II - Experimental Tasks Touch 1 Block and Touch 3 Blocks

The tasks were as follows:

- **Touch 1 Block -** Blocks appear successively 1 after the other for 5 seconds at varied position. The participant has 4 seconds to touch a block with the third arm (the blocks cannot be touched with the operator's hands). As soon as the block is touched / time out, another block appears. The task lasted 300 seconds, regardless the number of block touched. The blocks were positioned in such a way that they were either easier to touch by mapping: (i) to the leg (block near the ground); (ii) to the arm (block at mid height of the operator); or (iii) to the head (block higher than the operator), c.f. Fig. 5;
- **Touch 3 Blocks -** Groups of 3 blocks appear successively 1 after the other for 10 seconds at varied position (similarly than in the task Touch 1 Block). The participant has 10 seconds to touch the 3 blocks at the same time using both his/her arms to "validate the group", moreover the third arm can only touch the middle block, to force the operator to control the third arm instead of just moving or rotating their body), c.f. Fig. 6. Similarly than "Touch 1 Block, the task ended after 300s and the blocks were positioned to favorite a given mapping, c.f. Fig. 5.

4.2.3. Step III - Tasks questionnaires

After doing both tasks, the participants removed his/her HMD, and filled out the following questionnaires on a computer:

- A body ownership questionnaire focused on the third arm (whom we will refer to as the Arm Ownership Questionnaire) with subjective experience ranging from (strongly disagree) to (strongly agree) on a 7 point Likert scale (adapted from Gonzalez-Franco and Peck's standardized embodiment questionnaire [GFP18]), c.f. Tab. 1;
- A body ownership questionnaire focused on the whole body (whom we will refer to as the Body Ownership Questionnaire) with subjective experience ranging from (strongly disagree) to (strongly agree) on a 7 point Likert scale, c.f. Tab. 1;
- The NASA TLX [HS88]

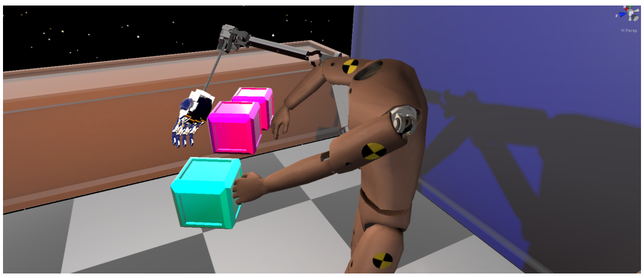

Figure 6: *The Touch 3 Blocks tasks. When a block is touched, it turns cyan.*

ID	Question
AO1	I felt as if the virtual third arm was my own arm
AO2	It felt as if the virtual third arm was not a part of my body
AO3	It felt as if the virtual third arm was synchronized with my motions
AO4	It felt like I could control the virtual third arm as if it was my own body part
AO5	The movements of the virtual third arm were caused by my movement
AO6	I felt as if the virtual third arm was moving by itself
BO1	I felt out of my body
BO2	I felt as if my body was located where I saw the virtual body
BO3	I felt as if the virtual body was drifting toward my (real) body

Table 1: *The Arm Ownership and Body Ownership Questionnaires*

Then the participant put back on the HMD if there was still a condition to do.

4.2.4. Step IV - Post experimental questionnaires

After the doing both conditions, the participants filled out the following post experimental questionnaires:

- A demographic questionnaire, including sex, age, ethnicity and experience with VR;
- A handedness questionnaire adapted from Oldfield [Old71] and a footedness questionnaire adapted from van Melick et al. [vMMH*17];
- A System Usability Scale (SUS) questionnaire [B*96] for the remapping system specifically, and a SUS questionnaire for the robot arm specifically (both on a 5 points Likert scale);
- The Presence Questionnaire from Usoh et al. [UCAS00] (on a 7 points Likert scale);
- 3 open questions about the experiment (*"What did you think about the experiment?"*, *"What do you think experiment purpose was?"*, *"Could you see yourself using a third arm in your day to day life? If so, in what context could you see yourself using it?"*).

5. Results

In this section we present the results of our experiment.

5.1. Score

For the task Touch 1 Block, we recorded and labeled every remapping done during the tasks (the label associate the remapping to the remapped limb) as well as the limb touching a block. We present the results in Tab. 2.

We also computed paired Student t-tests on the number of blocks

	Remapping		Non remapping	
Number of...	M	SD	M	SD
Block touched	59.7	25.42	98	48.9
Head touched	20.3	16.7	0	0
Left hand touched	8.5	8.91	52	72.5
Right hand touched	21.7	15.85	46	49.6
Left leg touched	2	3.77	0	0
Right leg touched	7.2	10.9	0	0
Remap	16.6	8.7	0	0
Remap head	4.6	3.4	0	0
Remap left hand	2.3	1.82	0	0
Remap right hand	4.7	2.89	0	0
Remap left leg	1.9	1.96	0	0
Remap right leg	3.1	4.2	0	0

Table 2: *The number of block touched and the number of time each body part touched a block, as well the number of remapping and the number of time each limb was remapped.*

touched ($t = -4.002, df = 11, pvalue = \mathbf{0.0031}$). Participants in the non remapping condition touched significantly more blocks than in the remapping condition.

5.2. Body ownership

Since the AO and BO questionnaires were heavily adapted, we verified their internal consistency by computing their Cronbach's alpha coefficients. The results for AO (6 items) and BO (3 items) were respectively 0.66 (internally consistent) and 0.14 (not internally consistent). We then computed paired Student t-tests on the grouped AO items and on each BO items, c.f. Tab. 3.

Item	t	df	p-value
AO	-3.17	11	**0.0113**
BO1	0	11	1
BO2	0.318	11	0.752
BO3	0.688	11	0.509

Table 3: *The Arm Owernship and Body Ownership paired Student t-tests*

We can see in the Tab. 3 and Tab. 4 that the Third Arm ownership is significantly higher in the non remapping condition.

Condition	M	SD
Remapping	30.4	5.36
Non remapping	34.6	3.84

Table 4: *The Arm Ownership score*

5.3. NASA TLX

We weighted and calculated the NASA-TLX regarding the workload of the system (remapping + manipulating the third arm), c.f. Tab. 5. We then computed paired Student t-test on the overall workload ($t = 0.76, df = 11, pvalue = 0.46$).

Condition	M	SD
Remapping	10.52	3.62
Non remapping	9.52	3.4

Table 5: *The NASA TLX score*

The overall workload for both conditions was average as deemed by 10 being average on the NASA-TLX scale.

5.4. System Usability Scale

Both SUS have a score near average, c.f. Tab. 6 (the SUS has a cutoff around 68, but since we removed 1 irrelevant item we believe the cutoff to be at 61.2). The results are somewhat surprising as we were excepting a bigger score.

Tested on	M	SD
Remapping	63.5	19.44
Third Arm	64.5	15.17

Table 6: *The SUS score*

5.5. Presence

The Presence has a mean score of 27.3, out of a total of 42, which is acceptable. We present in Tab. 7 the score of each item. The last question *"During the experience I often thought that I was really standing in a room"* might have been misunderstood by some participants (as the VE is not a room per se).

Question	M	SD
P	27.3	5.46
P1	5.7	0.95
P2	4.8	1.62
P3	5.6	1.71
P4	3.6	1.96
P5	3.7	1.34
P6	3.9	2.08

Table 7: *The Presence items*

5.6. Open questions

We highlight here some of the relevant comments reported by the participants:

- *"It was difficult to move the robot arm with my feet while I was standing up"* (mentioned 3 times) this might give insight in the low number of block touched with the legs;
- *"The second experiment [task] was more tiring because there was only one arm I could use"* (mentioned 5 times);

- *I liked to use the head control when the box is in the air, and I liked to use the leg control when the box is on the floor* (mentioned 4 times);
- *Although I could not imagine it so much, I felt that it might be easy to use for the action of grabbing or touching something high when operating the third arm with my head* (mentioned 8 times). Most of the participants felt that the remapping was not very useful, although they could think of a few use cases.

All participants noticed the change in condition "I think the purpose is to investigate the effect of changing the control method". This was excepted (and wanted) as it is a within-subject design.

6. Discussion

We wanted to know if a real time remapping of a third arm will have any influence on the body ownership (**HH1**, c.f. Sec. 1.2). The Sec. 5.2 showed us that on the contrary, real time remapping has an influence on body ownership, thus HH1 is not verified. This result was not expected. We were basing our hypothesis on the Homuncular Flexibility [WBLL15] in VR, showing a relatively quick adaption of supernumerary limbs. As a possible explanation of this result, it is likely that the adaptation of the supernumerary limbs (here the third arm) depends not on the limb itself, but on the mapping done between the limb and the operator's body. It is also likely that every mapping needs its very own "training session" in order for the operator to feel comfortable with it.

We were also interested in the relation between the dominant hand / foot, and the preferred mapping (**HH2**, c.f. Sec. 1.2). Most of our participants were right handed (and most right legged has well), and only 2 were left handed. Those numbers make it difficult to draw a definitive conclusion. As an observation, in the Tab. 2, we can nonetheless see that the number of remapping done to the right hand is higher than those done to the left hand. However this observation is not visible on the leg.

We also wanted to know if the real time remapping will reduce the overall workload (**HH3**, c.f. Sec. 1.2). As stated in Sec. 5.3 there is no significant difference in the overall workload, thus HH3 is not verified. Yet the tiredness of the system was brought up by several participants in the open questions: "I'm tired when I use only the left hand to control robot arm.", "I was tired when I used only the right hand.", "When I cannot change the arm, it is tiring to always go down to catch the cubes".

Regarding the near average SUS score for the switching system, we were surprised as it was designed with usability in mind. We will however point out that the worst scores are the item 7, *"I would imagine that most people would learn to use the remapping very quickly"* and the item 10, *I needed to learn a lot of things before I could get going using the remapping*). Those 2 items are focused on the "learning" aspect of the system, which indeed needed some training to get used to. It would be useful to compare the current switching system with a system using only gaze tracking or only buttons.

7. Conclusion

From this paper, we presented initial results for an experiment investigating the effects on performance, body ownership, workload and usability of a method to switch operator limbs for controlling a third arm. From the results we have obtained, we have drawn some conclusions on the development of such a system. For one, further work needs to be made in the area of *usability*, in order to explore how to make users feel comfortable when switching limbs to control supernumerary limbs. This work is especially important in a variety of applications and domain areas. For example, in labour work, where additional limbs could potentially make specific tasks easier to conduct simultaneously. Potential avenues for investigation include simpler processes for switching limbs, such as non-verbal switching, or using AI to learn to switch limbs based on a user's behaviour. Subsequently, this may also have a direct effect on body ownership results and objective measures.

In a future work, we will use a real third arm and study further the effect of body ownership with a real world task.

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