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Effects of Frequent Changes in Extended Self-Avatar Movements on Adaptation Performance

Agata M. Soccini*, **Alessandro Clocchiatti***, **and Tetsunari Inamura**** ***

*University of Torino, Italy
E-mail: agatamarta.soccini@unito.it
*University of Torino, Italy
E-mail: alessandro.clocchiatti@unito.it
**National Institute of Informatics, Tokyo, Japan
***The Graduate University for Advanced Studies, SOKENDAI, Tokyo, Japan
E-mail: inamura@nii.ac.jp
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Abstract. Among several perceptive traits of virtual reality, the relationship between the physical body and a self-avatar is unclear. In this study, we investigate a case of hyper-adaptability, i.e., the capability of users to adjust to the movements of an altered self-avatar when such movements abruptly and frequently change. Focusing on movements of the upper limbs, we show experimentally the effect of the frequency of variations in virtual body alterations on adaptability. Moreover, we report a positive evaluation of the sense of embodiment and the overall user experience with virtual reality, and finally underline how these studies can be considered a basis for the design and development of virtual rehabilitation systems.

Keywords: virtual reality, sense of embodiment, self-avatar, hyper-adaptability, motor control and adaptation

1. Introduction

1.1. Background

The process of embodying a full or partial self-avatar includes several perceptive factors, mainly based on the ability to adapt the body schema to the new setup [1–8]. The concept of hyperadaptability [9] has recently been proposed to explain the function of achieving a desired movement by adapting to changes in one's own body structure or motor control functions beyond the scope of normal adaptation. Hyperadaptability often refers to the ability to adapt to irreversible changes, such as the loss of a limb owing to an accident, or damage to the cranial neural circuits. However, when we consider the use of prosthetic limbs, our brains are exposed to frequent changes in body structure. Adaptation in such cases is naturally included in the scope of hyperadaptability; however, no studies targeting such frequent changes in body structure or motor control function have been conducted. Thus, in this study, we consider the use of a prosthetic or virtual limb, the behaviors of which change abruptly over time. In the physical world, such changes occur while wearing and removing a prosthesis, whereas in the virtual world, they may refer to interference owing to a glitch or lag. Under a virtual rehabilitation scenario, where self-avatars are used as a guide to lead users, a divergence of virtual movements from the actual physical movements is possible [10]. However, there are no clear criteria or a specific adaptive model determining which avatar movement optimizes a particular exercise.

To investigate this topic, we initially define the main concepts of the multidisciplinary scenario based upon which our study was conducted [11]. The sense of embodiment (SoE) has different meanings depending on the context of the study. Herein, it refers to a set of sensations related to having, controlling, and processing a body (or a part of it) as if it is one's own. According to the definition given by Kilteni *et al.* [12], the main components of SoE are the sense of self-location (SoL), sense of agency (SoA) and sense of body ownership (SoO). Proprioception can be defined as the perception of the position and orientation of parts of the human body [13] or position, movement and balance [14]. Proprioceptive drift, particularly in the field of virtual reality (VR), refers to the difference between the perceived and actual positions of the body being investigated. The embodiment illusion occurs when the visual information given by a self-avatar matches that perceived through proprioception, touch, and motion [15]. In this way, a virtual body is perceived and processed as a real body, producing an SoE.

To the best of the authors' knowledge, the concept of adaptation inertia is novel and can be defined as the human resistance to adaptation to the movements of an avatar (or an embodied fake limb) when changes in the behavior of the avatar frequently occur over time. Following this definition, the goal of the system is to measure the adaptation inertia and find the best strategy to minimize it. During the experiment sessions, we also relied on the concept of accumulation as the incremental amount of variation.

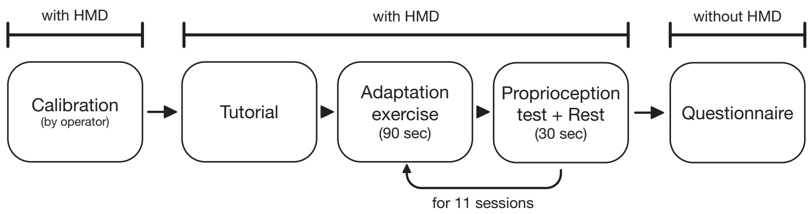


Fig. 1. : Experiment procedure.

1.2. Related Work

Since the rubber hand illusion was first introduced by Botvinick *et al.* [2], several studies have focused on an understanding of the SoE toward fake and virtual limbs (for a review, see Riemer *et al.* [16]). Several studies have focused on the understanding of a virtual embodiment, as well as the physical kinetic response of the users, when the self-avatar movements or features are altered. Through a VR experiment, Inamura *et al.*[17] investigated the effects of virtual hand length and appearance on proprioception. They showed that it is possible to intervene in proprioception through a virtual motor experience lasting several minutes. However, they did not discuss the after-effects. In addition, the question of how quickly the proprioceptive sense returns to normal remains unanswered.

Soccini *et al.* [18, 19] defined the induced finger movement effect as the appearance of unintentional movements in the real body when an external movement (alien motion) is introduced into the hand and fingers of an avatar. These studies showed that an alteration in the movements of a self-avatar does not necessarily nullify the SoO and SoA, and that movements are only induced when the self-avatar is embodied. Gonzalez-Franco *et al.*[15] showed how introducing a variation in embodied self-avatar movements results in users following the self-avatar itself, creating a drift. Note that in all of the aforementioned studies, some alterations to the bodily movements of a self-avatar still allow an SoE to occur. However, in cases in which the self-avatar abruptly and frequently changes, the persistence of an embodiment is an open topic. In addition, for the same case, the physical responses of the users are still unknown. As a research question, we focus on clarifying the relationship between adaptation inertia and the variations in self-avatar behaviors and understanding how proprioception is influenced by such variations.

1.3. Hypotheses

Based on the described scenario, as a contribution to the knowledge of the self-avatar and its human perception, we investigated the embodiment, adaptation, and proprioception for cases in which the amplitude of the movement alterations of a self-avatar frequently or abruptly changes. Such an alteration is mathematically defined based on a coefficient indicating the amount of motion illusion that occurs. Regarding virtual rehabilitation, although a standard strategy would change the coefficient over time (i.e., over several weeks), we questioned how much we can accelerate the effectiveness of rehabilitation by changing the coefficient of the motion illusion within a short timeframe. In particular, because adaptation inertia and proprioceptive drift can be used as indicators to verify the effectiveness of rehabilitation, we questioned whether we are able to modify them using an aggressive change in the motion coefficient. Regarding the SoE, although an alteration of the movements may lead to the belief that the rubber hand illusion would not occur, studies have shown that the illusion still exists in several cases [15, 18, 19]. We therefore hypothesized that our case will continue, and the sense of embodiment will remain.

We therefore defined the following hypotheses:

- **H1** The adaptation inertia changes according to aggressive alterations in the self-avatar behavior, expressed through frequent changes in the coefficient.
- **H2** The proprioceptive drift changes according to aggressive alterations in the self-avatar behavior, expressed through frequent changes in the coefficient.
- **H3** The sense of embodiment persists despite the introduction of an alteration in movements.

In the current study, we first present the experimental setup and protocol based on altered movements of a virtual forearm. We then define the methods used to collect and process the subjective data related to embodiment and the overall VR experience, and propose quantifiers for adaptation inertia and proprioceptive drift. We then report the results and conclude the paper with a summary of the overall findings.

2. Experiment

2.1. Setup

We developed a VR application for Meta Quest2[1] using a the native hand-tracking system. This application can amplify and reduce the movements of the forearm of the users according to a coefficient value defined in the experimental design. Fifteen volunteers (3 female and 12 male, age $\mu = 27.9$, and $\sigma = 9.15$), living in Europe or Japan, participated in the experiment, 6 of whom had never experienced VR.

1. www.oculus.com/

Although the experiment was conducted in VR, the physical environment also included some elements of the virtual world, including a chair, table, and two markers (i.e., some tape) placed on a table to fix the position of the elbows. The application initially required a calibration phase preceding the actual experiment, which was conducted by the operator. During this phase, the operator set the height of the virtual table and position of the elbow placeholders to match the physical setup. At this point, the operator assigned each user to one of the experimental groups, which we will discuss further in our description of the applied protocol. Once the calibration was completed, the users went through a tutorial, during which they received instructions on the tasks and learned how to interact with the specific virtual setup. In particular, the participants could experience clicking a virtual button by applying a specific hand gesture (pinch), which was required to start the sessions.

2.2. Protocol

We defined an experiment as consisting of 11 sessions, each comprising two phases: an adaptation exercise and a proprioception test. **Figure 1** shows a schematic of the entire procedure.

The adaptation exercise followed the method proposed by Inamura *et al.* [17] and required the users keep their left elbow fixed over a specific point on the table (called an elbow placeholder) positioned in front of the user, as shown in **Fig. 3a**. The requested task was the flexion/extension of the left arm toward the center of two virtual boxes, or targets, several times during a 90 s period. The users were required to follow the pace given by the sound of a metronome beat at 60 bpm.

Based on the research questions defined in the hypotheses, we designed the experiment as follows: we defined two series of alteration values, and therefore different accumulation values, which we assigned to the two groups of participants. In this way, we were able to measure the adaptation inertia for the two different cases by analyzing the behavior under frequent or infrequent changes (H1). During the experiment, we measured the proprioceptive drift several times at the end of every session and related it to the accumulation (H2). To assess the possible existence of a sense of embodiment, we proposed a questionnaire at the end of the experiment to collect subjective quantified data (H3).

In a 3D space, we consider the angles of movements on only a single plane, that is, the angle given by the table in front of the user *(X, Z)* (**Fig. 2**). We define θ_R as the angle of the real hand, whose zero value is on the Z-axis.

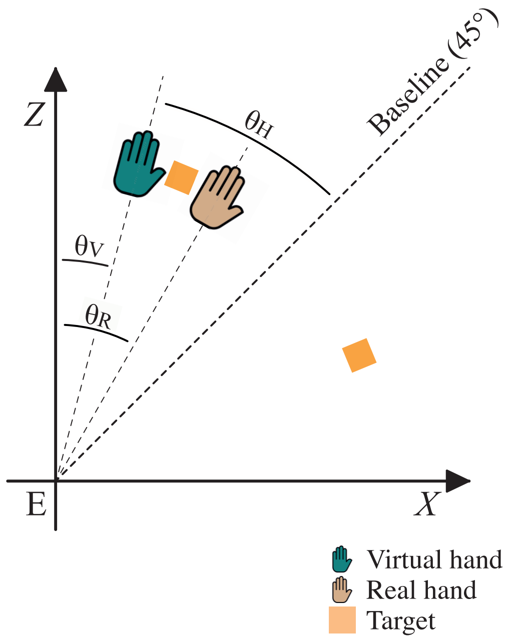
Here, θ_V is defined as the angle of the virtual hand and is calculated according to the following formula:

$$\theta_V = c\,(\theta_R - 45^\circ) + 45^\circ, \quad (1)$$

where coefficient c is a numerical value that defines the amount of visual alteration between the real and virtual hands.

For calculation purposes, we finally define θ_H as the angle between the baseline and the virtual hand.

Fig. 2. : Schematic representation of the rotation angle of the hands. The represented plane *(X, Z)*) is the table top, whereas E indicates the position of the elbow.



$$\theta_H = 45^\circ - \theta_V \quad (2)$$

During the proprioception test phase, the participants were asked to touch the target with their left hand and place their right hand symmetrically to their left (as shown in **Fig. 3b**), always keeping both elbows on the placeholders. During the adaptation exercise, only the virtual left hand was visible, and both the real and virtual hands were hidden during the proprioception test. The participant wore the HMD for the entire experiment.

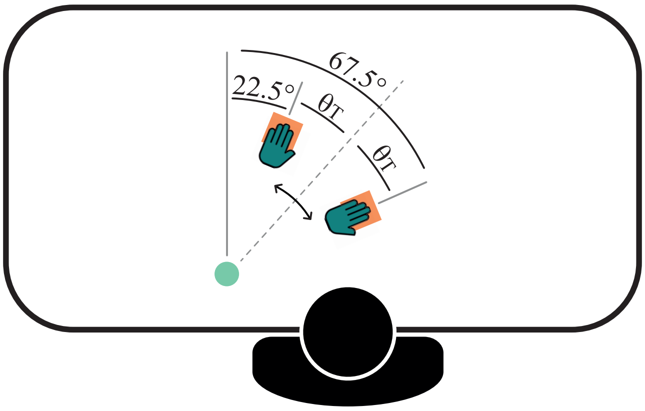
We divided the population into two groups, each of which underwent one of two conditions. As shown in **Table 1**, coefficient c varied differently throughout the sessions.

In group A, the coefficient was stable in the first part of the experiment (low frequency of variation, low accumulation of change), whereas it changed during every session in the second part. Group B, consisted of an opposite approach, in which there was a high frequency of variation in the first part of the experiment (high accumulation of change) and a low frequency of variation in the second part.

The values of the coefficient (0.5 and 2.0) were chosen to set the modification to half and double the amplitude of the movement. We designed the experiment to make both groups experience both conditions (high- and low-frequency changes), and thus we could make a comparison of the adaptation of the users under both conditions, with or without having previously experienced the opposite setup. To apply two different values of accumulation for the two groups and thereby evaluate their impact on

Fig. 3. : Schematic representation of the adaptation exercise and the proprioception test. The green hand represents a virtual hand.

(a) Adaptation exercise scheme



(b) Proprioception test scheme

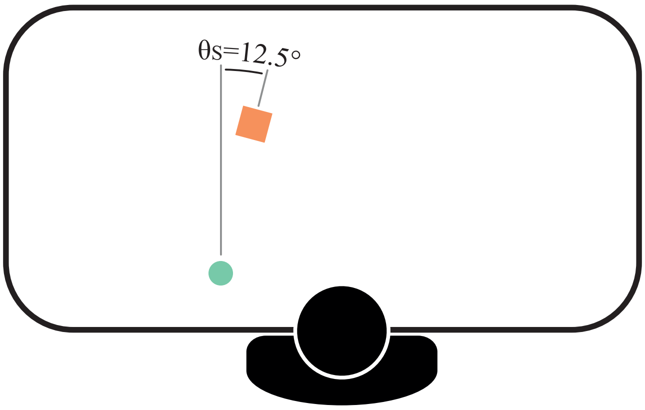


Table 1. : Exaggeration coefficients achieved through the experiment.

Group	Values
A	[1.0, 2.0, 2.0, 2.0, 0.5, 0.5, 0.5, 2.0, 0.5, 2.0, 1.0]
B	[1.0, 2.0, 0.5, 2.0, 0.5, 2.0, 0.5, 2.0, 2.0, 2.0, 1.0]

the accumulation inertia, the balance between the coefficients of both groups was chosen to be unequal. In addition, we aimed to provide a pattern that would produce the same accumulation values in the two experimental parts with quick changes.

The position of the targets was the same during all sessions, and was described using spherical coordinates (22.5° and 67.5° for the targets of the adaptation exercise, 12.5° for the proprioception test box). The distance between the target and elbow was calculated once at the beginning of the first session according to the length of the lower arm of the participant.

At the end of the experiment, the participants were asked to respond to a questionnaire (**Table 2**), to assess the quality of the user experience and training, to report any possible illness, and to measure their embodiment.

3. Methods

3.1. Measuring the Adaptation Inertia and Proprioceptive Drift

During the adaptation exercise, the baseline is defined as a line equally dividing the angle between the two targets.

Ideally, the flexion and extension angles of the virtual arm θ_H corresponded to the angle θ_T between the targets and the baseline when the participant tried to touch the target. As shown in **Fig. 3a**, the value of θ_T could be either $-22.5°$ or $22.5°$, on the target the user was reaching toward.

san We mathematically defined the adaptation inertia $G(t)$ as the cumulative difference between the angle of the target θ_T and the angle of the virtual hand $\theta_H(t_i)$ at the moment t_i, that is, the moment when the target should be touched by the participant. The calculation of adaptation inertia was applied during the first $n = 5$ seconds of each session, as shown in Equation 3.

$$G_i(t) = \sum_{i=1}^{n} |\theta_H(t_i) - \theta_T| \quad \text{. . . . .} \quad (3)$$

Because an alteration of a self-avatar behavior can make it more difficult to follow the suggested rhythm, the participant was unable make all expected attempts to reach the targets during the first 5 s. Therefore, the value calculated in Equation 3 is divided by the number of attempts p made during the first $n = 5$ s, as shown in Equation 4.

$$G_{ii}(t) = \frac{1}{p} \sum_{i=1}^{n} |\theta_H(t_i) - \theta_T| \quad \text{. . . . .} \quad (4)$$

During the final part of each exercise, we expected the participants to adapt to the new self-avatar behavior. During the last part of each adaptation exercise, we expected the flexion and extension angles to correspond to the angles of the targets. However, as shown in **Fig. 4**, this did not occur, probably for the following reasons: involuntary displacement of the left elbow from the placeholder, the participant simply touching the target instead of reaching toward its center, or a rotation of the wrist instead of a rotation of the full arm. Based on these considerations, we introduced θ_M as the mean value of the angles during the last 30 s of the exercise. Starting from Equation 4, we replaced the angle of the targets θ_T with the mean angle of the movements θ_M and defined the working formula of the adaptation inertia, as presented in Equation 5. In other words, $G(t)$ is the mean distance of the user's movement from the ideal movement during the first 5 s of the session.

$$G(t) = \frac{1}{p} \sum_{i=1}^{n} |\theta_H(t_i) - \theta_M| \quad \text{. . . . .} \quad (5)$$

As previously described, during the proprioception test,

Table 2. : Questionnaire.

N	*Question*
General info	
1	Age
2	Gender
3	Have you tried Virtual Reality before?
User Experience	
4	What is the level of immersion you experienced?
5	What was your level of enjoyment of the VR experience?
6	How was the quality of the VR technology overall (i.e hardware & peripherals)?
In-Game Assistance	
7	How helpful was/were the tutorial(s)?
8	How easy was to complete the tasks?
9	How helpful were the in-game instructions for the task you needed to perform?
VR Induced Symptoms and Effects	
In this section -3 indicates Absent, 0 indicates Moderate Feeling, and +3 indicates Extremely Intense Feeling	
10	Did you experience nausea?
11	Did you experience disorientation?
12	Did you experience dizziness?
13	Did you experience fatigue?
14	Did you experience instability?
Sense of ownership	
15	I felt as if I was looking at my own hand
16	I felt as if the virtual hand was part of my body
17	It seemed as if I were sensing the movement of my hand in the location where the virtual hand moved
18	I felt as if the virtual hand was my hand hand
Sense of agency	
19	The virtual hand moved just like I wanted it to, as if it was obeying my will
20	I felt as if I was controlling the movements of the virtual hand
21	I felt as if I was causing the movement I saw
22	Whenever I moved my hand I expected the virtual hand to move in the same way
Sense of self location	
23	I felt as if my hand was located where I saw the virtual hand
24	I felt as if my real hand were drifting toward the virtual hand or as if the virtual hand were drifting toward my real hand
	(Optional) Insert any additional comment

the users were asked to reach a target, placed at $\theta_S = 12.5°$ (as shown in **Fig. 3b**).

However, drift may occur between the expected and actual positions of the real hand. We therefore geometrically defined the proprioceptive drift $D(t)$ as the difference in angle between the actual and expected positions of the real hand θ_R, as shown in Equation 6.

$$D(t) = |\theta_S - \theta_R| \quad (6)$$

We proceeded with an analysis of the variation in drift over time, $\Delta D(t)$, as indicated in Equation7.

$$\Delta D(t) = D(t) - D(t-1) \quad (7)$$

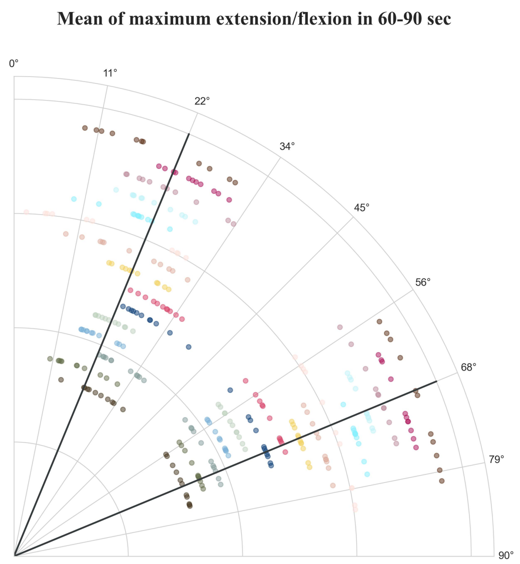
To simplify the calculations during the data analysis and allow tests with different coefficients, we mapped the coefficient values to a discrete variable, defining $C(t)$ as the discrete state of the fluctuation of c:

$$C(t) = \begin{cases} -1 & \text{if} \quad c = 0.5 \\ 0 & \text{if} \quad c = 1.0 \\ +1 & \text{if} \quad c = 2.0 \end{cases} . \quad (8)$$

Although the middle value of coefficient c must be 1, the two other values can be slightly different without a change in $C(t)$ as long as they are < 1 and > 1, respectively.

To exclude a learning effect from occurring throughout the different sessions with the same coefficient value, we considered the change in the exaggeration coefficient in each session, $C_{diff}(t)$, and the accumulation of the change in the coefficient $C_{acc}(t)$ up to session t. As shown in **Table 3**, there were some common patterns between the

Fig. 4. : Flexion and extension angles during the last 30 s of the exercise, shown per user. Each subject is represented with a different color, and the distance from the origin corresponds to the numerical ID of the subject.



two groups, in which the values of $C_{diff}(t)$ and $C_{acc}(t)$ in the first part (sessions 4,5, and 6) and the second part (sessions 8, 9, and 10) parts are equal. In particular, in sessions 5 and 8, the values of $C(t)$ and $C_{diff}(t)$ are equal in both groups, whereas in the second part of group A (A2) and the first part of group B (B1), both $C_{diff}(t)$ and $C_{acc}(t)$ have the same values.

We therefore investigated the following pairings of groups:

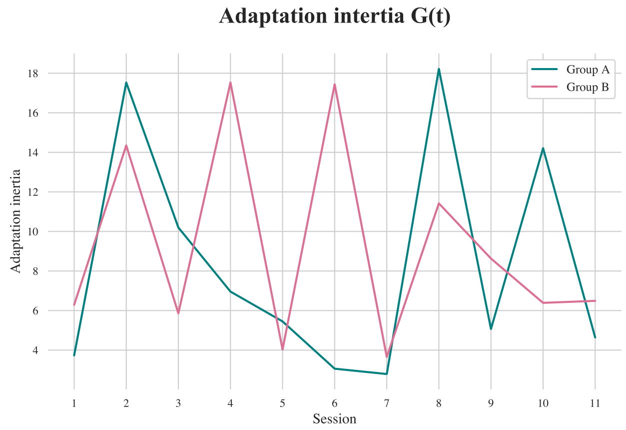
- the first part of group A and the first part of group B (A1 versus B1);
- the second part of group A and the second part of group B (A2 versus B2);
- the second part of group A and the first part of group B (A2 versus B1).

For each couple, we only focused on sessions in which the values of $C(t)$ and $C_{diff}(t)$ were the same in both groups. Therefore, we separated the cases in which $C_{diff}(t)$ increased (up) from those in which it decreased (down) and conducted several significance tests (t-test) to evaluate the impact of the accumulation and number of past sessions on the adaptation inertia and proprioceptive drift. We omitted the fact that the evaluation in case $C_{diff}(t)$ did not increase or decrease.

3.2. Measuring the Sense of Embodiment

The questionnaire given to each participant at the end of the experiment is reported in **Table 2**, and is a combination of seven groups of items from different questionnaires. Categories 2, 3, and 4 concern factors related to the subjective perception of the overall VR experience, user experience (UX), in-game assistance (IGA), and VR induced symptoms and effects (VRISE), and were taken from the virtual reality and neuroscience questionnaire (VRNQ) questionnaire [20]. Although the questionnaire originally included additional items, we selected only those relevant to our experiment. Responses were given on a 7-point Likert scale ranging from -3 (strongly negative) to $+3$ (strongly positive). For the VRISE category, the ranging scale was inverted as specified in the questionnaire.

Fig. 5. : Mean values of the adaptation inertia $G(t)$ for the two groups during all sessions of the experiment.



Categories 5, 6, and 7 are related to SoO, SoA, and SoL, respectively, and define the overall SoE perceived by users during the entire experience. Whereas categories 5 and 6 were from the questionnaire proposed by Kalckert *et al.* [21], category 7 was from the questionnaire by Gonzales Franco *et al.* [22]. We found this combination to be an accurate option for measuring the three main components of the SoE. Again, the responses are given on a 7-point Likert scale, in which –3 indicates that the user strongly disagrees, and +3 means that the user strongly agrees. The sense of embodiment is calculated as shown in Equation 9, where the factors SoO, SoA, and SoL are calculated as the mean values of the responses to the questions in the category.

$$SoE = \frac{SoO + SoA + SoL}{3} \qquad (9)$$

In a further investigation, we checked for a significant difference between the two groups of participants, A and B.

4. Results

4.1. Results on the Adaptation Inertia

As shown in **Fig. 5** and **Table 4**, the adaptation inertia of the two groups differed over time. In particular, when the coefficient c was stable for several sessions, (i.e., the first six sessions of group A and the last four sessions

Table 3. : Summary the variables that allow highlighting similar patterns in groups A and B.

				First part (1)				*Second part (2)*			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
cA	1.0	2.0	2.0	2.0	0.5	0.5	0.5	2.0	0.5	2.0	1.0
$C(t)A$	0	$+1$	$+1$	$+1$	-1	-1	-1	$+1$	-1	$+1$	0
$C_{diff}(t)A$	-	$+1$	0	0	-2	0	0	$+2$	-2	$+2$	-1
$C_{acc}(t)A$	-	1	1	1	3	3	3	5	7	9	10
cB	1.0	2.0	0.5	2.0	0.5	2.0	0.5	2.0	2.0	2.0	1.0
$C(t)B$	0	$+1$	-1	$+1$	-1	$+1$	-1	$+1$	$+1$	$+1$	0
$C_{diff}(t)B$	-	$+1$	-2	$+2$	-2	$+2$	-2	$+2$	0	0	-1
$C_{acc}(t)B$	-	1	3	5	7	9	11	13	13	13	14

Table 4. : Results of the adaptation inertia $G(t)$ between the two groups.

t (session)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
$G(t)$ $(group A)$	3.73	17.53	10.2	6.96	5.45	3.06	2.79	18.22	5.07	14.21	4.64
$G(t)$ $(group B)$	6.29	14.35	5.86	17.53	4.03	17.44	3.65	11.42	8.63	6.39	6.49

of group B), the adaptation inertia decreased, confirming the natural adaptation to the new self-avatar behavior. Instead, when the coefficient c changed for each session, the adaptation inertia was higher and changed over time. We noticed that the adaptation inertia is typically lower when coefficient $c = 0.5$ in comparison with the sessions in which $c = 2.0$.

Figure 6 compares the mean values of the adaptation inertia in the pairings presented earlier for both groups.

The results of the t-tests underlined a significant difference in the adaptation inertia between A2 and B2 ($p < 0.05$), for which the numbers of sessions were the same. However, no significant differences were observed between A1 and B1. This means that there was little difference in the adaptive performance during the first half of the session; however, Group B adapted more easily during the second half of the session.

The comparison between A2 and B1 showed no significant differences for the sessions with the same accumulation of change (**Table 5**). Moreover, we observed that the adaptation inertia was lower in Group B, which had less experience than Group A, which had more experience when the gain decreased.

4.2. Results of Proprioceptive Drift

The analysis of the proprioceptive drift followed the methods used for the adaptation inertia. In particular, we investigated the variations in proprioceptive drift for the two groups during all experimental sessions.

As shown in **Fig. 7** and **Table 6**, the initial sessions presented different proprioceptive drift behaviors between the two groups. In particular, whereas group A conducted

Fig. 6. : Comparison of the mean values of the adaptation inertia in the areas for which the values of $C(t)$ and $C_{diff}(t)$ are equal.

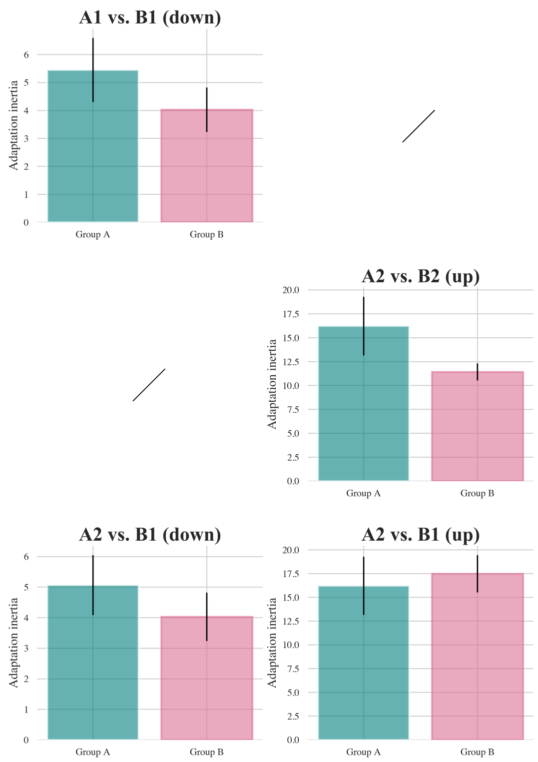


Table 5. : Results of the significance tests (t-test) of the adaptation inertia.

	p - Down	*p - Up*
A1 - B1	$t = 1.78$ $p = 0.17$	- -
A2 - B2	- -	$t = 1.72$ $p < 0.05$
A2 - B1	$t = 1.77$ $p = 0.22$	$t = 1.71$ $p = 0.31$

the adaptation exercises with fairly stable fluctuations, the drift tended to increase, whereas for group B, the coefficient changed during each session, and the proprioceptive drift was unstable. In the final part of the experiment, both groups tended to converge toward a specific drift value (approximately 6°) and the increment tended toward 0°.

The analyses of the t-test results did not reveal any significant difference between the first and second parts of the experiment (A1 versus B1, and A2 versus B2); therefore, the accumulation did not seem to influence the proprioceptive drift.

However, the t-tests revealed a significant difference between A2 and B1, underlining the idea that, under the same accumulation values, the drift differs according to the previous experience of the group members. In particular, it is worth noting that when starting A2, the members of group A went through seven sessions with infrequent changes, whereas when starting B1, the members of group B went through three sessions with frequent changes.

4.3. Results of Sense of Embodiment

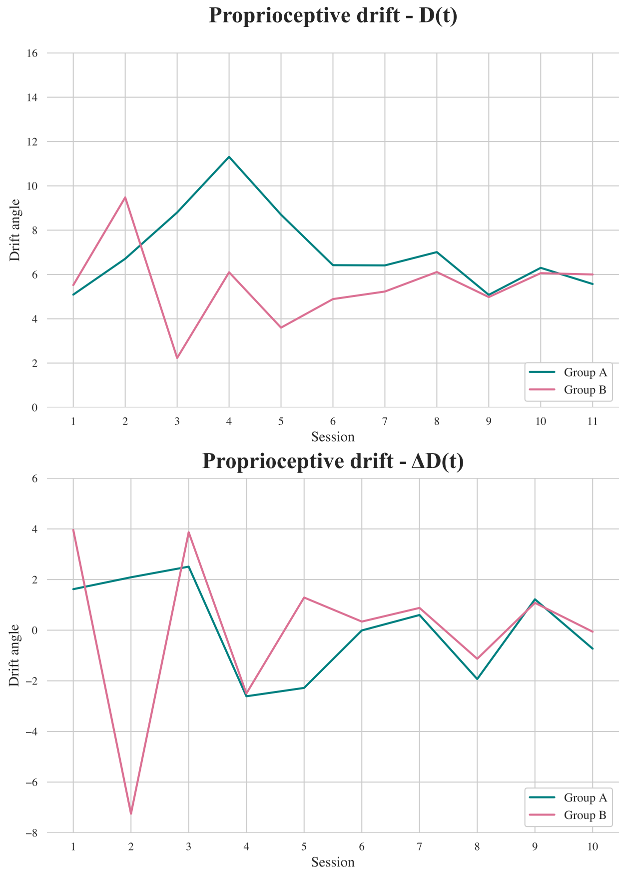
The responses to the questionnaire showed that, because the mean values of the components SoO, SoA, and SoL are all above zero, as shown in **Table 8**, a sense of embodiment occurred. We also provided the value of the overall SoE, calculated as shown in **Equation 9**, which is the mean value of the three components, and was therefore also above zero.

However, we could not find a significant difference in the responses of groups A and B regarding the single factors (SoO, SoA, and SoL). The results of the t-tests are presented in **Table 9**.

4.4. Report on the Experience

Figure 8 shows the overall ratings for each question related to the subjective perception of the user experience (see **Table 2** for the questionnaire). The results show a general appreciation of the experience (UX) in terms of immersion, enjoyment, and quality of the system. The tutorial was found to be useful and effective, as were the instructions given to allow the users to move through the experience (IGA). In addition, because low values are ideal

Fig. 7. : Proprioceptive drift $D(t)$ and increment of drift $\Delta D(t)$ during the different sessions divided by group.



in the present case, the ratings show that no symptoms or effects (VRISE) were reported. However, as underlined by Question 13 (or VRISE 4), some participants perceived fatigue at the end of the experiment.

5. Discussion and Conclusions

In the current study, we conducted an experiment to investigate the resistance of humans in adapting to altered self-avatar behaviors, formalized as the adaptation inertia, under specific circumstances. In particular, our goal was to understand whether adaptation inertia and proprioceptive drift are influenced by a high frequency of variations in the altered behaviors of a self-avatar. Regarding the sense of embodiment, we analyzed the main components, expecting to find positive values in congruence with the those of previous studies.

The analysis of the results suggests that the accumulation of changes in the coefficient influences the adaptation inertia, as described in section **4.1** (**Fig. 6** and **Table 5**). We can therefore state that hypothesis **H1** is supported in that the adaptation inertia changes according to aggressive changes in the behaviors of a self-avatar.

However, regarding the proprioceptive drift, the values

Table 6. : Results of the mean of the proprioceptive drift $D(t)$ and its increment $\Delta D(t)$ divided by group.

t (session)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
$D(t)A$	5.09	6.71	8.8	11.31	8.7	6.42	6.41	7.01	5.08	6.3	5.57
$\Delta D(t)A$	-	1.62	2.09	2.51	-2.61	-2.28	-0.01	0.6	-1.93	1.22	-0.73
$D(t)B$	5.52	9.48	2.23	6.1	3.6	4.89	5.23	6.11	4.98	6.06	6
$\Delta D(t)B$	-	3.96	-7.25	3.87	-2.5	1.29	0.34	0.88	-1.13	1.08	-0.06

Table 7. : Results of the significance tests (t-test) of the proprioceptive drift.

	p - Down	*p - Up*
A1 - B1	$t = 1.89$ $p = 0.07$	- -
A2 - B2	- -	$t = 1.76$ $p = 0.25$
A2 - B1	$t = 1.71$ $p < 0.01$	$t = 1.77$ $p = 0.36$

Table 8. : Results of SoE components.

SoO	SoA	SoL	SoE
$\mu = 0.32$ $\sigma = 1.79$	$\mu = 0.90$ $\sigma = 1.85$	$\mu = 0.63$ $\sigma = 1.92$	$\mu = 0.61$ -

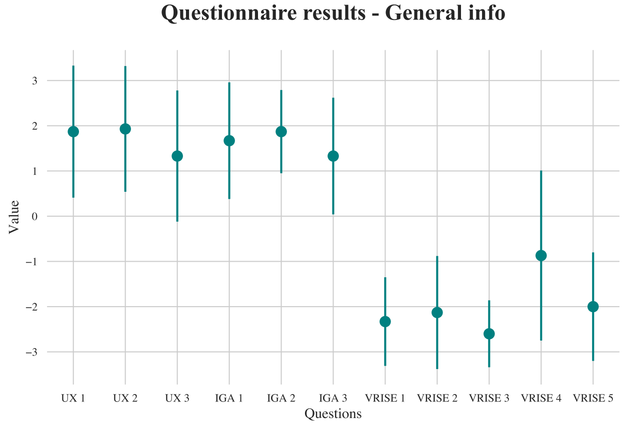
reported in section **4.2** (**Fig. 7** and **Table 7**), suggest that the proprioceptive drift is not influenced by changes in the self-avatar behavior, and thus **H2** is not supported. Nevertheless, we found that the same adaptation parameters lead to a significantly higher value of drift (reported in **Table 7**, A2-B1, p-Down) when the users went through a series of infrequent changes. Therefore, the proprioceptive drift seems to be influenced more by the previous experience of the users and their time spent during the experiment.

The results of a questionnaire also underlined how the

Table 9. : Results of the significance tests (t-test) of SoO, SoA, and SoL between the two groups, A and B.

	SoO	SoA	SoL
A vs. B	$t = 2.02$ $p = 0.21$	$t = 2.13$ $p = 0.35$	$t = 2.92$ $p = 0.31$

Fig. 8. : Mean values of the responses related to the experience. Each column represents one statement related to the user experience (UX), in-game assistance (IGA), and VR induced symptoms and effects (VRISE), as proposed in the questionnaire.



SoE persisted, despite the introduction of alterations in the movements of the self-avatar, as shown in section **4.3** (**Tables 8 and 9**). We can therefore state that **H3** is supported.

The results of the questionnaire showed an overall appreciation of the VR experience, as reported in section **4.4** and shown in **Fig. 8**.

The overall results suggest that it may be possible to push the adaptation inertia and thus enhance the effectiveness of the rehabilitation by controlling the frequency of changes in movement alterations of the self-avatar.

Despite these positive findings, a few improvements can be made to certain characteristics of the present study. First, the number of participants (15) was limited from a statistical perspective. Second, to better understand how the adaptation inertia and proprioceptive drift both vary, each participant should experience both conditions (groups A and B). Third, the overall data analysis can be improved by considering additional factors such as the learning effect. It would be interesting to add a set of user studies, crossing the subjective and objective data to better understand which subjective traits correlate with specific kinetic behaviors. The refined analysis will open new opportunities to define an optimized series of values of the coefficient to minimize the adaptation inertia and drive the movements of the physical body according to its specific capabilities and reactions. This will lead to defined personalized models of proprioception and adaptability, and therefore provide a basis for personalized rehabilitation strategies.

The importance of the present study lies in its insight into human behavior during alterations of a self-avatar under a specific case that, to the best of the authors' knowledge, has yet to be investigated. As mentioned in the **Introduction**, this case of hyper-adaptability can be applied to the use of prosthetic limbs. Although the current study involved healthy subjects, we are willing to test the protocol on individuals whose limbs have been amputated, with the goal of providing a system that generates a set of induced movements in training the use of prosthetic devices. In addition, we are willing to test the principle in post-stroke patients having difficulties in conducting movements with their upper limbs, with an attempt to achieve movements that have thus far been lost. It is also important to emphasize that the use of VR in rehabilitation brings about a strong environmental advantage in terms of transportation costs or the use of materials during therapy.

Users seemed to learn about the relationship between the motion of their own hand and that of their virtual version. The importance of becoming accustomed to a virtual body goes beyond the habit of using a device to interact with certain technology, such as applying a mouse to move a cursor on a computer, because it opens up a series of opportunities through new embodied experiences. Furthermore, recent commercial trends related to the metaverse promise the widespread use of self-avatars in everyday life. Under this futuristic scenario, it will be important to know what happens to the human body while an embodied self-avatar is active in a virtual environment. A rapid lifestyle, together with a greedy use of technology, requires knowledge of the frequent changes occurring through a new embodiment and the immersive concept of the Internet, which involves the physical body itself.

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References:

[1] Sotaro Shimada, Kensuke Fukuda, and Kazuo Hiraki. Rubber hand illusion under delayed visual feedback. *PLoS ONE*, 4(7):e6185, July 2009. DOI:10.1371/journal.pone.0006185.

[2] Matthew Botvinick and Jonathan Cohen. Rubber hands 'feel' touch that eyes see. *Nature*, 391(6669):756–756, February 1998. DOI:10.1038/35784.

[3] Donna M. Lloyd. Spatial limits on referred touch to an alien limb may reflect boundaries of visuo-tactile peripersonal space surrounding the hand. *Brain and Cognition*, 64(1):104–109, June 2007. DOI:10.1016/j.bandc.2006.09.013.

[4] Mel Slater, Bernhard Spanlang, Maria V. Sanchez-Vives, and Olaf Blanke. First person experience of body transfer in virtual reality. *PLoS ONE*, 5(5):e10564, May 2010. DOI:10.1371/journal.pone.0010564.

[5] Jean-Marie Normand, Elias Giannopoulos, Bernhard Spanlang, and Mel Slater. Multisensory stimulation can induce an illusion of larger belly size in immersive virtual reality. *PLoS ONE*, 6(1):e16128, January 2011. DOI:10.1371/journal.pone.0016128.

[6] Konstantina Kilteni, Antonella Maselli, Konrad P. Kording, and Mel Slater. Over my fake body: body ownership illusions for studying the multisensory basis of own-body perception. *Frontiers in Human Neuroscience*, 9, March 2015. DOI:10.3389/fnhum.2015.00141.

[7] Tabitha C. Peck, Sofia Seinfeld, Salvatore M. Aglioti, and Mel Slater. Putting yourself in the skin of a black avatar reduces implicit racial bias. *Consciousness and Cognition*, 22(3):779–787, September 2013. DOI:10.1016/j.concog.2013.04.016.

[8] Yasuyuki Inoue and Michiteru Kitazaki. Virtual mirror and beyond: The psychological basis for avatar embodiment via a mirror. *Journal of Robotics and Mechatronics*, 33(5):1004–1012, 2021. DOI:10.20965/jrm.2021.p1004.

[9] Harry Eberle, Yoshikatsu Hayashi, Ryo Kurazume, Tomohiko Takei, and Qi An. Modeling of hyper-adaptability: from motor coordination to rehabilitation. *Advanced Robotics*, 35(13-14):802–817, June 2021. DOI:10.1080/01691864.2021.1943710.

[10] Agata Marta Soccini and Federica Cena. The ethics of rehabilitation in virtual reality: the role of self-avatars and deep learning. In *2021 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*, pages 324–328, 2021. DOI:10.1109/AIVR52153.2021.00068.

[11] Agata Marta Soccini, Francesca Ferroni, and Martina Ardizzi. From virtual reality to neuroscience and back: a use case on peripersonal hand space plasticity. In *2020 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*. IEEE, December 2020. DOI:10.1109/aivr50618.2020.00082.

[12] Konstantina Kilteni, Raphaela Groten, and Mel Slater. The sense of embodiment in virtual reality. *Presence: Teleoperators and Virtual Environments*, 21(4):373–387, November 2012. DOI:10.1162/pres_a_00124.

[13] Mark R. Mine, Frederick P. Brooks, and Carlo H. Sequin. Moving objects in space. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques - SIGGRAPH '97*. ACM Press, 1997. DOI:10.1145/258734.258747.

[14] Irene Valori, Phoebe E. McKenna-Plumley, Rena Bayramova, Claudio Zandonella Callegher, Gianmarco Altoè, and Teresa Farroni. Proprioceptive accuracy in immersive virtual reality: A developmental perspective. *PLOS ONE*, 15(1):e0222253, January 2020. DOI:10.1371/journal.pone.0222253.

[15] Mar Gonzalez-Franco, Brian Cohn, Eyal Ofek, Dalila Burin, and Antonella Maselli. The self-avatar follower effect in virtual reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, March 2020. DOI:10.1109/vr46266.2020.00019.

[16] Martin Riemer, Jörg Trojan, Marta Beauchamp, and Xaver Fuchs. The rubber hand universe: On the impact of methodological differences in the rubber hand illusion. *Neuroscience & Biobehavioral Reviews*, 104:268–280, September 2019. DOI:10.1016/j.neubiorev.2019.07.008.

[17] Tetsunari Inamura, Satoshi Unenaka, Satoshi Shibuya, Yukari Ohki, Yutaka Oouchida, and Shin ichi Izumi. Development of VR platform for cloud-based neurorehabilitation and its application to research on sense of agency and ownership. *Advanced Robotics*, 31(1-2):97–106, December 2016. DOI:10.1080/01691864.2016.1264885.

[18] Agata Marta Soccini, Marco Grangetto, Tetsunari Inamura, and Sotaro Shimada. Virtual hand illusion: The alien finger motion experiment. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, March 2019. DOI:10.1109/vr.2019.8798193.

[19] Agata Marta Soccini. The induced finger movements effect. In *SIGGRAPH Asia 2020 Posters*. ACM, December 2020. DOI:10.1145/3415264.3425448.

[20] Panagiotis Kourtesis, Simona Collina, Leonidas A. A. Doumas, and Sarah E. MacPherson. Validation of the virtual reality neuroscience questionnaire: Maximum duration of immersive virtual reality sessions without the presence of pertinent adverse symptomatology. *Frontiers in Human Neuroscience*, 13, November 2019. DOI:10.3389/fnhum.2019.00417.

[21] Andreas Kalckert and H. Henrik Ehrsson. Moving a rubber hand that feels like your own: A dissociation of ownership and agency. *Frontiers in Human Neuroscience*, 6, 2012. DOI:10.3389/fnhum.2012.00040.

[22] Mar Gonzalez-Franco and Tabitha C. Peck. Avatar embodiment. towards a standardized questionnaire. *Frontiers in Robotics and AI*, 5, June 2018. DOI:10.3389/frobt.2018.00074.

Name:
Agata Marta Soccini

Affiliation:
University of Torino,
Computer Science Department

Address:
Corso Svizzera 186, Torino, Italy

Brief Biographical History:
2022 Assistant Professor and Head of the Virtual Reality Lab - Computer Science Department, University of Torino, Italy
2019 PhD in Computer Science

Main Works:
- The Ethics of Rehabilitation in Virtual Reality: The Role of Self-Avatars and Deep Learning, Soccini, A.M., Cena, F., 4th IEEE International Conference on Artificial Intelligence and Virtual Reality, AIVR 2021
- The Induced Finger Movements Effect, Soccini, A.M., SIGGRAPH Asia 2020
- Virtual hand illusion: The alien finger motion experiment Soccini, A.M., Grangetto, M., Inamura, T., Shimada, S., IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2019

Name:
Alessandro Clocchiatti

Affiliation:
University of Torino,
Computer Science Department

Address:
Corso Svizzera 186, Torino, Italy

Brief Biographical History:
2022 Research Fellow, Virtual Reality Lab, University of Torino
2022 MSc in Computer Science, Virtual Reality

Name:
Tetsunari Inamura

Affiliation:
National Institute of Informatics / The Graduate University for Advanced Studies, SOKENDAI

Address:
2-1-2, Hitotsubashi, Chiyoda-ku, Tokyo, Japan

Brief Biographical History:
2000 Project Researcher, Japan Science and Technology Agency, Japan
2003 Lecturer, Graduate School of Information Science and Technology, The University of Tokyo, Japan
2006 Associate Professor, National Institute of Informatics, Japan
2006 Associate Professor, The Graduate University for Advanced Studies, SOKENDAI, Japan

Main Works:
- SIGVerse: A Cloud-Based VR Platform for Research on Multimodal Human-Robot Interaction Tetsunari Inamura, Yoshiaki Mizuchi, Frontiers in Robotics and AI, 8, 2021.
- VR platform enabling crowdsourcing of embodied HRI experiments – case study of online robot competition, Tetsunari Inamura, Yoshiaki Mizuchi, Hiroki Yamada, Advanced Robotics, 35(11), pp.697-703, 2021.
- Survey on Frontiers of Language and Robotics, T. Tangiuchi, D. Mochihashi, T. Nagai, S. Uchida, N. Inoue, I. Kobayashi, T. Nakamura, Y. Hagiwara, N. Iwahashi, T. Inamura, Advanced Robotics, 33(15-16), pp.700-730, 2019.

Membership in Academic Societies:
- Institute of Electrical and Electronics Engineers (IEEE)
- Association for Computing Machinery (ACM)
- The Robotics Society of Japan (RSJ)
- Japanese Society for Artificial Intelligence (JSAI)
- The Virtual Reality Society of Japan (VRSJ)