The Self-Avatar Follower Effect in Virtual Reality

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ABSTRACT

When embodying a virtual avatar in immersive VR applications where body tracking is enabled, users typically are and feel in control the avatar movements. However, there are situations in which the technology could be tweaked to flip this relationship so that an embodied avatar could affect the user's motor behavior without users noticing it. This has been shown in action retargeting applications and motor contagion experiments. Here we discuss a different way in which an embodied avatar could implicitly drive users movements: the self-avatar follower effect. We review previous evidences and present new experimental results showing how, whenever the virtual body does not overlay with their physical body, users tend to unconsciously follow their avatar, filling the gap if the system allows for it. We discuss this effect in the context of the relevant neuroscientific literature, and propose a theoretical account of the follower effect at the intersection of motor control and inference theories.

Index Terms: Human-centered computing—Virtual reality—;——Embodiment—Perception—Motor control

1 INTRODUCTION

Virtual Reality (VR) technology supports the possibility of embodying a virtual avatar seen from a first person perspective [35, 78]. Users perceive their body as substituted by a virtual avatar [77], with remarkable on-line adaptation of their body image and schema to that of the avatars [24, 60, 85]. These avatars can be of various and different bodily shapes [37, 54], sizes [2], ages [7], races [59] or gender [73].

Extensive research in the field of cognitive and perceptual neuroscience converged on the view that the illusory experience of embodiment over a fake body, e.g. a virtual avatar, is rooted in the multisensory correlations of stimuli streaming from the two bodies, the real and the fake. This phenomenon was first exemplified in the rubber hand illusion (RHI) where visuo-tactile stimulation generated ownership over a fake hand situated in front of participants [9].

A general explanation of the illusion is that when visual information from the virtual body is congruent –within a given range of accuracy– with that experienced through the physical body by proprioception, touch and kinestesis, the brain attributes all the available information about the body to a common cause, which is the self-body [36]. In this way, the seen virtual body is processed and interpreted as the same body from which somatosensansations arise, resulting in the embodiment of the virtual avatar.

Numerous studies and applications have shown VR embodiment to be easy to trigger and extremely robust. The embodiment illusion is so strong that it can be produced even on static avatars when a high degree of spatial matching between the virtual and the physical body is given [26, 46], and also on bodies that are mostly invisible, but for the hands and feet, when the latter are seen to move in synch with the movements performed by users [40, 42, 75]. While static visuo-proprioceptive congruent cues – as in the case of an avatar overlapping with the user body – can be sufficient to trigger the embodiment illusions [46], congruent dynamic visuo-haptic [39, 76], and visuo-motor cues –as in the case of an avatar replicating the tracked movements of the users in real-time– are much stronger triggers [27, 36, 38]. In this case, as illusory embodiment is triggered and supported by visuo-motor correlations, some degree of spatial misalignment and temporal lag can be tolerated without breaking the illusion [27, 77, 81].

Embodiment illusions have been shown to be crucial to users experience in immersive virtual reality. When interacting in immersive VR scenarios, having a virtual body was shown to significantly decrease cognitive load and improve performance in motor and cognitive tasks with respect to [56, 57, 79]. Furthermore, researchers have shown how being embodied in virtual avatars could dramatic implications at the psychological, cognitive and perceptual levels, with plenty of interesting applications in therapy [44, 48, 51, 67], rehabilitation [13, 53], learning and recreation [28, 50, 58].

In the present work we are particularly interested on the impact that avatar embodiment may have on motor behavior, which has been observed in different forms. Motor behavior can be significantly affected by the appearance of the embodied virtual avatar depending on its semantic and socio-cultural value. For example, in drumming task experiment, participants embodying a self-avatar dressed in a business suit exhibited less engagement in a musical drumming task (more rigid and less complex movements) with respect to participants embodying a casual avatar [34]. Participants might undergo this behavioural adaptations so to better fit socially in a very stereotypical and mimicry approach [24].

Motor behavior can be also affected when the tracked users' movements are not exactly reproduced on the avatar, but are coded to spatially or temporally deviate from performed actions. For example, in a VR experiment where participants were asked to draw lines while their embodied avatar was programmed to synchronously perform circular movements, their actual performance was distorted as they started to drawing ellipses instead of lines [10]. Interestingly, in the drawing study, participants remained unaware of the deviations in the performed motion, as they report to keep drawing lines and not ellipses. Similarly, in applications of haptic retargeting, goal-directed actions in VR are effectively redirected to a different end-location, without users noticing it, by introducing ad-hoc deviations in the avatar movement [6, 14].

Users motor behavior can also be affected by slowing down the avatar movement with respect to the tracked users movements. In this case, participants tend to unconsciously slow down to keep

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"attached" to their self-avatar [65]. This form of fit-into-the-avatar behavior is consistent with a curious trend recurrently observed and anecdotally reported from a number of VR experiments setups. When participants are fitted with an HMD showing a static avatar from a first person perspective, they tend to quickly adapt to the avatar posture moving their limbs and body so to be aligned with the virtual body. This effect has been reported mostly when participants are seated and the avatar is shown in a similar but not exactly fitting position, **and is consistent with formal results from an experiment in which the classical RHI setup was adapted to have participants laying their occluded hand on a moving slider instead than resting on a fixed table [4]. The study showed that, when experiencing the illusion (i.e., when receiving synchronous visuo-tactile stimuliation), participants, even if instructed to rest their arm and not move, unconsciously drifted their hand towards the rubber hand when the slider was unlocked, or applied a force in the direction of the RHI if the slider was locked.** In the present study we explored more in detail this form of motor behavior in immersive VR, which we coin as the self-avatar follower effect. We hypothesize that the self-avatar follower effect is driven by an implicit need to fill the spatial gap between the physical and the self-avatar bodies, whenever the system allows for these types of compensation.

To better document and understand the self-avatar effect, we conducted an experimental study to explore whether and how the effect extends to different situations in which the users movements are tracked and can be used to control the avatar. To do so we implement a system that is able to alter the general idea of one-to-one mapping. The user movements could indeed be mapped so to control a lower number of degrees of freedom in the avatar body. For example the extension of the avatar arm along a fixed direction could be controlled by extending the real arm independently on the arm lateral and dorsal elevation. In this case, there may be a spatial mismatch between the two arms and users would be free to compensate for such mismatch even if this is not demanded by the task (Figure 1).

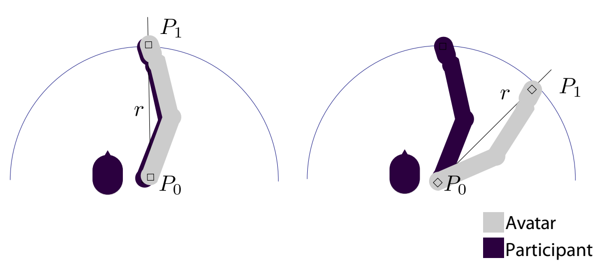

Figure 1: On the left the avatar is controlled via a one-to-one mapping. On the right, the avatar hand is re projected to a particular axis while the person can freely move on other directions.

We tested participants in a various mapping configurations and measured the extent to which they spontaneously compensate for spatial offsets introduced either gradually or instantaneously. This compensation would be due to a follower effect. In discussing the results we propose a theoretical account for the self-avatar effect, inspired to established cognitive and neuroscientific theoretical framework.

2 Related Work

2.1 Models of embodiment

Several theoretical frameworks have been proposed to describe and explain illusory embodiment. Most them derives from equivalent formularizations developed to explain the original findings of the Rubber Hand illusion (RHI) [9].

Since the first report of the RHI, the experience of embodying an external object as part of the own body, has been explained as the result of multisensory integration processes, whereby different sensory cues informing the brain about the body state are merged into a single percept [9]. The modulation of top-down cognitive factors, accounting for the need for the external objects to satisfy minimal anatomical constraints for the embodiment to occur has been further introduced in the earlier theoretical frameworks [46, 82].

Complementary theoretical frameworks have instead emphasized the role of agency, and more specifically the of actions affordance of the external limbs in control of the users as key mechanisms for [5]. Still, experimental research supports evidence for embodiment being possible also over static bodies, mediated by the merging of visual and proprioceptive bodily cues [46].

Computational models have also been proposed, which are inspired to hierarchical generative models of perception and action [17, 63]. These models are based on the main concept that the brain infers the hidden causes of sensory signals by minimizing the prediction error, i.e. the conflict between the predictions made by the adopted generative model of the environment (including the self) and the sensory evidence available. In this context the self-attribution of external object is explained as the result of minimizing the sensory conflicts arising when seeing a fake body replacing the physical body, even more in presence of congruent correspondences between vision, touch and movement [3, 43].

Causal inference models [41, 74] have been also proposed to explain body ownership illusions, which may be extended to embodiment in VR. Such models propose that the illusory sense of ownership emerges as the result of attributing all sensory information available about the body to a single common cause: the self-body [36, 71]. In these models, the seen virtual body is then processed as being the *same body* as the one streaming tactile, propioceptive and kinesthetic sensations. As a result the brain tends to respond to events seen on the body, such as attacks to the virtual body, as if they were to happen on the own physical body [26].

Previous work suggests that some of the effects associated with illusory ownership could indeed be resulting from prediction error minimization. For example, the reduction of tactile sensitivity [16, 88] observed during ownership illusions, have been interpreted as a strategy for minimizing sensory conflict. The diminishing accuracy of somato sensations would result in a reduction of the perceived discrepancies (e.g. in the location, or in the spatiotemporal attributes of visuo-tactile events) between the real and the fake bodies [3, 87]. Furthermore, causal inference models can account for the visuoproprioceptive binding (between real and virtual bodies) that have been observed during virtual embodiment [47], and the associated increased thresholds for unnoticed visuo-tactile asynchronies [45].

2.2 Visually guided motor behavior

2.2.1 The motor control loop

Standard theories of motor control hold that the enactment of a voluntary movement is based on a sensorimotor controlled loop [19, 23].

The voluntary movement is initially planned based on the current (initial) and the intended (final) state, and formulated as a specific sequence of motor commands. The motor commands are sent out to the motor system that through the muscles executes the action and changes the body configuration towards the intended state. As well-established in the motor control community, a copy of the same motor commands (efference copy) is used in parallel as an input for an internal model of the motor system (forward model) that predicts the new body configuration (predicted next state) and its associated sensory consequences [49].

The forward model can be regarded as a unit able to compute the impact of motor commands on the configuration of the skeleto-muscular system, together with the sensory consequences associated with the transformations into the new configuration. The predicted state is combined with the current state as informed via sensory (afferent) feedback into the perceived current state. Furthermore, the sensory feedback is combined with the predicted sensory consequences to return a prediction error which is continuously monitored to check for the corrections required to achieve the intended state.

The primary role of the forward model is therefore to predict the behavior of the body and its influence on the world. It has been shown that the forward model can account for a number of functional operations. Among others, it compensates the intrinsic delays of the sensorimotor system allowing for fast feedback control, it suppresses redundant sensory consequences of self-generated action, and supports long-term learning of motor skills as well as quick adaptation to external perturbations [84].

In the pervasive attempt of the brain to minimize prediction errors, during motor control the brain can adopt different strategies, depending on the nature of the motor task at hand and on the amount of error detected. For example, when performing pointing actions under the false visual feedback of a prism (Figure 2), the detected error is primarily associated with the systematic altered relationship between motor outputs and their corresponding visual feedback. In this case, it is well established that the strategy adopted to minimize the error consists in adapting to the new mapping, i.e. in updating the forward model so that the predicted state matches the altered visual feedback [21, 64].

These models have been also largely adopted to explain how the sense of agency over willed actions emerges, as well as to explain the mechanisms underlying delusions of control [12, 18].

Figure 2: Participant of the Insbruck Prism Goggle Experiments of Theodor Erismann and Ivo Kohler: "The world is upside down" , trying to reach for a cup of tea and compensating due to visual feedback [70].

To summarise, motor control theories holds that, when performing a willed action, we will try to minimize the error between the predicted consequences of the performed action, and its current sensory feedback (visual, proprioceptive or else). Given the fact that humans are very visual animals, compensations in the motor the motor control loop will work under visual guidance.

2.2.2 Motion Re-targeting

Since we want to achieve the motor intention, for example reaching for an object, we will compensate any action to match our intended state. And this has applications to implement movement retargeting for interacting and reaching for objects in a first person perspective. By displacing the virtual body while performing a reaching action, experimenters have shown that we can redirect the movement of the real body to specific locations [6, 14, 80], relying on the principles of sensorimotor control [23, 24, 83]. When the virtual effector, typically the hand, is deviated ad-hoc from the intended virtual target, a motor correction is implemented to compensate for the detected error.

This way researchers have shown we can redirect participants to specific physical props that provide users with fulfilling haptic experiences. When the retargeting is done for haptic purposes, it is generally referred to as haptic retargeting [6, 14]. This type of retargeting can also be used to reduce aliasing on shape displays [1], increase perceived weight [72] and even create illusions of movement on active haptics [42, 75].

Motion retargeting and the control models also enable some forms of redirectional walking for locomotion inside Virtual Environments. Using re-directional walking, users can walk much larger environments in a small real space [52], mainly through scale changes [2, 32], or by bending the actual path of users [80].

2.2.3 Motor contagion

Motor contagion has a biological foundation. Contagion is mostly an involuntary behaviour, e.g. when someone yawns you yawn [61]. Motor contagion has strong neuropsychological basis: simply observing or even imagining a goal-directed action activates its corespondent motor program. A specific network of neurons called "mirror system" show indeed such behavior, as described in studies with monkeys [68] and humans [15, 33].

Motor contagion might facilitate learning, as well as communication and interaction [20]. It is thought to support the acquisition of new motor skills [22], and to the understanding of actions intentions and underlying goals [8].

Motor contagion is also effective when embodying and avatar that is programmed to perform distorted actions with respect to those performed by the user, as shown in the VR drawing experiment described in the Introduction [10]. Importantly, the drawing study clearly showed how the effects of motor contagion are stronger during embodiment with respect to when the distorted motion is attributed to a different agent.

The perceived mismatch between intended and seen movements are considered differently according to the level of body ownership attributed to the agent (my body versus other bodies); errors produced by the own body (or avatar, as in this case) are treated as more relevant and activate compensatory systems in the motor control model, so they are more susceptible to interferences or motor contagion effects [10, 11].

2.2.4 Mimicry

Although motor contagion and mimicry result in a similar outcome (i.e., my movements and behaviour are affected completely or partially by someone else's actions) mimicry seems to have a stronger social and cultural meaning.

Mimicry appears, typically, during human interactions to reduce social exclusion and adapt to stereotypes. People tend to automatically mimic their partners during social interactions with body postures, gestures and facial expressions, more so if the partners is an in-group member [86]. In fact, mimicry might be an important factor for social exclusion/inclusion, so that it can automatically alter psychological and behavioral functions in order to fit in the social context [29].

Mimicry and its implications have been shown to apply also in VR settings. In a virtual environment, the avatar's body may assume somatic features different from the real one, e.g. the subject might have a white skin but the self avatar can have a black skin; in this context of mismatch and during a virtual interaction with both, a white-skin and black-skin avatar, the subject tends to mimic more the avatar that represents the in-group of the self-avatar, not participants' actual racial group (i.e., white subjects embodying a black avatar mimic more the black rather than the white virtual partner) [30]. These results prove once again that self-avatar embodiment is quite effective independently from somatic features, and mainly that this embodiment in such condition of mismatch can have motor effects (i.e., mimicry) with social consequences (i.e., empathy) [31].

3 Experiment

We propose an experiment to better understand and demonstrate the follower effect, by which if participants have the possibility to compensate a spatial offset with their embodied avatar, they will act to reduce the offset.

3.1 Protocol

We create an experiment in which we ask participants to reach forward while experiencing avatar embodiment with inverse kinematics. In each trial participants reach from a point near the body (P0) and a point away from the body (P1) (Figures 1 and 3).

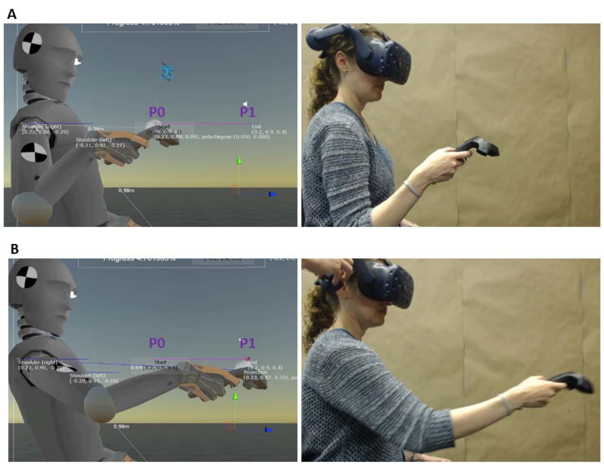

Figure 3: Reaching task performed by participants. A) represents the P0 point near the body, and B) represents the P1 point far from the body. Here we can see a participant performing the reaching task between P0 and P1 and the avatar matching in the straight reach. Reaches were performed in quick succession of one another (μ =1.1s, sd =0.19)

After two trials the avatar hand gets snapped to a predefined trajectory between P0 and P1. This means that if participants were willing to move away of their avatar they could perfectly do so and still be performing the reaching task between the two targets. To produce the snapping effectively the x,y,z position of the participants is re-projected to a point in the predefined trajectory to which the avatar hand is snapped. Using such projection let's user's physical arm sway away or get closer to the virtual avatar without any visual cost towards the task performed.

Hence agency is not broken in this snapping while users are directed only to do a 1D motion, so that their motions correspond directly to those of the dislocated avatar, and participants are still in full control of the avatar motion as well as perform their task between the two points. However propioception is dissociated with this snapping. Such so that participants can continue their reach forward task while the avatar moves or drifts from their propioceptive match.

We then implement an effect in which the avatar hand drifts up to 30 degrees towards the outward side. We perform the movement either gradually or instantaneously.

In an additional condition, we do not introduce any drift, and the virtual hand continues to move in the straight direction the same as the participant.

The gradual onset consists of directing the avatar towards the 30 degree target by a fixed amount over each motor interaction. In the instantaneous condition the avatar moves directly to the final spot. The instantaneous condition is designed to be much more disrupting of the embodiment illusion.

3.2 Participants

21 participants (8F, 13M) between the ages of 18-65 ($\mu = 29$) participated in our experiment—wearing an HTC Vive Pro, with a series of conditions proctored through a Unity environment (tracking at 90Hz).

The reaching task consisted on 16 reaches from P_0 to P_1. The reaching task was repeated 6 times for each of the gradual, instantaneous, and no-drift conditions. The order of conditions and repetitions were block-randomized, totalling 18 blocks (completed in about 20m).

3.3 Embodiment Questionnaire

After every completed task, participants evaluated their sense of embodiment in the avatar with one of the following questions extracted from [25]:

1. "I felt embodied in the avatar during the reaching task."
2. "I felt like I had two bodies during the reaching task."
3. "I felt satisfied with the interaction during the reaching task."

Participants would respond on a Likert-scale from strongly disagree(-3) to strongly agree (+3). We aggregate them as $Embodiment = Q1 - Q2 + Q3$, and then perform a z-score normalization to get the dynamic range and normalize the intra-subject variability.

3.4 Results

In order to see whether participants try to follow and match the virtual avatar during the different conditions we calculated the drift as the angular distance between the avatar hand and the participant hand. The angle was centered at the shoulder of the participants.

We found significant effect of on the condition, i.e. a difference in the horizontal **drift** between gradual ($\mu = 0.2°, sd = 7.9°$) an instantaneous onset ($\mu = -6.9°, sd = 9.2°$) (Welch Two Sample t-test $t = 2.7, df = 39.16, p = 0.009$), where a negative drift means the real hand did not completely follow the projection all the way to the 30 degrees. Results indeed show that participants followed the avatar to a larger extent when the Side-directed projection is introduced gradually, rather than instantaneously (Figure 4).

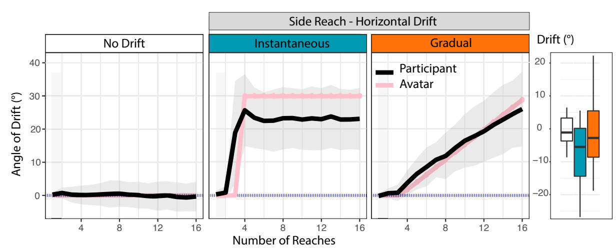

Figure 4: Grand averaged drift across participants in the **No-Drift**, **Instantaneous** and **Gradual** condition.

Participants reported higher embodiment when they underwent a gradual onset projection than with an instantaneous onset (Figure 6). Wilcoxon signed rank test revealed a significant difference between No Drift condition, and Drift conditions in terms of embodiment (for both instantaneous or gradual p= 0.0002). Whereas embodiment for participants during instantaneous drift was significantly lower than in the gradual condition (p = 0.02).

By design, the instantaneous jump of the arm is very unnatural motion that the user can not physically do. It is very obvious that the result is a drop of embodiment. However right after the jump,

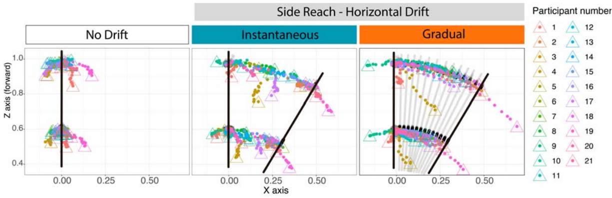

Figure 5: Overhead view of reaching results: with each participant a different color, here we can see an overhead view of how reaching is affected by the **No-Drift**, **Instantaneous** and **Gradual** conditions. The lower and upper clusters for each condition are the hand positions during the P_0 and P_1 targets, respectively. The follower effect of the avatar (horizontal match) was higher in the gradual condition than in the instantaneous. The final drifted location of the participant on their last reach of the condition is shown as a triangle. Reach distances were scale-normalized to the mean of 0.65m so distances are comparable across differing anatomies.

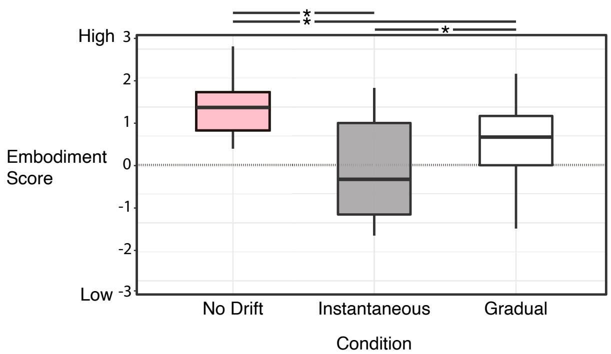

Figure 6: The embodiment illusion was significantly higher when the movement projection was introduced gradually than when the projection was instantaneous.

the similarity of the 1D motion, starts build the embodiment back. This is in agreement with previous findings on semantic violations of movements [55].

4 Discussion

Our experiment presents an example of the power of the follower effect, showing how when a spatial offset is introduced between the real and the virtual body, and the system allows for compensations, participants automatically act to reduce the spatial offset. Results are shown for the specific case of an arm reaching task, but we expect it to apply alike in other type of motor actions on the basis if the theoretical account proposed for the effect.

In our experiment agency was maintained throughout the VR experiments, as the spatio-temporal congruence of visual and motor information was always preserved a part for the spatial offset introduced by projecting the hand movement on a different direction. The associated sense of agency over the avatar movements therefore assured to maintain participants embodied, although with different degree of illusory ownership.

Results show that when participants have the possibility to do so, they adjust their position to reduce the spatial offset between their real arm and the one of the avatar. Furthermore we find that the extent to which participants follow their self-avatar depends on whether the spatial offset is introduced gradually or not. In the case of instantaneous drift the follower effects is reduced.

Our results suggest that the follower effect is a byproduct of embodiment and, as such, its strength is modulated by the degree of embodiment: the higher the embodiment the stronger the need to fit into the self-avatar. Self report about the sense of embodiment further support this account.

The proposed account is consistent with well-established theoretical accounts of ownership and embodiment illusions. The first-person perspective over the virtual avatar, partially collocated with the participants physical body, plus the sensorimotor temporal alignment of the performed and observed reaching actions induce a strong sense of ownership and agency [5, 36, 46], therefore establishing embodiment [35]. In turn, illusory ownership establishes a causal binding of visual and proprioceptive cues between the virtual and the real body [46]. Previous experimental work has indeed shown that when an embodied virtual body is seen to move into a new posture, while participants are forced to stay still, the body posture as perceived through proprioception only is recoded in the same direction of the observed movement [47].

Given the visuoproprioceptive binding established during embodiment, the follower effect can be explained as a part of an internal conflict minimization strategy, in line with current predicitive coding accounts of body ownership illusions [3, 43, 87].

Along these lines, the self-avatar follower effect could be seen as an active strategy to minimize the visuo-proprioceptive conflict arising from the spatial mismatch between the real and the virtual body. It is not a compensation in the motor control loop, but rather an internal mechanism that is rooted in the multisensory processing underlying body ownership illusions.

4.1 Breaking the Follower Effect

In essence, when participants are allowed to move, they actively compensate the spatial mismatch by moving the physical body to fit the virtual body location whenever the system allows for it. I.e., when there is a constant offset between the real body and the virtual body that cannot be overcome by the follower effect, then participants will not be able to compensate and will reduce their embodiment.

If embodiment is reduced so will be the follower effect. In our experiment we observe this dependency on embodiment through the instantaneous condition vs. the gradual condition. In line with computational models of the ownership illusions [36, 71], in the instantaneous condition participants lower their embodiment, as a sudden sensory conflict is introduced. Still, because of the synchronized motion embodiment is preserved and regain after the disruption to some extent, as shown by subjective ratings to the embodiment questionnaire. In this case, the follower effect might work only partially as a result of the reduction of visuo-proprioceptive coupling associated with a dampening of the illusion.

Accordingly, we expect that in those occasions in which embodiment is disrupted by drastic changes and errors on the avatar motions (as in the case of movement semantic violations [55]), the follower effect won't apply.

A complementary effect that may further contribute to the only partial follower effect observed in the instantaneous condition, could be habituation to a constant offset. As participants quickly compensate the large offset suddenly introduced, they may reach a configuration in which they actually feel aligned with the avatar. This may indeed explain the observed quick adaption to a plateau that only partially compensates the spatial offset.

4.2 Instantaneous versus Gradual

There is a major difference in our brain on how we interpret changes in gradient or 'AC', versus 'DC' offsets. The difference between the gradual motor displacement and the jump shows that the follower effect is very visually driven, but also the fact that the instantaneous drift also elicited a certain level of following, is the proof that the the follower effect also has a propioceptive component.

Motor control is generally governed by the derivative of the stimuli [19, 23]. When the change is gradual, our mind sees the changes of the hand and expects the real hand to move in a similar way (and feels the corresponding accelerations), very visually driven, and indeed we see that the participants follows such gradual motion correctly.

When there is a sharp change, we first feel that something is wrong – we see that the participants try to correct the angle toward the virtual hand, yet they do not completely reach it. This maybe due to the resolution' of proprioception – when the angular difference is smaller than than this 10° angle we feel 'OK'. Nevertheless as they continue doing the task the gradient part of the brain control takes over and they gain again embodiment. This effect was also found in experiments producing full body semantic violations [55].

Furthermore, we can see that there is not enough to have a difference between the avatar and the body to generate a full convergence of the body to the avatar, as can be seen by inserting an instantaneous difference between the two. Although participants moved to lower the difference, they did not reach the virtual avatar fully and maintained a 10° significant static difference. On the other hand, when a constant gradual motion is applied, participant managed to keep a much smaller distance to the avatar, although the difference was much smaller than the static difference. One possible explanation for this observation may be an existence of two control processes - a main one is mostly sensitive to motion and differences (as very common in many cognitive processes) and another coarser one that compares absolute values.

4.3 Follower effect versus Motion Retargeting

While motion retargeting provides a very clear example of how a VR user's motor behavior can be implicitly controlled ad-hoc, it relies on different mechanisms w.r.t. those from which the follower effect emerge. In fact, the explicit goal of a reaching task, i.e. getting to the target, overrides the need to be aligned with the self-avatar. Indeed, in this case it is the minimization of the error detected in the motor control loop that drives the action, not the minimization of sensory conflict arising from illusory embodiment.

Importantly, in most cases compensation in motion retargeting occurs with no impact on the illusion of embodiment. This provides further evidence on the flexibility of embodiment in VR, showing how the spatio-temporal constraints on the sensory conflicts that users can sustain is modulated by the context and the task.

4.4 Follower effect versus Mimicry

The follower effect can also be considered a subclass of mimicry behavior, which has long been described outside of the embodiment of avatars as the natural tendency that humans have to follow others. This happens in real life, in what has been known as mimicry [62]. The effects of which can affect from economic behaviour to sociological or political inclinations and blog comments. But this effect also happens in VR and in crowd simulations where people will tend to follow where other avatars go [66] or get affected by bystanders [69].

However, the embodied follower effect, here described, is different in that is not affected by what others do, but by what one self does. In that regard it could be considered a subset of herding but also an independent effect. Suppose the user stands among avatars of other users - Due to herding it will mimic their behaviors. What if the user own avatar starts stray in a different motions - will the user follow her avatar or mimic the population?.

This proves once again how the bodily self is a key component of motor control theories. Anyhow, herding provides more evidence of how malleable our behaviour is.

5 Conclusion

Here we have presented new evidence for the self-avatar follower effect, and proposed a new theoretical account rooted on causal inference and predictive coding models of embodiment.

Results from our experiment show that, when allowed to do so, participants will accommodate their own body positioning to match that of the avatar they are embodying. If an offset is introduced participants will have the tendency to reduce it. Results further show how the "magnetic effect" of an avatar is modulated by the level of the illusory experience of being embodied in it.

In our theoretical account we propose that the follower effect emerges as a consequence of the visuo-proprioceptive coupling established between the physical and the virtual body during embodiment, and it is drived by the intrisic need of the brain to minimize sensory conflict. Because the seen virtual body and the physical body experienced through somato-sensations are interpreted as the *same* body, any spatial conflict between that two will be compensated.

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