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To Stick or Not to Stick? Studying the Impact of Offset Recovery Techniques During Mid-Air Interactions

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Abstract—During mid-air interactions, common approaches (such as the god-object method) typically rely on visually constraining the user's avatar to avoid visual interpenetrations with the virtual environment in the absence of kinesthetic feedback. This paper explores two methods which influence how the position mismatch (positional offset) between users' real and virtual hands is recovered when releasing the contact with virtual objects. The first method (sticky) constrains the user's virtual hand until the mismatch is recovered, while the second method (unsticky) employs an adaptive offset recovery method. In the first study, we explored the effect of positional offset and of motion alteration on users' behavioral adjustments and users' perception. In a second study, we evaluated variations in the sense of embodiment and the preference between the two control laws. Overall, both methods presented similar results in terms of performance and accuracy, yet, positional offsets strongly impacted motion profiles and users' performance. Both methods also resulted in comparable levels of embodiment. Finally, participants usually expressed strong preferences toward one of the two methods, but these choices were individual-specific and did not appear to be correlated solely with characteristics external to the individuals. Taken together, these results highlight the relevance of exploring the customization of motion control algorithms for avatars.

Index Terms—Offset Recovery, Hand Interactions, Sticky

1 Introduction

Due of the large range of interactions humans can perform, and the technical limitations of current VR systems, novel interaction methods are required to improve user abilities in such applications. A number of approaches have therefore been proposed, such as haptic retargeting to give users haptic feedback using a prop [1], methods for precise positioning [2], or redirected walking techniques for walking through large-scale VEs while physically remaining in a smaller workspace [3]. More recently, there has also been a rising interest in the community in exploring these interaction techniques in relation to the users' representation (i.e. their avatar) [4], as users are becoming increasingly demanding in terms of realism, naturalness, and coherence between their real and virtual behaviors [5].

Among the factors that can influence the overall user experience, spatial and temporal synchronization between the avatar and user's motions, can have an impact on user performance [6], but also modulate the sense of embodiment towards their avatar [7]. While perfect synchronization is desired [8], it is common to decouple the avatar and user's movements [9]. For example, in the absence of haptic feedback, avatar motions can be constrainted in order to avoid visual interpenetrations between the avatar and virtual objects during touch/exploration [10] or grasping [11] interactions. In these situations, this motion alteration, under the guise of providing more natural interactions in VR, lets users create an uncontrollable offset between their virtual and real hands. In most applications, the offset must be fully recovered before the virtual hand can be lifted off the surface, i.e. a virtual movement is only possible again when the real hand is raised to the surface. However, the time that elapses between the moment when users move their real hand and the moment when their virtual hand moves gives the feeling that the virtual hand is sticking to the virtual surface, thus generating a "sticky" effect [12]. In this case, the movement of the hand must be exaggerated in order for the contact to be released, which is on the one hand unnatural, and on the other hand prevents the users from knowing the exact moment of the contact release.

The goal of this work is to propose an alternative hand control method to mitigate/avoid this "sticky" effect. We therefore propose a control law to avoid visual interpenetration during virtual contacts without preventing contact release, that is without creating a sticky effect (see Figure 1). Through two user studies we compared the proposed unsticky control law with the sticky control law. The first user study focused on users' behavioral adjustments and users' perception. The second study focused on the sense of embodiment, feeling of control, and user preference. Overall, the results showed that the unsticky control law achieves comparable performances, level of embodiment, and feeling of control as the sticky control law without the drawback of the latter. In addition, the design of the unsticky control law ensures that the offset correction happens during fast motions which creates a less noticeable motion alteration. However, participants usually expressed strong preferences toward one of the two methods, but these choices were individual-specific and did not appear to be correlated solely with characteristics external to the individuals (task, amount of offset etc.).

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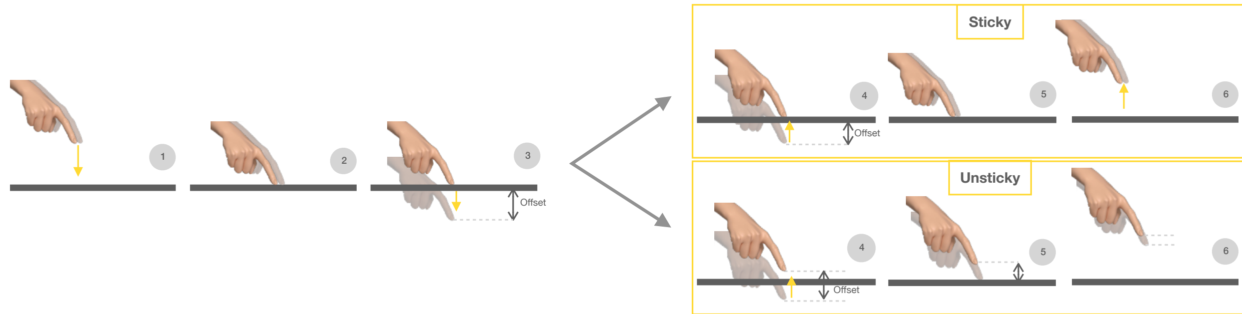

Fig. 1. Illustration of the considered contact release methods. (1-3) Contact phase: when a virtual contact between the user's hand and a virtual object occurs, a spatial offset is generated between the real user's body (transparent) and its virtual counterpart (opaque) to avoid interpenetration, keeping the later at the level of the virtual object surface. (4-6) Release phase: two explored alternatives to recover the offset generated. Top: in the "sticky" approach, the virtual hand is constrained on the virtual surface until the offset is recovered. Bottom: our proposed "unsticky" technique uses an adaptive offset recovery control law that provides an instantaneous contact release at the expense of a longer offset recovery phase.

2 Related Work

This section reviews several works exploring the usage of control methods to alter users' motions in the virtual environment (anisomorphic control methods), with a specific focus on how the offsets generated with these methods could be recovered. Then, we discuss works which specifically explored how users perceive motion alterations and positional offsets.

2.1 Anisomorphic Interaction Methods

Users' movements in the virtual environment can be modulated by altering the control-display gain (CD gain). The CD gain is a factor that upscales (if greater than one), or downscales (if smaller than one) the users' movement, thus creating an offset between the real and virtual representations. The potential usages of control-display gains are numerous: increasing precision [2], [13], increasing reach [14], [15], altering the users perception of weight [16], or effort [17].

From a 3D user interaction point of view, the control-display gain has been typically used to increase users' accuracy by distorting the gain when precise tasks are required [18]. For example, the prism technique [2] uses an adaptive control law, reducing the control display gain when the hand motion is below a certain threshold. Movement guidance improving the retention of target movements was also made possible by control-display gain modulations [19]. Another example is the Pin'n'Pivot manipulation technique [20], which requires explicit user control to reduce the CD gain. Other techniques enable for enhanced interactions, such as the Go-Go technique [14] which can be used for the selection and manipulation of objects at a distance by increasing the movement made by the user (CD gain larger than one), and which was recently explored in the context of avatar interactions in VR [21] and AR [22].

Anisomorphic gains can also be used to imperceptibly redirect users during the interaction process. For example, redirected walking [3] methods aim at altering the positional and rotational mapping between users' real and virtual positions to reorient them in their working space. When applied to manual interactions, the same method can be applied to redirect hand motions to alter the perception of a tangible object being touched [23], [24], or to enable the physical interaction with multiple virtual objects when using only one physical counterpart [1], [25], [26]. Several methods have also been considered to increase the amount of redirection, such as redirecting users when they blink [27], or look away [28].

In the context of avatar interactions, the issue was raised as to whether it is better to modify user motions to block their virtual hand outside of virtual objects to replicate "natural" interactions, or to let users interpenetrate virtual objects to respect their real movements [10]. It was found that users tend to prefer the absence of interpenetration even though visual interpenetration enhances performance. When following user preferences concerning the absence of visual interpenetrations, techniques introduce a positional offset during the contact, which is often recovered using the sticky control law. This method introduces a delay, that can have an impact on the sense of agency [29], especially with increasing delays [30]. Finally, the alteration of the CD gain can be used to alter the perception of the motion being performed. In this respect, pseudo-haptics [31] leverages the dominance of visual over proprioceptive feedback [9], [32], [33] to generate visuo-haptic illusions. Several pseudo-haptic inspired techniques have for example explored the modulation of the perceived weight [16] or effort [17].

A side effect of anisomorphic interaction methods is that they can accumulate positional and rotational offsets between the user and the virtual representation. It raises the question of how and when to recover this offset, as well as the degree of sensitivity of users towards these offsets and their recovery. To avoid motion artifacts, and avoid users noticing this offset, several methods try to recover the accumulated offset as imperceptibly as possible, e.g., using a variant of a spring model [12], [34]. Without physical constraints from a real object, users tend to close their real fingers into virtual objects, so their real and virtual fingers are in different configurations. The proposed spring model allows for a transient incremental motion metaphor that prevents the sticky effect from occurring. Another example is a blink-induced suppression that was used in the context of redirected walking for translation and rotation [35], to enhance the redirected walking technique and lower the size of the needed workspace. Other methods were proposed in the context of manual interactions, such as progressively decreasing the offset when users' hand speed is below a given threshold [2]. Conversely, methods proposed to imperceptibly generate offset could be adapted to imperceptibly recover an offset as well. For instance, generating offset when blinking for haptic retargeting [27] resonates with the previously introduced study [35].

2.2 Perception of Offset and Motion Alterations

Interaction techniques that modify the user's movements introduce trade-offs between enhanced user capabilities and natural interactions. Many studies have therefore investigated detection thresholds for different remapping techniques. In particular, detection thresholds have been explored for the anisomorphic methods presented in the previous section, such as haptic retargeting [36], [37], or redirected walking [38].

Hand remapping techniques were also evaluated to avoid visual interpenetration between the user's virtual hand and virtual objects [32]. Detection thresholds were found for visual interpenetration and visual-proprioceptive discrepancies, showing that humans are more sensitive to visual interpenetration than to proprioceptive inconsistency. It has also been shown that users are more sensitive to decreases than increases in hand velocity [39]. Based on this, more natural hand placements when users' virtual hands collide with objects have been proposed [40]. In addition, hand redirection methods using fixed gains, in general, have also been studied [41]. Limits were investigated for scaled hand movements in each direction. Detection thresholds were found to vary by direction, suggesting varying sensitivity of humans depending on the direction of motion [42]. Other authors have also explored participants' tolerance to fixed positional [43], [44] and angular [45] offsets.

There is also evidence that other factors associated with remapping techniques can influence detection. For example, higher fidelity avatars result in less detection of remapped hands [46]. Interactions between the sense of embodiment [47] and motion alterations have also been widely studied. On the one hand, embodied avatars were found to increase the just noticeable differences of motion alterations, such as for the Ownershift interaction technique [48], and to influence movements amplitude in the case of altered visual feedback [49]. On the other hand, the effects of motion alterations [50] and delay [29] on the sense of embodiment were also studied. The sense of self-agency is affected by motion artifacts such as noise, latency, motion jump, and offset rotation of joints. Increased delay has also been shown to decrease the self-reported sense of agency.

The related work shows how alterations of the control-display gain can be used to improve user interaction. However, it also highlights the potential impact these alterations can have on the user experience. Although some studies explored the impact of the virtual and real hand couplings in mid-air grasping interactions [12], no study has explicitly explored the potential impact of control-display adaptations in terms of user performance and virtual embodiment when avatar motions are constrained by virtual objects during active exploration. The following section characterizes the problem and proposes an alternative method to mitigate the "sticky" effect.

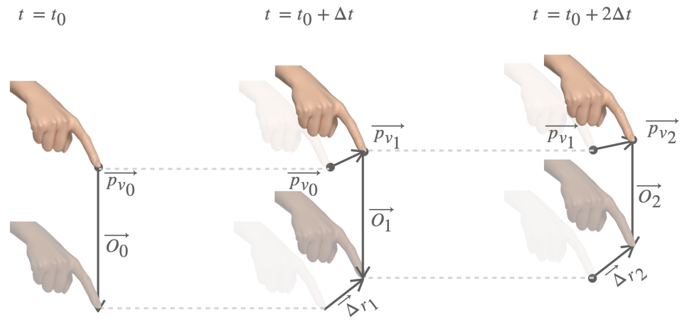

Fig. 2. Our alternative control law offset recovery mechanism. The real hand (grey) moves by a Δ_r in a time step Δt. The virtual hand (beige) position at $t + \Delta t$ is computed depending on the real motion Δ_r, the offset between real and virtual position $\vec{O_t}$ and the recovery factor c (see Equation 1).

3 Unsticky Contact Release Method

While performing unconstrained mid-air interactions, users can generate virtual contacts with their virtual hand. The virtual contact sequence can be decomposed into two main phases (described in Figure 1): the contact phase and release phase. During the contact phase, the user initiates the contact and maintains it to interact with the virtual object (see sub-phases 1-3 in Figure 1). During this phase the visual hand is constrained by the virtual surface to avoid interpenetration. However, in the absence of physical constraints, the amount of offset generated during the contact phase is difficult to control, as the motions on the virtual surface normal are negated. Although the addition of other feedback modalities, such as the use of tactile feedback [51] could be considered, it is beyond the scope of this paper.

During the release phase, the user first moves his/her real hand away from the surface, eventually leading to a release of the visual contact (see sub-phases 4-6 in Figure 1). A common approach consists in forcing the virtual hand to remain on the virtual surface until the whole offset is recovered, often resulting in a sticky effect. Users are therefore moving their real hand while the virtual hand is forced to remain on the surface (see Figure 1).

To mitigate this effect, we propose to rely instead on a reactive contact release and to progressively recover the offset generated during the virtual contact. Our method resonates with the spring model technique proposed by Prachybrued et al. [12] for improved release of whole-hand virtual grasps. While their method already provides a reactive contact release, our approach differs in the offset recovery technique. The general idea is to let the virtual hand move away from the surface as soon as the real hand moves away from the surface, while progressively recovering the offset generated during the contact. However, care should also be given to the speed of the compensation, as faster recovery might be more noticeable by users which could potentially decrease their sense of agency, while too slow recovery might not enable users to fully recover the offset in a reasonable time, leading to larger offset accumulation during future contacts.

Thus, we propose a method (unsticky law) dependent on users' hand speed and the quantity of the current offset, to take into account these constraints. Let $\vec{p_{r_t}}$ be the position of the real hand at t, $\vec{p_{v_t}}$ the position of the virtual hand at t, $\vec{\Delta_{r_t}}$ the movement achieved by the real hand between t and $t + \Delta t$, Δt the time between two successive frames, $\vec{O_t}$ the offset between the two hands at t. Let c be the recovery applied to the virtual hand. Computing the position of the virtual hand is done this way (see Equation 1 and Figure 2):

$$p_{\vec{v_{t+1}}} = p_{\vec{v_t}} + \vec{\Delta_{r_t}} + c \times \vec{O_t} \quad (1)$$

The recovery factor c depends linearly on the speed s of the users' real hand and on a constant a, which defines the efficiency of the offset recovery. The role of speed is the following: the slower users move, the smaller the offset recovery assuming users might want to achieve a precise interaction. Conversely, the faster users move, the greater the offset recovery, because we assume users might not notice it during fast movements. s_ϵ is an additional condition on speed, that prevents any recovery under a given speed threshold to avoid disturbing precise movements and seeing the virtual hand move by itself when the real hand is stationary. The threshold was empirically set to $0.1\ m.s^{-1}$.

$$c = \begin{cases} 0 & \text{if } s < s_\epsilon \\ a \times s & \text{otherwise} \end{cases} \quad (2)$$

The offset recovery ratio a is a critical parameter of the unsticky law, as it provides a trade-off between rapidly recovering the offset at the expense of strong motion alterations, or small motion alterations at the expense of requiring too much time to recover the generated offset. Thus, we conducted a pilot study to explore the impact of the offset recovery ratio and to determine interesting values to be used during the experiment. In the pilot study ($N = 17$) participants performed pointing tasks after generating a fixed amount of offset ($20\ cm$), with and without visual feedback of their virtual hand, and a repetitive tapping task. Five different offset recovery ratios were tested $a = \{0.3, 0.5, 1.0, 1.6, 2.5\}$, in addition to the sticky control law. Performance and objective measurements such as selection time, offset generated, and trajectories were recorded. The subjective impressions of participants were also gathered, exploring their ability to detect motion alterations due to the offset recovery and residual offsets at the end of the tasks.

The results of the pilot enabled us to determine two groups in the values of a tested: those for which participants perceived a higher residual offset at the end of the task, and those for which they perceived a noticeable modification of their trajectory. We selected one value from each group to test both behaviors during the next experiment, but did not select a value that was perceived as difficult to use or unpleasant by participants. The two selected offset recovery ratios are:

- Slow unsticky control law ($a = 0.5$). This configuration slowly recovers the offset, yet the virtual motion is closer to the real motion.
- Moderate unsticky control law ($a = 2.5$). This configuration more rapidly recovers the offset, at the expense of stronger motion alterations.

It also seems interesting to mention that participants commented that lower values of a gave the impression that the virtual hand was a bit "behind" or out of sync with the real hand, while higher values of a gave them the impression that the virtual motion was accelerated compared to real motion.

Based on the results of this pilot study, we designed two experiments to evaluate the impact of the different control laws on the objective performance and behavior of users (Section 4), and on their sense of embodiment and preference (Section 5).

4 Experiment 1: Impact of Motion Alteration and Positional Offset on Performance and Perception

The aim of this experiment was to explore the impact of offset and of motion alteration on aimed movement when considering different hand control methods. In addition of the two versions of the unsticky control law defined in the previous section (moderate unsticky and slow unsticky), we also considered a classical offset recovery method in which the offset is recovered before the contact is released (sticky). In this experiment we were particularly interested in assessing the impact of the offset recovery methods with different interaction tasks and under different offset magnitude conditions.

4.1 Participants and Apparatus

Twenty-one participants took part in the experiment (5 females, 15 males, 1 other), aged from 21 to 33 ($M = 25$, $SD = 3$). The majority of participants were students and staff recruited on our campus. They did not receive any economical compensation for their participation. They all had normal or corrected vision. Participants were immersed in the virtual environment using a Valve Index head-mounted display. We also used a Vive Tracker to track their hand position and orientation, which was represented using a realistic virtual hand with an index pointing pose. Participants were instructed to mimic the hand pose during the experiment , as the hand pose was fixed and not captured. Right-handed and left-handed participants took part in the experiment. They used their dominant hand, and the virtual environment was adapted. The experiment was performed using a desktop computer ensuring a minimum of $90\ fps$ under all conditions and developed using Unity 2019.4.31f1. The experiment was approved by the local ethics committee (COERLE 2022-23).

4.2 Experimental Tasks

Two main tasks (Pointing and Path following) and one control task (Blind Pointing) were considered in this experiment. They aimed at observing the impact of the control law when the duration of the contact varied, short vs. long contacts. The control task was included to compare the impact of the visual feedback on motion dynamics. No control condition was considered for the Path following tasks as the task was harder to perform without visual feedback.

Pointing Task. In this task, we explored the impact of the control law when performing fast aimed movements. Before performing the aimed motion, participants had to generate a pre-defined positional offset. This offset was meant to simulate an offset that could have been created by interacting with virtual objects. In order to generate the offset, participants were asked to press on a virtual flat target placed on a virtual table and move their real hand further under the table until two sound signals were heard. As the virtual hand is constrained by the flat target, this procedure allowed for the generation of a vertical offset. The first signal instructed them to stop moving, and the second signal instructed them to start an aimed motion towards a mid-air target (see Figure 3, up). To examine a range of offset magnitude, we controlled the amount of offset generated ($0\ cm$, $15\ cm$ or $30\ cm$) and the height of the virtual target ($0\ cm$, $25\ cm$ or $50\ cm$), which resulted in 9 possible combinations. The different offset levels were determined empirically. The target heights were chosen so that all participants could comfortably perform the pointing tasks. The reference height of the table was set according to the height of the HMD.

The overall aim of this task was to stress the different control laws under the need of recovering a certain positional offset during a mid-air aimed motion task. When the offset was $0\ cm$, there was no impact of the control law used. The acoustic feedback ensured that the offset generated was consistent among trials, and that the targets provided enough end-point variability to generate different hand motion profiles (in position and speed).

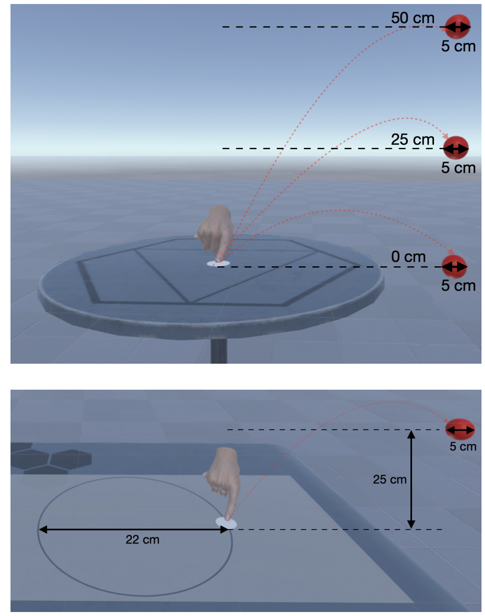

Fig. 3. Up, pointing task. Down, path following task.

Blind Pointing Task. In the pointing task, the visual feedback provided by the virtual hand during the aimed motion was expected to have a large influence on the actual hand motion. Thus, we designed a blind pointing task, which followed the same protocol as the previous pointing task, to investigate the behaviour of participants when they know that they generate an offset but do not have any visual feedback about their pointing motion. To this end, we modified the pointing task so that participants' virtual hand disappeared after the second sound signal. Yet, they were still instructed to touch the virtual target. The aim of this task was to explore how the offset generated before performing the aimed motion would influence the motion planned, and whether participants would touch the virtual target by considering their actual hand or based on the last visual position of their virtual hand. Furthermore, we were interested in comparing the motion profiles of this task and of the regular pointing task. For this task, we considered the same offset and target positions, yet, as no visual feedback was provided during the aimed motion, this task was not influenced by the offset recovery control law.

Path Following Task. One of the potential drawbacks of the unsticky method is that it could be hard for users to keep the contact over a virtual surface during a prolonged contact period, because any vibration of the real hand position would result in a contact release. During informal tests, we observed that participants tend to generate large amounts of offsets during prolonged contacts (e.g. moving their hand further and further inside the virtual objects). Thus, we designed a third task which required to follow a pre-defined circle path (see Figure 3, bottom) to further explore offset generation during prolonged contacts. Participants were asked to start the path following task from a virtual flat target on the table, and to follow the circular path for 10 seconds, until the flat target became green. They were also instructed to finish following the circle until reaching the flat target, and then to touch a mid-air virtual target.

4.3 Experimental Protocol and Design

After reading and signing the consent form, participants were asked to fill in a questionnaire to gather demographic information. Then, they were briefed regarding the purpose of the experiment and were equipped with the VR equipment. The experiment was organized as follow. First, participants performed the tasks that were not dependent on the control law, i.e. the blind pointing task and the pointing task with the $0\ cm$ offset. These were considered to be the baseline conditions. Then, they performed the blind pointing task with the remaining offset conditions. The remaining of the experiment was structured into three blocks, one for each control law (sticky, slow unsticky and moderate unsticky). Within each block, participants first performed the pointing task with the remaining offset conditions ($15\ cm$ and $30\ cm$), then the path following task. For each combination of factors, four repetitions were performed. The experiment followed a full within-subject design and the order of the control law conditions was counterbalanced using a Latin-Square design, and for each task the order of the trials was randomized. In total, participants performed 108 pointing tasks, 36 blind pointing tasks and 12 path following tasks. Moreover, 2 training trials were performed each time a new task was presented. Participants were informed that they could take a break whenever they needed. Participants were immersed in the virtual environment for approximately 30 minutes.

4.4 Experimental Data

4.4.1 Subjective Measures

After each trial of the pointing and path following tasks, we asked participants one unique question, to assess their appreciation of the trial. For the pointing task, we asked participants: "how much do you feel you needed to correct your movement to reach the target?", which they rated on the following 7-point Likert scale: (1) not at all, almost not at all, negligibly, a little, significantly, quite a lot, (7) a lot. For the path following task, we asked participants: "during the drawing phase, how often did you feel a shift between the position of your real hand and the position of your virtual hand?", which they rated on the following 7-point Likert scale: (1) never, rarely, occasionally, half the time, frequently, repeatedly, (7) always.

4.4.2 Objective Measures

For the pointing tasks, we recorded the selection time (from the second sound signal until reaching the target), the residual offset (distance between the real and virtual hand when touching the target), as well as the trajectory of the virtual and tracked hands. For the blind pointing tasks, we recorded the accuracy (positional error at the end of the trajectory with respect to the virtual target) and the trajectory of the tracked hand. Finally, for the path following tasks, we recorded the maximum generated offset.

4.5 Hypotheses

Based on our experimental design we had five main hypotheses.

[H1.1] The slow unsticky method will result in higher residual offsets at the end of each pointing task. Its lower offset recovery ratio will maintain an overall higher offset compared to the other two methods.

[H1.2] The slow unsticky method will result in higher task completion time for the pointing task. The movement during the aiming task can be broken down into the ballistic phase (fast, direct movement towards the target), and the correction phase (slower, to correct the ballistic movement) [52]. During the ballistic phase, the majority of the offset correction will be performed, potentially resulting in a larger variability in the endpoint of the virtual hand after the ballistic phase. Thus, we expect longer correction phases which will also generate higher task completion times due to the additional corrective movements.

[H1.3] Participants will notice a greater need to correct their movement when using the slow unsticky method during the pointing task. Because the slow unsticky method generates a larger error, participants will be more aware of the need to correct their movements to aim at targets. This behavior was already observed in the pilot study.

[H1.4] Unsticky methods will generate higher offsets during the path following task. When using unsticky laws, the virtual contact with the surface is released as soon as the real hand moves in the direction of the plane normal. Thus, to enforce the contact, participants might tend to move their hand toward the surface continuously. This will result in artificial increase of the offset which will not happen with the sticky law as the contact is only released when all the offset is recovered. We further expect that the moderate unsticky law will generate lower offsets than the slow unsticky law since it recovers the offset faster.

[H1.5] Participants will be more aware of the offset generated for the two unsticky methods during the path following task. Since we assumed that participants would generate more offset with these methods, we expected them to perceive these offsets more.

4.6 Results

The analysis was done using full-factorial repeated-measures ANOVAs. The normality assumption was verified with a Shapiro test as well as a visual inspection of the QQ plot of residuals. When the normality assumption was violated, data was first transformed using the aligned-rank transform [53]. Finally, when needed, the Greenhouse–Geisser degrees of freedom correction was applied. The Bonferroni correction was applied for the Post-hoc tests ($\alpha < 0.05$). Only significant effects are discussed. The statistical analysis was done using R using the Afex and ArTool packages.

Residual offset. The three-way ART ANOVA analysis (offset, law, target) showed two two-way interaction effects: between law and offset ($F\,(1\,,20) = 186.145$,$p < .0001$,$\eta_p^2 = 0.903$) and between law and target ($F\,(2\,,40) = 15.664$,$p < .0001$,$\eta_p^2 = 0.439$). Regarding the first interaction effect, post-hoc analysis showed that slow unsticky provides significantly higher residual offsets, which are significantly dependent on the initial offset (see Figure 4, left). Regarding the second interaction effect, post-hoc analysis also showed that slow unsticky provides significantly higher residual offsets for all targets, yet, the residual offset was the smallest for farther away targets. These results support **H1.1**.

Task completion time. The three-way ART ANOVA analysis (offset, law, target) showed a significant main effect on offset ($F\,(1\,,20) = 61.761$,$p < .0001$,$\eta_p^2 = 0.755$) and on target ($F\,(2\,,40) = 5.503$,$p < .01$,$\eta_p^2 = 0.216$). Post-hoc tests showed significant differences between the two offsets, and between high and low, and high and middle targets (all $p < .05$). Completion time was larger when the distance between the initial real hand position (given by the offset) and the target was larger (for the 15 cm offset: $M = 2.2$, $SD = 0.6$; for the 30 cm offset: $M = 2.5$, $SD = 0.78$; for the low target: $M = 2.3$, $SD = 0.8$; for the middle target: $M = 2.3$, $SD = 0.7$; for the high target: $M = 2.5$, $SD = 0.7$). There was no main effect of law ($F\,(2\,,40) = 1.093$,$p = 0.345$,$\eta_p^2 = 0.052$). These results do not support **H1.2**.

Motion correction perception. The three-way ART ANOVA analysis (offset, law, target) showed a main effect of law ($F\,(2\,,40) = 9.936$,$p < .0001$,$\eta^2 = 0.332$), offset ($F\,(1\,,20) = 41.221$, $p < .001$,$\eta^2 = 0.673$), and target ($F\,(2\,,40) = 3.266$, $p < .05$,$\eta^2 = 0.140$). Post-hoc analysis showed that slow unsticky was perceived to require more corrective motions ($MD = 4.3$, $IQR = [3.4\,;5.3]$) with respect to moderate unsticky ($MD = 2.6$, $IQR = [1.8\,;4.2]$) and sticky

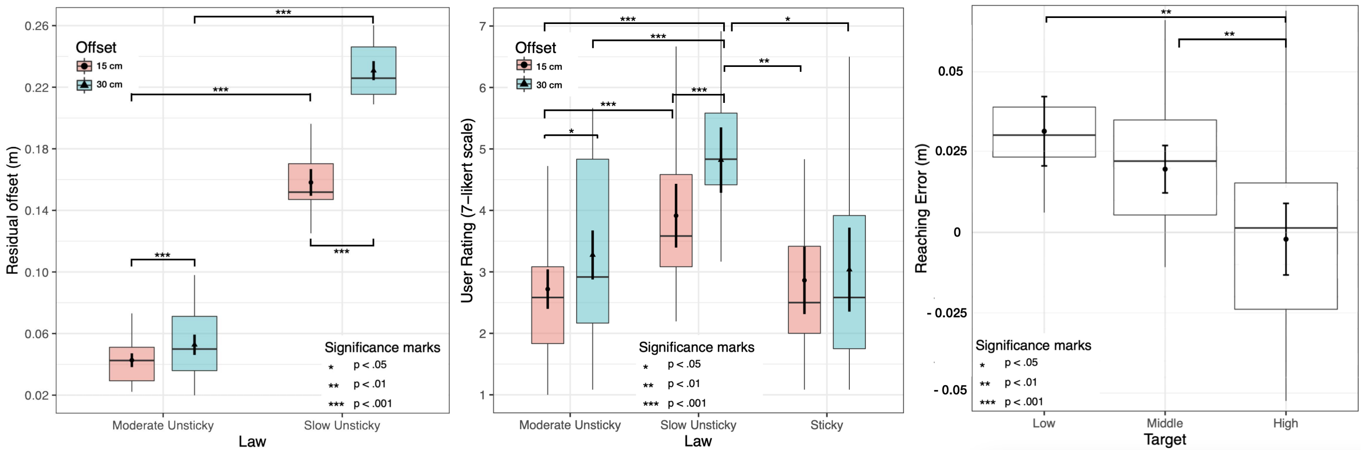

Fig. 4. Left, boxplot for the average residual offset for the pointing task. Only the slow and moderate unsticky laws are displayed as the sticky law always recovers all the offset. The mean and the 95% CI bars are also displayed. Middle, boxplot for the answers to the subjective assessment during the pointing task, grouped by law and offset. The mean and the 95% CI bars are also displayed. Right, boxplot of the reaching error during the blind pointing task. As the target was $0.025\ m$ radius, values between $-0.025\ m$ and $0.025\ m$ can be considered as a perfect hit. Note: only significant pairs are shown on the graphs.

($MD = 2.5$, $IQR = [1.8\,;4.0]$) (both $p < .05$). Regarding the main effect of offset, the 30 cm condition was also perceived to require more corrective motions.

Moreover, there was a significant interaction effect between law and offset ($F\,(2\,,40) = 9.520, p < .0001, \eta_p^2 = 0.323$). Post-hoc analysis revealed significant differences in the evolution of ratings between the two offsets, between slow unsticky and sticky ($p < .0001$), and between slow and moderate unsticky ($p < 0.05$) (see Figure 4, middle). These results show that the offset only generated an effect for the unsticky laws. Finally, the post-hoc analysis for the main effect of target were non-conclusive. These results support **H1.3**.

Hand trajectories. We analyzed the temporal evolution of the virtual and tracked hand positions for the pointing task (only the vertical component). Figure 5 shows an example of the average temporal evolution of the vertical component of the index finger tip position for the 30 cm offset and mid target condition. The figure shows that the tracked trajectories for each law were similar for the first part of the motion, while motion differences appeared in the second half of the trajectory, which aimed at compensating the offset between the visual and the tracked hands. Regarding the visual trajectories, we can observe that for the unsticky laws, the hand left the surface of the table earlier, and that both trajectory profiles differed from the sticky law during the approach motion. For the slow unsticky technique, a clear overshooting motion is observed, which required a moderate correction from the participants. Figure 6 presents the average tracked hand trajectories (vertical axis) for the different laws tested. Overall, if we compare moderate unsticky (left) and sticky trials (right), we can observe that trajectories present similar profiles (although higher discrepancies can be found in the low target condition). However, we can clearly see the discrepancies increase for the slow unsticky condition (middle). We observed that participants were starting the motion in a similar way in spite of the different motion alterations. Then, the correction phase started at different timings depending on the control law: it seems that the larger the positional offset, the earlier the correction phase starts. An increased overshoot is also observed with the increase of the positional offset.

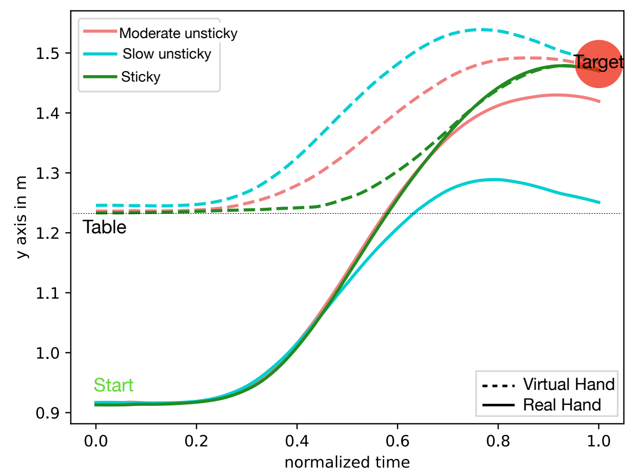

Fig. 5. Mean temporal evolution of the hand y-axis during the pointing task for the virtual and tracked hand. This plot considers the trials in which the initial offset was $30\ cm$ and the target was placed at a height of $25\ cm$ over the virtual table.

4.6.1 *Blind Pointing Task*

Positional error. The two-way ART ANOVA analysis (offset, target) only showed a main effect of target ($F\,(2\,,40) = 17.982, p < .0001, \eta_p^2 = 0.473$) (see Figure 4, right). Post-hoc tests showed significant differences between all three levels of target (high/low $p < .0001$, high/middle $p < .01$ and low/middle $p < .05$). Overall, participants were precise while performing the blind pointing task and would have ensured only successful trials with a target of about 10 cm diameter.

4.6.2 *Path Following Task*

Maximum offset. The one-way ANOVA analysis (law) showed a significant main effect

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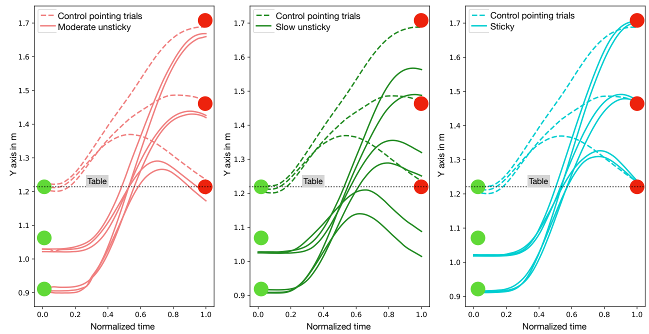

Fig. 6. Comparison of average y-axis trajectories for the pointing tasks. The control trials (dotted lines) are identical on all three graphs because no motion alteration was performed. The trajectories displayed in solid lines correspond to the real hand.

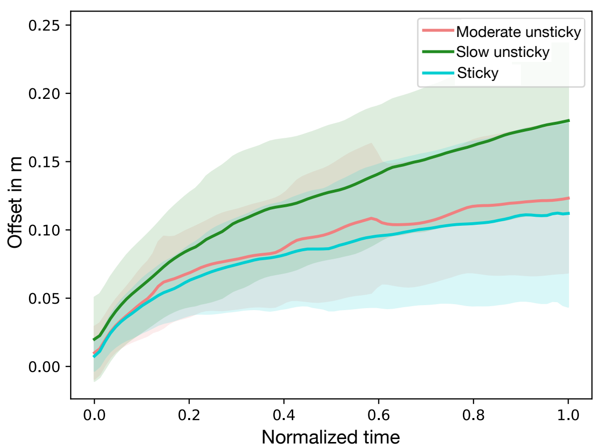

Fig. 7. Averaged temporal evolution of the offset generated during the path following task, and standard deviation.

$(F(1.786, 33.725) = 7.795, p < .01, \eta_p^2 = 0.28)$. Post-hoc tests showed that users generated significantly more offset with the slow unsticky law ($M = 0.18$, $SD = 0.07$) compared to the moderate unsticky law ($M = 0.12$, $SD = 0.05$) and the sticky law ($M = 0.11$, $SD = 0.07$). This result shows that the slow unsticky control law causes users to generate significantly more offset than the other two laws, which partially supports **H1.4**. Furthermore, Figure 7 shows the mean temporal evolution of the offset during the task, which was globally increasing for all conditions. Yet, the visual exploration of the data suggests that the evolution of the positional offset was similar for the moderate unsticky and the sticky laws, and higher for the slow unsticky law.

Subjective assessment. The one-way ANOVA analysis (law) showed a significant main effect of the perceived offset $(F(1.437, 28.744) = 6.525, p < .01, \eta_p^2 = 0.25)$. Post-hoc tests revealed that the offset was more noticed for the slow unsticky condition ($M = 3.7, SD = 1.6$) compared to the moderate unsticky ($M = 2.6, SD = 0.9$) and sticky ($M = 2.7, SD = 0.8$) laws. These results partially support **H1.5**.

4.7 Discussion

The main goal of this experiment was to assess the impact of motion alterations and positional offsets on users' behavior and performance under different hand control laws.

Regarding offset recovery, our results showed that the slow unsticky control law was only able to partially recover the initial offset, thus supporting **H1.1**. This was expected as the offset recovery ratio was defined for a slow recovery. However, even with a low offset recovery ratio, the slow unsticky law performed comparably to the others in terms of task completion time for both offset conditions. This result do not support **H1.2** and suggests that users were able to compensate for moderate and larger offsets. This result could be explained by the fact that under large offset conditions, the amplitude of the real motion was smaller as illustrated in Figure 5. However, users tended to overshoot during the pointing task with the slow unsticky control law (see Figure 5). This observation could indicate that participants were not able to take into consideration the offset to execute their ballistic motion, thus requiring them to perform a larger corrective motion to reach the target. If we model the actual aimed motion as a Fitts' law task, the decrease of the amplitude would indeed result in a decrease in the task completion time, but this might have been compensated by the lack of precision during the ballistic phase. Moreover, it is also interesting to notice, that during the blind pointing tasks, participants showed a high accuracy while aiming at the targets without any visual feedback. Considering that at the beginning of the motion, they could see their virtual hand, we can conclude that the aimed motion was mainly planned using proprioceptive information. Finally, we also observed that the moderate unsticky technique achieved a similar performance and had similar motion profiles to the sticky technique, even in situations with large offsets. Based on the previous result, if we consider that participants mainly relied on proprioception to perform their ballistic motions, both control laws should generate similar ballistic endpoint positions. This hypothesis is further supported by the accuracy results for the blind pointing task, as the initial offset did not have an impact on participants' accuracy.

We also hypothesized that users would be more aware of the offset generated **H1.3**. The subjective results support **H1.3**, as the participants' ratings while answering to the question "how much do you feel you needed to correct your movement to reach the target?" were higher for the slow unsticky condition. This result is coherent with the observation that participants tended to overshoot with the slow unsticky control law. Regarding the moderate unsticky law, although no significant difference was found with respect to the sticky law, we could observe a larger dispersion of the participants' ratings for the 30 cm offset conditions. We believe that this result could be dependent on participant strategies to reach the target, as participants performing fast aimed motions would tend to recover more offset than those performing slower ones.

Regarding the path following tasks, we also hypothesised that unsticky methods would generate larger offsets **H1.4**. The results partially support this hypothesis as only the slow unsticky method significantly generated more offset. While the differences between the slow unsticky and sticky methods were expected, the fact that moderate unsticky and sticky achieved similar results was surprising. Further examination showed that the moderate unsticky law was still able to correctly compensate for the offset, even when performing movements parallel to the surface. For prolonged contact tasks during which a large offset is generated, the moderate unsticky law tends to stick the virtual hand to the surface when trying to decrease the distance between the real and virtual hands. This result is also coherent with the subjective ratings, as participants were only more aware of the offset for the slow unsticky condition (partially supporting **H1.5**).

Overall, the results suggest that the moderate unsticky law enables users to interact efficiently with the environment, avoids the "sticky" effect, and ensures that the overall offset accumulated remains little noticed by participants. However, this experiment did not explore user preferences and the potential impact that motion alterations could have on the feeling of agency [47]. In the following section, we present a follow-up study which explores these matters.

5 Experiment 2: Impact of Motion Alteration on the SoE and User Preferences

This experiment aimed to evaluate the impact of the hand control method on the sense of embodiment, the feeling of control, and the user preference. Contrary to the first experiment participants were not instructed to artificially generate offsets. For this experiment, we considered only the moderate unsticky and the sticky control laws, based on the results from the first experiment.

5.1 Participants and Apparatus

Twenty participants took part in the experiment (4 females, 16 males), aged from 19 to 46 ($M=25$,$SD=7$) among with 25% already participated in the first experiment (which were separated by 5 months). The majority of participants were students and staff recruited on our campus, and none of them received any economical compensation for their participation. They all had normal or corrected vision. As for the first experiment, participants were immersed in the virtual environment using a Valve Index head-mounted display, and a Vive Tracker was used for tracking their hand. The users' virtual representation was a realistic virtual hand with index pointing pose. Participants were instructed to mimic the hand pose during the experiment , as the hand pose was fixed and not captured. Right-handed and left-handed participants took part in the experiment. They used their dominant hand, and the virtual environment was adapted. The experiment was performed using a desktop computer ensuring a minimum of 90 fps under all conditions and developed using Unity 2019.4.31f1. The experiment was approved by the local ethical committee (COERLE 2022-23).

5.2 Experimental Tasks

For this experiment, we selected tasks that required different surface exploration gestures. The main criteria were: precision (rough, precise), the nature of the contact (discreet, continuous), and the contact release event (user, object). Due to practical reasons, only a few combinations were selected. Users were not instructed on the speed at which they should perform tasks. They were free to go as fast as they wanted as long as they could complete the task.

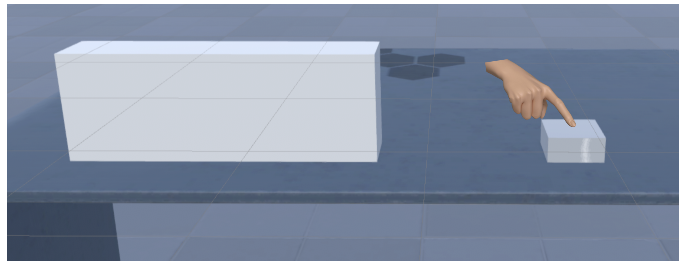

Fig. 8. The sliding task for right handed participants.

Tapping Task (User, Discreet, Fast). The tapping task consisted of repeatedly tapping on a cube for 10 seconds, after which a sound indicated to participants that the trial was over. A potential drawback of the unsticky method is the offset accumulation resulting from multiple contacts. At the same time, repeated and close contacts can also be detrimental to the sticky method, because participants might see more of the latency generated by this method.

Pointing Task (User, Discreet, Precise). For each trial, participants had to alternatively touch two targets (5 cm diameter, at 45 cm distance) for 10 seconds, after which a sound indicated that the trial was over. This task was presented either on a horizontal surface or an oblique surface (45 deg). In this task, we explored the impact of the control law when performing fast aimed movements on a surface.

Path Following Task (User, Continuous, Precise). Participants performed a task that required them to follow a predefined circular path on a virtual surface for 10 seconds, after which a target in the middle of the circle became green, which they then had to touch. To further explore the impact of unintentional release of contact, we asked participants to complete this task on a horizontal surface and a $45°$ oblique surface. One of the drawbacks of the unsticky method is that it could be difficult for a user to maintain contact on a virtual surface during prolonged contact, as any vibration of the real hand would cause the contact to be released.

Sliding task (Object, Continuous, Fast). Participants were instructed to slide their virtual finger over a virtual cube (length of 50 cm) and then touch another virtual cube positioned at a lower position (see Figure 8). They repeated this task for 10 seconds, which also ended when a beep sound was played. This task was designed to generate a contact release event due to the finger going outside the virtual surface. One of the drawbacks of the sticky method is that anytime a contact ends the virtual hand is snapped to the position of the real hand, generating a motion discontinuity.

5.3 Experimental Protocol and Design

After reading and signing the content form, participants were asked to fill in a demographic questionnaire. Then, they were briefed regarding the purpose of the experiment and were equipped with the VR equipment. The experiment had two main parts, one to assess the SoE and another one to assess user preferences.

In the first part, participants performed two blocks, one for each control law, aiming at assessing their SoE. In each block, they performed the flat and oblique pointing tasks, as well as the flat and oblique path following tasks. Each task was performed five times in a row. The order of the tasks was randomized. After each block, participants answered a questionnaire to assess the SoE [54]. The tapping and sliding tasks were excluded from the SoE part of the experiment because they were likely to confuse users, as we expected these tasks to explore the limits of both laws.

Then, in the second part, participants performed all six tasks aiming at assessing their preferences. Participants did all the tasks four times in total. In each trial, they performed one of the tasks successively with both control laws, to enable participants to directly compare them, starting with a randomly picked law, ensuring that each couple of tasks was presented once starting with Sticky and once starting with Unsticky. The order of the tasks was randomized. Each task started twice with unsticky, and twice with sticky.

In total, for the entire experiment, participants performed 18 flat pointing tasks and 18 oblique pointing tasks, 18 flat paths following tasks and 18 oblique paths following tasks, 8 tapping tasks, and 8 sliding tasks. Participants were informed that they could take a break whenever they needed. Participants were immersed in the virtual environment for approximately 30 minutes.

5.4 Experimental Data

During the first part of the experiment, the SoE was assessed using the Peck and Gonzalez-Franco questionnaire [54], composed of 16 questions. As recommended by the authors the questionnaire was adapted to better reflect the virtual body and experimental conditions. We mainly replaced the word “body” with the word “hand”. Moreover, after the five repetitions of each task, participants answered the following question to obtain additional insights into their feeling of control: “I had complete control over my hand”, rated using a 7-point Likert scale: (1) never, rarely, occasionally, half the time, frequently, repeatedly, (7) always.

Finally, during the second part, after completing each trial (one task with both control laws), participants answered the following question: “Did you prefer the first or the second control law?”, rated on a 7-point scale, of which 4 could not be used: (1) surely the first, (2) probably the first, (3) maybe the first, (5) maybe the second, (6) probably the second, (7) surely the second. Participants could not pick a rating of 4 to force them to select a control law.

5.5 Hypotheses

Our experimental design is led by three main hypotheses:

[H2.1] A comparable level of feeling of control will be induced by both control laws. From the first experiment (see Section 4), we could observe that both control laws were equivalent in terms of performance, and none of them generated visual effects that prevent interaction. Thus, we hypothesised that the potential impact on the overall feeling of control would be limited.

[H2.2] More generally, the sense of embodiment will not be affected by the control law. Similarly as H2.1, we did not expected strong fluctuations of the sense of embodiment as both laws were similar performance-wise.

Moreover due to the different nature of motions to be performed, user preferences will be task dependent, in particular:

[H2.3a]: The path following tasks will induce a higher preference for the sticky control law due to the expected increase of unintentional contact releases.

[H2.3b]: The pointing task will induce a higher preference for the sticky control law due the accuracy and speed requirements.

[H2.3c]: The sliding task will induce a higher preference for the unsticky control law. With the sticky control law, we expected a large visual motion discontinuity before touching the target, as the offset accumulated during the sliding task is recovered immediately. This will not be the case for the unsticky method.

[H2.3d]: The tapping task will induce a higher preference for the unsticky control law. Although this task might suffer from offset accumulation when using the unsticky control law, we expected that the repeated unnatural “sticky” contacts will be less appreciated.

5.6 Results

Feeling of Control. The answers to the question on the feeling of control were also analyzed using a Wilcoxon signed-paired test, w.r.t. the control laws (sticky vs. moderate unsticky), separately for each task. We did not find a significant effect of the control law for any of the tasks, which supports **H2.1** (pointing task horizontal surface: $V = 82$, $p = 0.06$, $r = 0.41$; pointing task oblique surface: $V = 58$, $p = 0.38$, $r = 0.14$; path following task horizontal surface: $V = 86$, $p = 0.14$, $r = 0.24$; path following task oblique surface: $V = 65.5$, $p = 0.76$, $r = 0.11$). On average, the global score was high ($M = 5.6$, $SD = 1.2$).

Sense of Embodiment. Non-parametric analysis was conducted using a Wilcoxon test on each sub-scale of the embodiment questionnaire [54] (i.e. appearance, response, ownership, multi-sensory), as well as on the global embodiment score, w.r.t. the control laws (sticky vs. moderate unsticky). We did not find a significant effect of the control law on any of the individual components or over the SoE in general, which supports **H2.2** (appearance: $V = 97$, $p = 0.95$, $r = 0.01$; response: $V = 47$, $p = 0.98$, $r = 0.37$; ownership: $V = 127$, $p = 0.2$, $r = 0.27$; multi-sensory: $V = 120.5$, $p = 0.31$, $r = 0.21$; agency: $V = 85.5$, $p = 0.69$, $r = 0.06$; overall: $V = 125$, $p = 0.47$, $r = 0.17$). On average, the global embodiment score was medium ($M = 3.7$, $SD = 1.9$).

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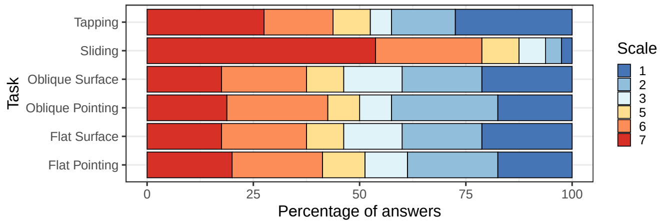

Fig. 9. Distribution of responses regarding user preference. The 7-point scale is (1) Surely Sticky, (2) Probably Sticky, (3) Maybe Sticky, (5) Maybe Unsticky, (6) Probably Unsticky, (7) Surely Unsticky. The neutral answer (4) was removed and could not be selected by participants.

User Preference. First, we visually inspected the distribution of responses, i.e. the percentage of responses for each scale value ((1) surely sticky, (2) probably sticky, (3) maybe sticky, (5) maybe unsticky, (6) probably unsticky, (7) surely unsticky). We observed a symmetrical distribution of responses for all tasks except the sliding task (see Figure 9), i.e. the proportion of response 1 was comparable to the proportion of response 7, the proportion of 2 to 6, and the proportion of 3 to 5. For the sliding task, almost all of the responses were in favor of unsticky, which only supports **H2.3c**.

It should be noted that the majority of responses were 'surely' or 'probably' and less frequently 'maybe', suggesting that participants made fairly strong choices on each trial. In addition, we investigated the average preferences per participant per task. For all tasks except the sliding task, about a third of the participants prefer sticky, a third prefer unsticky, and a third were undecided. To explain the inter-user variability, we explored the potential correlation between the generated offset or the speed of movement and user preference, but no significant correlation was found.

User Feedback. At the end of the experiment, we asked each user for feedback on their experience. Debriefing with them enabled us to observe that a large proportion of the participants had made conscious and justified choices, although the justifications of some were not compatible with those of others. For example[1], a participant said "*I preferred the [sticky] law for the tasks where I had to tap because this law gave me the impression that I could validate the contacts better. On the other hand, I preferred the [unsticky] law for tasks where I had to draw. The fact that my movement was more faithful seemed more important for this type of task*". Another participant said "*Overall, I preferred the [unsticky] law, but for the path following task, it was more difficult (...), so I preferred the [sticky] law*". So, here already, there is a complete contradiction between their preferences. A third participant declared that "*the [unsticky] law bounces around a bit too much, but the [sticky] law is more unpleasant to use*" while another participant said that "*objects appear soft when using the [unsticky] law, whereas they appear normal and hard with the other [sticky] law*". Again, when a user feels that the unsticky law is bouncy, another user feels that it gives a normal touch.

1. The name of the control laws between [] in the quotes were replaced for clarity, but these names were not known or used by participants.

5.7 Discussion

The goal of the second experiment was to assess the impact of the control law and the task on the sense of embodiment, the feeling of control, and user preference.

As a first hypothesis, we postulated that the feeling of control would not influenced by the offset recovery technique. The results showed that both laws obtained similar ratings, thus supporting **H2.1**. Moreover, these results are also supported by non-significant results regarding the sense of embodiment, for which no difference was observed in the global or individual sub-scales, which also supports **H2.2**. Both results suggest that the subtle effects of the control laws tested did not hinder users' ability to embody themselves in their avatar nor their ability to control it. It should be noted that the levels of embodiment reported in this experiment were moderate, probably due to the use of a single hand as an avatar. Thus, it is not excluded that a higher level of embodiment would enable the highlighting of small differences that went unnoticed in this experiment.

Regarding user preferences, we further hypothesised that they would be dependent on the task. Considering the results, only **H2.3c** was supported while **H2.3a**, **H2.3b**, and **H2.3d** were not. There may be many reasons why the task effect was not significant for the pointing, path following, and the tapping tasks. First, the visual consequences of each one could be too subtle or may represent a small proportion of the total interaction time to result in a unanimous preference. However, based on user feedback described in Section 5.6, it appears that users were able to detect the alterations, but did not appreciate them in the same way. In contrast, for the sliding task, as most users generated offsets while sliding over the first object, they generated a noticeable discontinuity of the virtual hand motion, which was not well appreciated, resulting in higher preferences for the unsticky law. In addition to visual artifacts, other factors could have influenced these results, such as the attention participants paid to their hand movements, the haptic sensations generated (e.g., soft/hard surface), or their ability to adapt to the motion alteration and thus their ability to perform the task. Although some correlation analyses were performed taking into account hand speed, generated offset and user preferences, no significant correlation was observed.

Overall, these results suggest that, unless strong noticeable motion artifacts are present, user preferences were strongly driven by individual differences. This hypothesis is supported by the fact that participants reasoned their choices based on subtle impressions. More experiments are however needed to further explore the specifics of such individual differences

6 General Discussion and Future Works

Through two experiments, we investigated how the positional mismatch between the user's real and virtual hands is recovered upon release of contact with virtual objects. In the first experiment, we explored the impact of positional offset and motion alterations on aimed movements. Although the results showed that all methods achieved a comparable level of performance, faster offset recovery methods were preferred by users. Furthermore, the slow recovery method was unable to absorb the offset generated, altering the motion profiles during aiming gestures. In the second experiment, we assessed the impact of the control law on the sense of embodiment, the feeling of control, and the user's preference with a larger variety of interaction tasks without artificially generating offsets. Overall, as both methods did not generated noticeable visual disturbances and enabled users to perform the proposed tasks, users rated both methods similarly regarding the sense of embodiment and the feeling of control. In the following, taken together the obtained results, we discuss the user preferences and the potential implications for design of interactive VR applications.

Overall, the results highlight that participants are sensible to visual discontinuities of the hand (e.g., during the sliding task), which has been previously shown to be detrimental to the virtual embodiment [55]. However, in the absence of visual discontinuities, user preferences were strongly dependent on the task and individual differences. The different control laws can have an impact on the judgment of agency, and in particular on the principles of priority and consistency [56]. While the sticky law can introduce a delay between the action and the sensory feedback, the unsticky law introduces a mismatch between the predicted and the performed visual motion. While the magnitude of the mismatches could be explained by the speed profiles of the overall offset generated, the analysis yielded inconclusive results. We believe that further exploring their causes would be valuable in the future to better adapt the experience to each user, for example, exploring whether the detection thresholds, users' attention or individual skills could modulate their preferences.

However, we believe that these results could go beyond user preferences. For example, some users mentioned the control laws elicited different physical sensations while interacting with the virtual objects. This elicitation can be explained by how each control law alters the control/display (CD) gain during the release phase. While the sticky law could generate a CD gain of zero, the CD gain for the unsticky control law during the offset recovery phase is lower than 1. A large body of literature has shown that the alteration of the CD gain could indeed elicit pseudo-haptic sensations [31], and in particular sensations of weight [17], [57]. This observation highlights that the control law could have an impact, not only on how the motion of the avatar is perceived, but also on the elicited sensations. Further studies on detection thresholds or just noticeable differences could better determine when such illusions arise.

In our opinion, these results highlight the need for letting users choose the control scheme of their visual representation, similarly as desktop users can customize the sensitivity of their mouse. Customizing the interaction method could be beneficial to the majority of users whatever the application, as long as manual interactions are central. This includes, for example, object manipulation applications (e.g., solving puzzles, drawing, constructing, training in machine operation). While choosing the control law according to the task to be performed does not seem to be the priority given the results of these experiments, our results show that it is still important in simple cases where visual discontinuities created by the sticky control law can easily be anticipated, such as in the case of the sliding task. Similarly, choosing the control law according to the user's movements could be an interesting alternative to explore in the future, which would however require the ability of predicting the user's movements to enable seamless dynamical adaptation.

Finally, it remains unclear how the extension of the proposed methods could be applied to full-body avatars, and if they will yield similar results. Future research is required to provide a holistic control method for avatars to ensure coherent and plausible interactions with complex virtual environments, minimizing the impact on the sense of embodiment.

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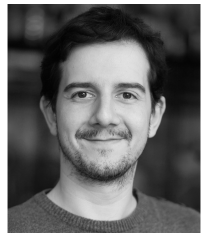

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