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Self-attribution of distorted reaching movements in immersive virtual reality



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ABSTRACT

This study explores the extent to which individuals embodied in Virtual Reality tend to self-attribute the movements of their avatar. More specifically, we tested subjects performing goal-directed movements and distorted the mapping between user and avatar movements by decreasing or increasing the amplitude of the avatar hand movement required to reach for a target, while maintaining the apparent amplitude – visual distance – fixed. In two experiments, we asked subjects to report whether the movement that they have seen matched the movement that they have performed, or asked them to classify whether a distortion was making the task easier or harder to complete. Our results show that subjects perform poorly in detecting discrepancies when the nature of the distortion is not made explicit and that subjects are biased to self-attributing distorted movements that make the task easier. These findings, in line with previous accounts on the sense of agency, demonstrate the flexibility of avatar embodiment and open new perspectives for the design of guided interactions in Virtual Reality.

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1. Introduction

Human perception is not a perfect capture of reality, and much of the information we experience as being collected from the external world is the product of brain inference [1]. This is an important enabling factor for Virtual Reality (VR) technologies, as they do not have to match the physical reality and the physiological limits to be effective. An interesting consequence of faulting human perception is that of cross-modal illusions. For instance, in the well known ventriloquist effect, the synchronicity of the moving puppet mouth and the ventriloquist voice gives the perception that the sound is being projected from the puppet. This illusion implies that auditory perception can be shaped by vision – in an example of visual capture [2,3] – and that the perception of a coherent whole may predominate in spite of incongruent multimodal input.

Researchers in VR have long explored faulty perception and modal predominance to improve interaction. For instance, in a family of navigation techniques known as redirected walking, the predominance of visual over vestibular sensory information is exploited to maximize the virtual space accessible through natural walking [4,5]. Moreover, incongruent visual and tactile sensory input was used to evoke richer haptic sensations in a perceptual illusion known as pseudo-haptics [6], where visual stimulation could induce haptic sensations that are more complex than the physical interaction device is capable of representing. On the other hand, little attention has been given to the perception of avatar movement distortion in embodied VR. That is when the movement of limbs or end effectors of an avatar representation are manipulated relative to the actual movement of the subject.

In this paper we use VR to analyze the extent to which participants self-attribute a distorted movement (Fig. 1). Here we define self-attribution as the state where users are more likely than not to acquire the perception that they have complete control over the movements of a virtual hand. Self-attributing movements of a virtual body as one's own is essential in establishing and sustaining the senses of ownership and agency over that body [7], i.e. the

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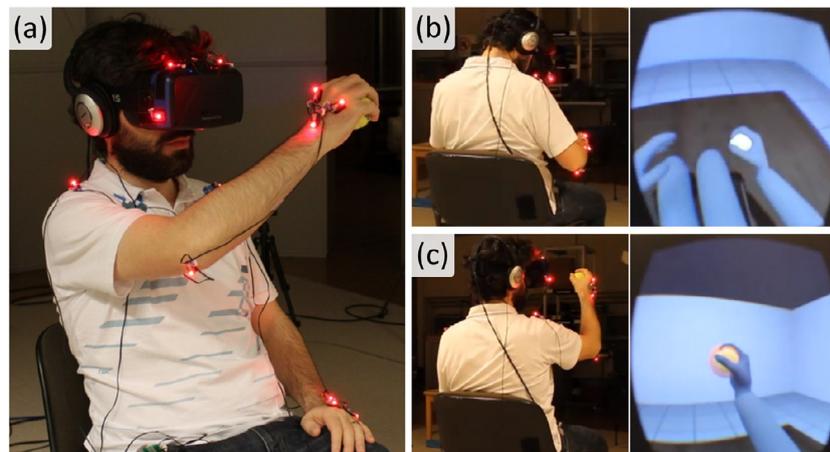


Fig. 1. Overview of the experimental setup. (a) shows a subject equipped with HMD, headphones and motion capture markers. In (b) the subject observes the virtual body, and in (c) performs the reaching task.

feeling that a body is one's own, and the feeling that one has control over the actions of that body.

We manipulate the movement of a virtual hand (of a fully-embodied subject) in order to help or hinder the completion of a reaching task. This effect is achieved by decreasing or increasing the (physical) amplitude of the hand movement necessary to reach the target as compared to the apparent (visual) amplitude of the task. Consequently, when a reaching is helped (or hindered), the physical movement becomes shorter (or longer) in amplitude than the visual inspection of the task suggests. One of the most salient features of the distortion during the movement is that the virtual visual feedback of the hand may move faster or slower than the physical hand. This visuo-motor discrepancy characterizes a spatiotemporal distortion that consequently builds into a visuo-proprioceptive mismatch.

We conducted two experiments with this distortion model. The first aims at quantifying the limits of self-attribution of the distorted movement, in which subjects are asked if a seen movement matches the movement they have performed. The second experiment acquires subject's judgment on whether a given level of distortion makes the reaching task easier or harder to complete than when no distortion is applied. The latter is not always obvious because it involves a trade-off between the manipulated movement amplitude (objective manipulation of difficulty) and one's capacity to promptly correct an ongoing movement that has been distorted. It is our hypothesis that we can manipulate (i.e. distort) movements to effectively alter the difficulty of a task without the awareness of the subject. We relate our results with the literature and demonstrate that currently known threshold estimates are conservative. Moreover, we argue that embodied VR experiences could take advantage of flawed human perception and self-attribution optimization mechanisms to improve interaction with virtual environments.

This paper is organized as follows. The next section discusses the sense of agency in cognitive neuroscience and related work in the field of VR. Section 3 describes the materials and methods, including the details on the distortion model that we used in the experiments. Sections 4 and 5 present the experiments and respective results. Results are discussed in Section 6, followed by the conclusion in Section 7.

2. Background

The sense of embodiment is intimately related to the sensation of being the subject of an experience [8], which is at the core of VR

experiences. One feels embodied due “to the ensemble of sensations that arise in conjunction with being inside, having, and controlling a body” [9] (p. 374). Therefore, the feeling of being in control of the actions of a body, the so-called sense of agency [10], is a crucial component of the sense of embodiment. Agency in humans represents an adaptive causal link, that seems to be constantly modeled by action and outcome contingencies developed by repetition [11].

When referring to one's body, the sense of agency seems predominantly related to the sensation of motor control over that body. As a consequence, the ability to self-attribute a movement by correlating motor commands with the acquired sensory information, as we study here, is a significant factor to sustain an elevated sense of agency of a virtual body. In a pioneering study, Nielsen [12] has demonstrated that healthy subjects can be tricked to self-attribute movements that have been produced by another person. This was the case even when there was a discrepancy between the performed and seen movements, with subjects reporting the feeling of strangeness and the impression that their hands have been pulled by some external force. This experiment shows that someone else's hand can be perceived as one's own, and that up to a certain limit, one can be fooled to self-attribute the actions of that hand.

Notably, a related effect can be observed in a series of publications in the field of VR, where authors explore the notion of pseudo haptics proposed by Lecuyer et al. [6,13,14]. Pseudo haptics relies on cross-modal perception in order to elicit the sensation of haptic interaction with objects of different physical properties. For instance, Lecuyer et al. [6] manipulate the control-display ratio (CDR - the ratio mapping the input of a device to an output in a display) of a mouse to convey pseudo haptic sensations. The mouse is used to control a cube in the screen, and when the cube passes through a delimited area, the CDR could either increase or reduce. Subjects reported the sensation of “lightness” and “gliding” when the CDR increase, and “friction” and “viscosity” when the CDR was reduced. That is, the added/reduced effort resulting from the longer/shorter distance the subject had to cover due to an incongruent visual, proprioceptive and tactile feedback was felt as a tangible obstacle. Push et al. [15] extend the use of pseudo haptics to deviate the visual representation of the user's hand position. In their system, the physical and virtual hand position become incongruent to convey the sensation of interacting with a force field affecting specific regions in space. The authors demonstrate that users may feel a “pushing” sensation, not unlike what was reported by Nielsen [12].

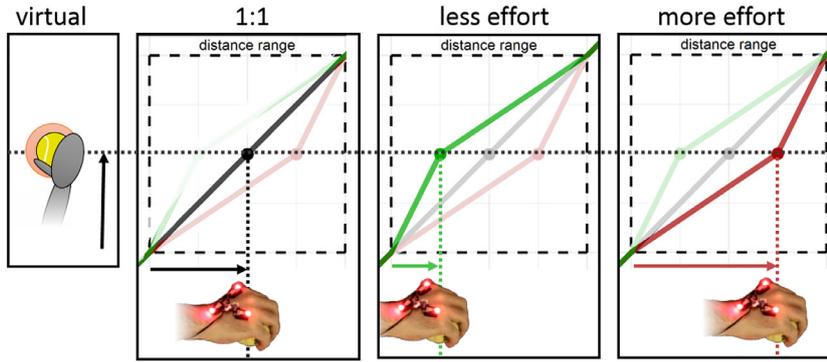


Fig. 2. Overview of the distortion manipulation. The horizontal axis depicts the physical hand position, while the vertical axis depicts the virtual hand position. The lines map a movement from the left to the right, where three distinct physical hand positions result in the same virtual hand position due to the parameters of our distortion model. The green and red colors represent a helping and a hindering distortion respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In a related topic, Kohli [16] explored the distortion of movements in order to redirect haptic sensations. The goal was to use a passive haptic device as a proxy to a more complex virtual object. To evaluate this concept the authors designed an experiment where subjects had to perform a multi-directional pointing task over a tilted plane, while the visual feedback presented a user facing tapping plane [17]. This sort of manipulation has been further explored by Ban et al. [18,19] and Azmandian et al. [20]. They demonstrate that users may self-attribute distorted movements provided that visuo tactile consistency is preserved, i.e. if they feel and see the tactile contact. In contrast to these experiments, our study examines aspects of incongruent visuo-motor feedback, eliminating the tactile component. Furthermore, Banakou and Slater [21], Kokkinara et al. [22], Debarba et al. [23], and Caola et al. [24] have recently shown that one may acquire some degree of agency of movements that they did not performed, but saw an avatar performing from a first person perspective. The work from Caola et al. [24] is of special relevance in our context as it investigates the sense of agency of arm movements that have only been performed by the avatar. Note, however, that their results do not imply a high likelihood of participants manifesting a sense of agency, but of some participants reporting an occasional feeling of control over the avatar. Overall, these results demonstrate that Nielsen’s findings also hold in the context of VR, and that VR is a valid tool for research in the subject of the sense of agency (see [25,26] for a discussion).

Few studies worked on the subject of perception quantification of distorted movements in VR. The work of Burns and colleagues is of particular interest as it explored two aspects of visuo-proprioceptive mismatch. The first concerns the perception of misplacement of physical and virtual hands, [27] shows that a person may be strikingly unaware of visuo-proprioceptive mismatches which were gradually introduced over a long period of time. In the study, participants primed to know that the mismatch would happen noticed the discrepancy when it reached 20deg, while unprimed participants only noticed it when the mismatch reached 40deg. The second aspect concerns the perception of movements with spatiotemporal distortions, in [28] the authors evaluated the perception threshold of hand movements that had their virtual speed reduced or amplified (results are reproduced in Table 2). In contrast to [28], here we aim to explore the question of self-attribution, while also introducing a full virtual body to the experience.

Furthermore, Kokkinara et al. [29] have shown that, by increasing the speed of reaching movements, an after effect change to the perception of space can be observed. More specifically, after being exposed to a spatiotemporal distortion mapping physical hand to

virtual hand (2x and 4x the speed), participants tended to overestimate the size of an object, an after effect indicating sensorimotor adaptation (visuo-proprioceptive remapping). They have also shown that this distortion seems to have only a small impact on the overall sense of embodiment of the virtual body. Distinct from this study, we aim at analyzing the perception of individual actions that have been manipulated, similar to how Hay [3] defines the concept of visual capture and contrasts it with sensorimotor adaptation.

3. Materials and methods

3.1. Distortion model

We propose a distortion model that alters the visual feedback of movements in order to help or hinder a reaching action. In practice, the model is used to decrease or increase the physical distance that one has to move to reach a target as compared to the apparent distance seen in VR. Therefore, the reaching may require a bigger or smaller amplitude of movement, and consequently more or less effort than the visual assessment of the task may suggest. This is graphically depicted in Fig. 2, where three different physical hand movements – correct, reduced and increased amplitude of movement respectively – result in identical virtual hand position.

The distortion model maps a physical position ($\mathbf{p}_{physical}$) into a virtual position ($\mathbf{p}_{virtual}$), and is only applied within the volume of the sphere with center and radius defined by the target position (\mathbf{p}_{tgt}) and the distance range of the distortion (d_{range}), respectively. As a result, when the physical distance to the target ($d_{physical} = \|\mathbf{p}_{physical} - \mathbf{p}_{tgt}\|$) is bigger than d_{range} , the virtual and physical positions are collocated, since the physical position is outside of the distortion volume. A limited distortion volume is used so that the distortion can be implemented in a variety of reaching task configurations. It makes the distortion related to each target independent and constrained to a volume. Therefore, it can be used in scenarios where multiple simultaneous targets, each with its own action volume, are present or where navigation is permitted. Mind that, although the distortion allows such scenarios, we explore the simpler case in our experiment. The following equation is used to update $\mathbf{p}_{virtual}$:

$$\mathbf{p}_{virtual} = \begin{cases} \mathbf{p}_{physical} + (\mathbf{p}_{tgt} - \mathbf{p}_{max}) \cdot \alpha, & \text{if } d_{physical} \leq d_{range} \\ \mathbf{p}_{physical}, & \text{otherwise} \end{cases}, \quad (1)$$

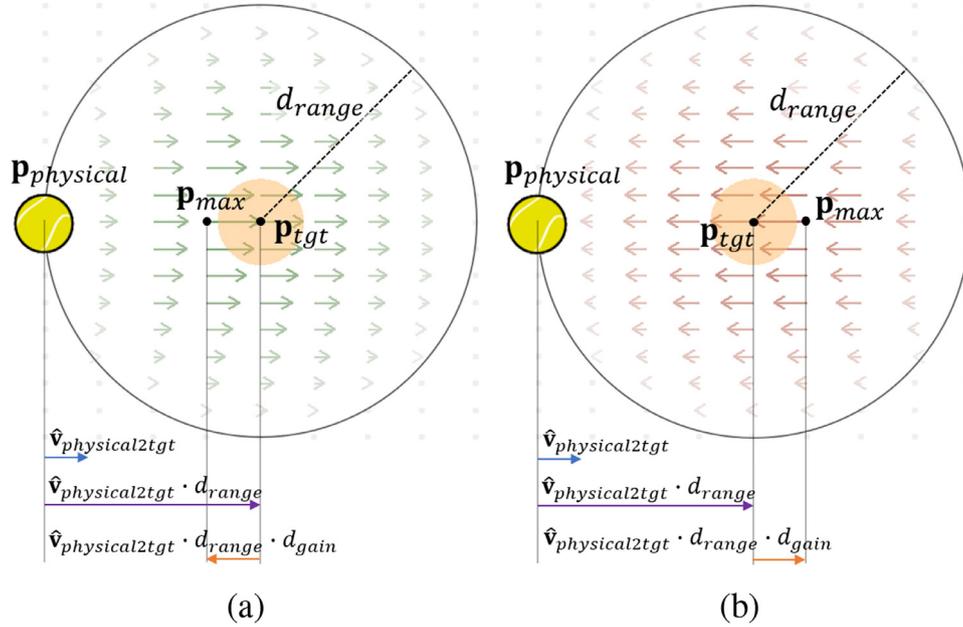


Fig. 3. Vector fields of a cross section of the distortion volume and variables defining the \mathbf{p}_{max} of the helping (a) and hindering (b) distortions. The yellow object represents the $\mathbf{p}_{physical}$ as it enters the distortion volume. The tip of any given arrow indicates $\mathbf{p}_{virtual}$ when $\mathbf{p}_{physical}$ is located at the base of that arrow. d_{gain} was set to -0.25 . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where \mathbf{p}_{max} defines the position in physical space where the distortion reaches its maximum, \mathbf{p}_{max} is computed by:

$$\mathbf{p}_{max} = \mathbf{p}_{tgt} + \frac{\mathbf{p}_{tgt} - \mathbf{p}_{physical}}{d_{physical}} \cdot d_{range} \cdot d_{gain}, \text{ when } d_{physical} > d_{range}. \quad (2)$$

where $\hat{\mathbf{v}}_{physical2tgt}$ is the normalized vector from $\mathbf{p}_{physical}$ to \mathbf{p}_{tgt} .

Note that \mathbf{p}_{max} is only updated if $\mathbf{p}_{physical}$ is outside of the volume of the distortion sphere. Its purpose is to align the distortion field with the incoming direction of the real hand before it enters the distortion field. Once the real hand is within the sphere the orientation of the distortion field is frozen. An overview of how \mathbf{p}_{max} is computed is presented in Fig. 3.

The value of α depends on the proximity of $\mathbf{p}_{physical}$ to \mathbf{p}_{max} :

$$\alpha = 1 - \frac{\|\mathbf{p}_{physical} - \mathbf{p}_{max}\|}{\|\mathbf{p}_{intersect} - \mathbf{p}_{max}\|}, \quad (3)$$

where $\mathbf{p}_{intersect}$ is the intersection point of the vector $\mathbf{p}_{physical} - \mathbf{p}_{max}$ with the surface of the distortion sphere, and is computed at every update. As a consequence, the closer $\mathbf{p}_{physical}$ is to \mathbf{p}_{max} , the closer $\mathbf{p}_{virtual}$ will become to \mathbf{p}_{tgt} .

Two parameters are used to control the magnitude of the distortion, d_{range} and d_{gain} . d_{range} defines the radius of the distortion sphere, as described earlier. d_{gain} , in turn, defines the proportion of d_{range} by which the movement may be distorted. Therefore, $d_{gain} \cdot d_{range}$ refers to the increase/decrease in the physical distance. For instance, if $d_{gain} = 0.5$, the straight line movement from the surface of the sphere to the target becomes 50% longer than the apparent visual distance. If $d_{gain} = -0.5$, the same movement becomes 50% shorter than the apparent distance. As a consequence d_{gain} is bounded by $-1 < d_{gain} < 1$ so that \mathbf{p}_{max} lays within the volume of the distortion sphere.

The distortion model that we described preserves the continuity of the movement as it enters and leaves the volume of the distortion sphere, this is true no matter the direction of the movement. For instance, once the physical hand enters the sphere, a negative d_{gain} distortion speeds up a straight movement towards the target until the virtual hand reaches the target, while a positive

d_{gain} distortion slows down the movement. However, if the movement resumes towards the same direction after reaching the target, the movement distortion is reversed so that the virtual hand is brought to collocation with the physical hand once it leaves the volume of the sphere. In addition, the inversion of the distortion after the target is reached ensures that the interaction size of the virtual target is kept constant along the direction of distortion for any value of the d_{gain} parameter. Fig. 4 shows the progression of a movement with a helping distortion until the virtual hand reaches the target (left to right).

3.2. Equipment and software

An Oculus development kit 2 Head Mounted Display (HMD) was used to display the virtual scene (960 x 1080 pixels per eye, ≈ 100 deg field of view, 75 Hz). A pair of Bose®Quietcomfort 15 headphones were used for environmental noise canceling and to provide non localized white noise, thus phonically isolating the user from the real environment.

A PhaseSpace ImpulseX2 optical tracking system with 18 cameras was used to track 14 LED markers. Four markers were attached to the HMD, three markers were fixated over the back of each hand to estimate its position and orientation in space, a marker was fixated over the top of each shoulder to estimate trunk movements, and a marker was attached to each elbow to solve for the ambiguity of the elbow bend direction around the shoulder to hand vector. We assessed a tracking latency in the range of 30 ms–40 ms from physical action to HMD display. HMD orientation tracking was performed using the built-in inertial sensors and corrected for drift around the vertical axis using optical tracking, this yields lower virtual camera update latency than using the optical tracking alone while preserving the correctness of the tracking (i.e. correction of the absolute tracking source happens at a higher rate than the drift of inertial sensors). Fig. 1a shows a subject wearing HMD, headphones and LED markers.

The virtual environment was developed using the Unity game engine. It consists of a room, with a virtual body, a chair, and a carpet that are collocated with the subjects' body, a real chair, and

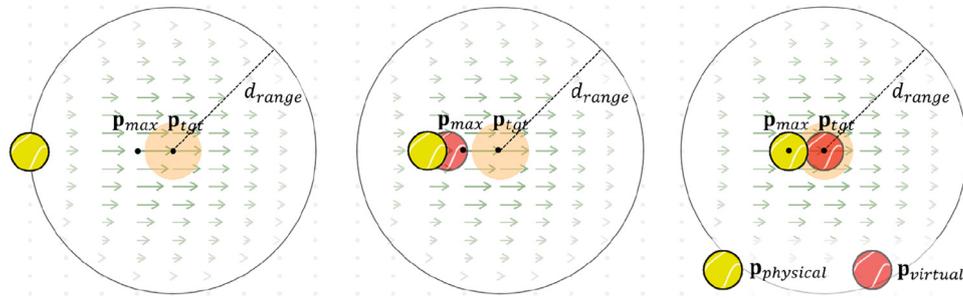


Fig. 4. Vector fields of a cross section of the distortion volume. The yellow and red objects indicate the development of a movement and its physical ($\mathbf{p}_{\text{physical}}$) to virtual ($\mathbf{p}_{\text{virtual}}$) mapping. The orange highlight indicates the target volume and position (\mathbf{p}_{tgt}). The tip of any given arrow indicates $\mathbf{p}_{\text{virtual}}$ when $\mathbf{p}_{\text{physical}}$ is located at the base of that arrow. d_{gain} was set to -0.25 . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a real carpet present in the physical environment. The subjects and their avatars held a tennis ball with the right hand to prevent the subjects from performing complex finger movements. This design decision ensures a similar visuo, proprioceptive and tactile stimulation between their hand and the virtual hand, in spite of the fact that fingers were not being tracked.

The virtual body was animated in real time using the FinalIK package¹. Virtual hands position and orientation have high priority. Therefore, the posture of the virtual body is defined while ensuring the collocation of the virtual hands with the rigid body defined by the LED markers plus the distortion added by our model. Hips and legs were not tracked nor animated, participants were asked to remain seated during the experiments. Fig. 1bc shows sample captures of the posture reconstruction used in the experiments. Moreover, the virtual body and its limbs were scaled to approximately match the body of the subject. This was done before the start of the experiment by measuring the height of the subject and the length of their right arm and leg segments.

Since the markers attached to the hands could not be placed at identical positions across subjects, a short physical to virtual hand registration was necessary. Once equipped with the HMD, participants could see small green spheres at positions corresponding to the LED markers being worn. The participants were asked to position these spheres over the hands of the virtual body at the equivalent position where the LED markers were located on their hands.

3.3. Task

The task consisted of two movements and a question. In the first movement, the subject had to place the tennis ball held with their right hand inside a semitransparent virtual target. After a random interval lasting between 200ms and 600ms, the target disappeared and a second semitransparent target appeared. The participant had to perform a second movement and place the ball inside the new target. However, the visual feedback of the second movement could be manipulated using our distortion model, thus interfering with the task. The task is completed once the ball is kept inside the second target for 150ms. The tennis ball and the semitransparent targets have a diameter of ≈ 6.7 cm and 10 cm respectively. Finally, the screen becomes black, and a question appears. Participants could answer the question by orienting their head to face the desired answer. The question and answer options were different according to the experiment. The subject was required to lower the right hand before the next trial could start. Fig. 5 provides the overview of a task trial.

We used four predefined positions for the targets. They were arranged around a central point at the height of the eyes of the

subject; one target above, one below, one to the left, and one to the right. These four target positions defined a plane in front of the subject. The distance of each target from the central point was equivalent to 25% of the subject's arm length. The central point was in front of the camera, at a distance of 50% of the arm length. In experiment 1, a trial would require either an upward, downward, leftward or rightward movement. For example, in a trial requiring a leftward movement, the subject had to first reach for the target in the right (first target), and then perform a movement to the target located in the left (second target). Therefore, the apparent (visual) distance of the movement is always equivalent to 50% of the subject's arm length, while the actual physical movement depends on our distortion model and the distance gain parameter (d_{gain}). The second target position was used to define the center of the distortion sphere while the radius (d_{range}) was defined by the distance between the first and second targets (i.e. 50% of the arm length). We emphasize that the movement to the first target was never distorted. Only the second movement, from the first target to the second target, could be distorted.

3.4. Movement distortion units

The distortion model described in Section 3.1 uses a distance gain (d_{gain}) to define the magnitude of distortion. This gain describes the increase or reduction of the physical distance necessary to reach a target. However, the most salient feature of our distortion model during the movement is the difference in velocity. A distortion that facilitates the reaching movement presents an increased velocity until the virtual hand reaches the target, and a reduced velocity if the movement continues on the same direction until virtual and physical hand positions match by leaving the distortion sphere. The opposite happens with a distortion that hinders the movement. In the experiments that we perform, the first part of this movement is always present. Thus, we opted to set the distortion in terms of gain in speed ($speed_{\text{gain}}$) instead of gain in movement amplitude. The d_{gain} parameter in the distortion model can be retrieved with $d_{\text{gain}} = -\frac{speed_{\text{gain}}}{speed_{\text{gain}}+1}$, for $speed_{\text{gain}} = \frac{speed_v}{speed_p} - 1$ where $speed_p$ and $speed_v$ are physical and virtual movement speeds respectively. However, based on pilot experiments that we conducted, as well as the results described by Burns and Brooks [28], we observed that the $speed_{\text{gain}}$ yields strong asymmetry when comparing the variances of the perception thresholds of helping and hindering distortions; this issue is detailed in the results section of the first experiment. Thus, we decided to define the measurement scale of the experiments in terms of speed gain in decibels, where $speed_{\text{gain}_{\text{dB}}} = 10 \log_{10}(speed_{\text{gain}} + 1)$. For instance, $speed_{\text{gain}_{\text{dB}}}$ values of -3 dB, 0 dB and 3 dB correspond to $speed_{\text{gain}}$ values of -0.5 , 0 and 1 respectively. That is, -3 dB is half

¹ root-motion.com

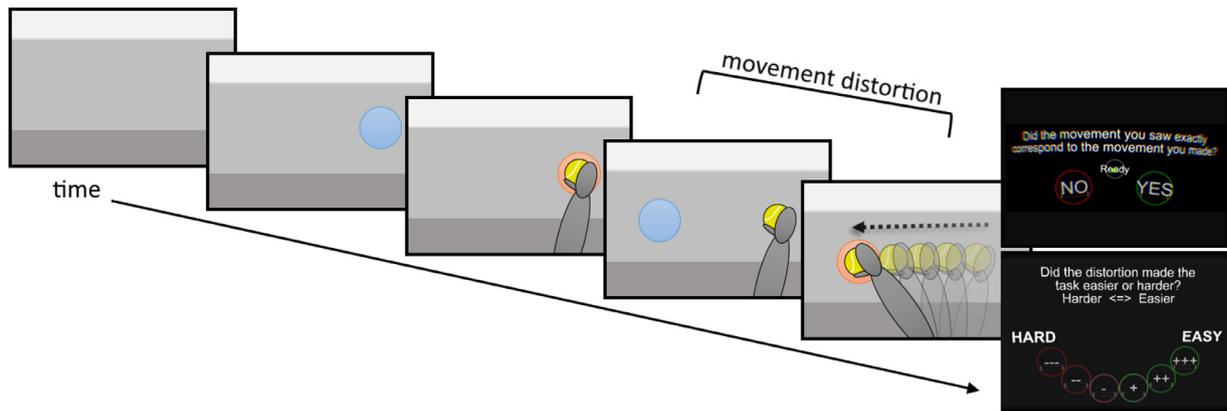


Fig. 5. Overview of a task trial. The trial consisted of two movements and a question: in the first movement the subject had to place the virtual hand inside a first target, this movement was not distorted; the second movement required the subject to move the virtual hand from the first target to a second target, this movement may or may not be distorted. The question was different for each experiment: experiment 1 asked whether the movement was exactly like the one performed by the subject; experiment 2 asked if the applied distortion made the task easier or harder than if no distortion was used (subject orient their head to face the desired answer).

the speed, 0 dB is the same speed (no distortion), and 3 dB is twice the speed.

3.5. Procedure

The experiment was carried as follows, subjects:

1. read an information sheet and signed an informed consent form;
2. filled a characterization form, with questions about their background and physical characteristics;
3. had the length of their right arm, forearm, thigh, and leg measured, and were equipped with the tracked markers;
4. received instructions and an overview of the task;
5. were equipped with the HMD and headphones;
6. performed experiment 1;
7. had a mandatory rest interval;
8. performed experiment 2;
9. debriefed with the experimenter.

A total of 20 subjects participated in both experiments (mean age 23.9 with SD of 4.5, 3 female). All of them declared to be right-handed. Six subjects reported having participated in an experiment using virtual reality in the past, while eight reported having tried an HMD in the past, one of which with weekly frequency.

This study was approved by the commission cantonale d'éthique de la recherche sur l'être humain in Vaud, Switzerland. Subjects signed a consent form and received 20 CHF/hour as a compensation for their time. The data collected in the experiments were made available at a public repository [30].

4. Experiment 1: Self-attribution thresholds

Experiment 1 was designed to estimate the thresholds of subjective self-attribution of redirected movements that help or hinder the completion of a goal-directed movement task. After the completion of each trial, we ask the subject "did the movement you saw exactly corresponds to the movement you made?", to which the subject had to answer by facing the "Yes" or "No" button. We define the interval of self-attribution as the range of distorted movements within which the subject is more likely to state equivalence between seen and performed movement (answer "Yes") than not (answer "No").

To quantify the limits of this range we adopt concepts and procedures from psychophysics. Psychophysics acts on the understanding of how a stimulus affects one's sensation/perceptions, and

is often employed to assess the minimum necessary change ΔI to a stimulus intensity I so that one can perceive a difference between $I + \Delta I$ and I with a high degree of confidence, normally more than 50% of the time. The minimum necessary change ΔI is also known as the just noticeable difference (JND) between a standard and an altered stimulus. While the JND describes an amount referent to a specific stimulus intensity, the Weber's Law states that the JND can be estimated by a constant proportion k of the stimulus when its intensity is not extreme. This has been shown to model the stimuli and perception threshold relation considerably well for different sensory modalities and tasks. The Weber constant k can be defined by the ratio:

$$\frac{\Delta I}{I} = k. \quad (4)$$

Therefore, we focus on measuring the constant k , which is used to approximate the ΔI for a given stimulus intensity I .

$$\Delta I = k \cdot I. \quad (5)$$

In order to assess the constant k , the distortion intensity was controlled by an adaptive staircase, a procedure that changes the intensity of the stimulus discrepancy based on the whether the subject could identify or not a discrepancy in the last trial [31]. In our particular case, if the participant answers "Yes" to a correct or distorted movement, the discrepancy is increased, i.e. the intensity of the distortion is increased as the participant could not identify it. If the subject answers "No" to a distorted movement, the discrepancy is decreased, i.e. the intensity of the distortion is decreased as the participant could identify it. Finally, as the staircases were oriented either to help or hinder the movement, a staircase was not allowed to switch from one of these modes to the other. This means that if the subject answers "No" in a trial where no distortion is present, the position in the staircase will not change (i.e. it is not possible to make the movement more correct), and an identical trial will be evoked next in that staircase sequence.

The staircase was complete when either the subject switched the direction of the staircase seven times (e.g. from a distortion increase to a distortion decrease trend) or performed a total of 20 trials in the same staircase. The ΔI , used to approximate the constant k , was computed as the mean of the four last staircase turns (Fig. 6). Each subject underwent a total of two blocks of 16 staircases, for a total of 32. Thus, for each combination of distortion type (helping or hindering) and movement direction (upward, downward, leftward or rightward) the subject performed four staircases: two starting with a correct mapping (0 dB) and an initial trend to increase the distortion magnitude, and two starting with

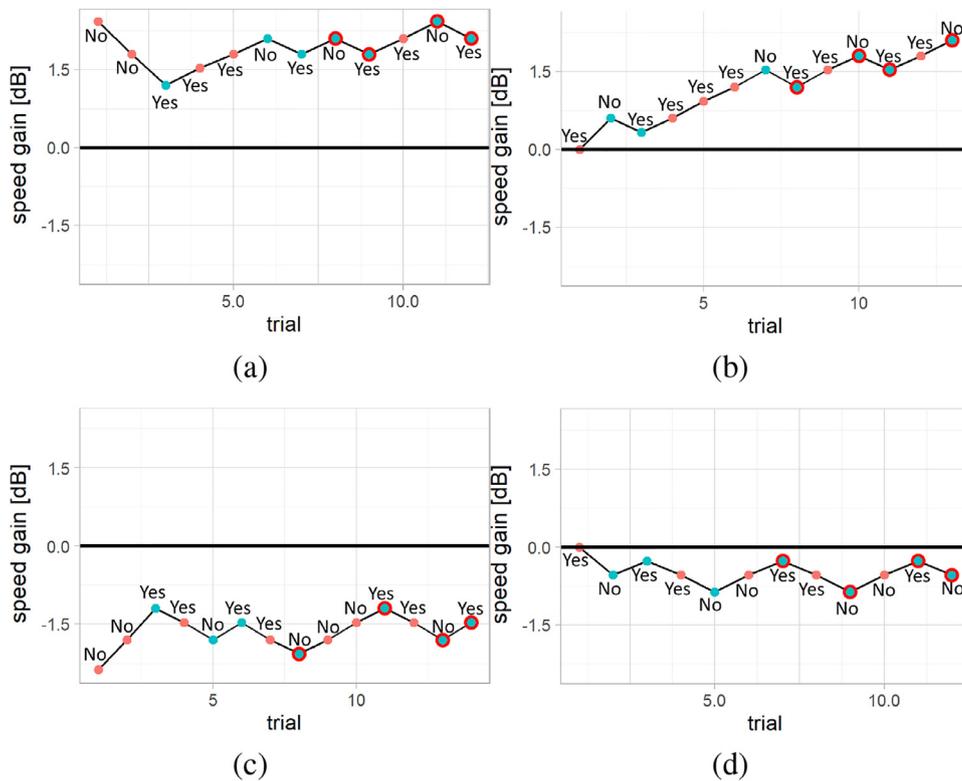


Fig. 6. Samples of adaptive staircases. Note that the staircases were oriented to either reduce (a,b) or increase (c,d) the required physical movement. A staircase could start either from a high (a,c) or a no (b,d) distortion condition. The self-attribution threshold estimate was computed as the mean of the last 4 blue points (circled in red), which represent turns in the trend of the staircase (Yes to No or No to Yes). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Variables defining all the starting conditions of an adaptive staircase.

Variable	Levels
Distortion type	Help or hinder
Direction	Left, right, up or down
Initial distortion	0 dB or 2.4/-2.4 dB

a high level of distortion (2.4 dB for helping and -2.4 dB for hindering distortions) and an initial trend to decrease the distortion magnitude. An overview of the factors defining a staircase is presented in Table 1. The size of the staircase step changed dynamically, it started as 0.6 dB, and it was halved to 0.3 dB after the first staircase turn. The latter value is used for the remaining trials of that staircase procedure.

A second relevant measurement is the point of subjective equality (PSE), i.e. the point at which the participant subjectively evaluates a presented stimulus to be equivalent to the standard stimulus. The PSE may be computed as the point in between the helping and hindering ΔI . This should yield a good approximation as long as we can assume symmetry of the relation of the measurement scale with perception around the PSE.

Note that our study aims at identifying the effect that a distortion can have when applied to a single movement, much like visual capture [3]. It is distinct from prior work on sensorimotor adaptation in that we do not provide the subject with an incentive for long-term adaptation to the distortion [29]. Instead, we seek to prevent such adaptation by implementing two mechanisms; (i) the first movement in a trial is never distorted, the subject is therefore exposed to a correct (to the extent that tracking, latency and visual display distortion allows for correct physical to virtual mapping)

movement at every trial; (ii) we prevent the presentation of trials from the same staircase in a sequence by running four of the 16 staircases in the block concurrently. As a result, the subject would experience helping and hindering trials in a sequence quite often.

Subjects had to complete two short training blocks before starting the experiment. In the first training block, the subjects completed eight trials without any movement distortion. In the second training block, the subjects completed eight additional trials with a significant distortion (-2.4 dB and 2.4 dB), one for each combination of direction and distortion type. The subjects were told beforehand whether there would be a distortion in the training block, and what answer was expected in such case. This procedure was adopted to ensure that the subjects understood the task, and that they were shown what a movement distortion looked like without any verbal description of its features. After completing the training the subjects went through the two blocks of trials, each taking between 15 and 25 min. A sequence of eight non-distorted movements were presented at the start and end of each block. A rest interval was given between the blocks, and whenever the subjects requested for a pause during an ongoing block.

4.1. Results

For the analysis of experiment 1, we exclude the staircases that failed to converge, we defined these as: (i) staircases that reached 20 trials before completing a minimum of five turns, (ii) answering “no” when the staircase was at a no distortion point in the range of the last four staircase turns. A total of 640 staircases were completed, 62 of which removed because of (i) and 39 because of (ii), leaving a total of 539 staircase procedures. We also excluded two subjects as they failed to converge in at least one staircase per

Table 2

Estimated self-attribution thresholds for $speed_{gain}$ and $speed_{gain_{dB}}$ scales (Mean \pm Standard Deviation), and comparison with literature.

Direction	Threshold [$speed_{gain}$] [28]* Faster – slower	Threshold [$speed_{gain}$] Faster – slower	Threshold [$speed_{gain_{dB}}$] Faster – slower
Left	+ .44 – – .08	+ .86(\pm .38) – – .13(\pm .07)	+2.42(\pm .81) – –0.63(\pm .36)
Right	+ .40 – – .06	+ .84(\pm .39) – – .21(\pm .06)	+2.49(\pm .87) – –1.08(\pm .36)
Up	+ .51 – – .16	+ .65(\pm .34) – – .18(\pm .06)	+2.04(\pm .87) – –0.87(\pm .30)
Down	+ .38 – – .27	+ .90(\pm .44) – – .27(\pm .06)	+2.55(\pm .87) – –1.41(\pm .33)

* Values from [28], in which the task was not target directed and the question explicitly concerned movement speed perception.

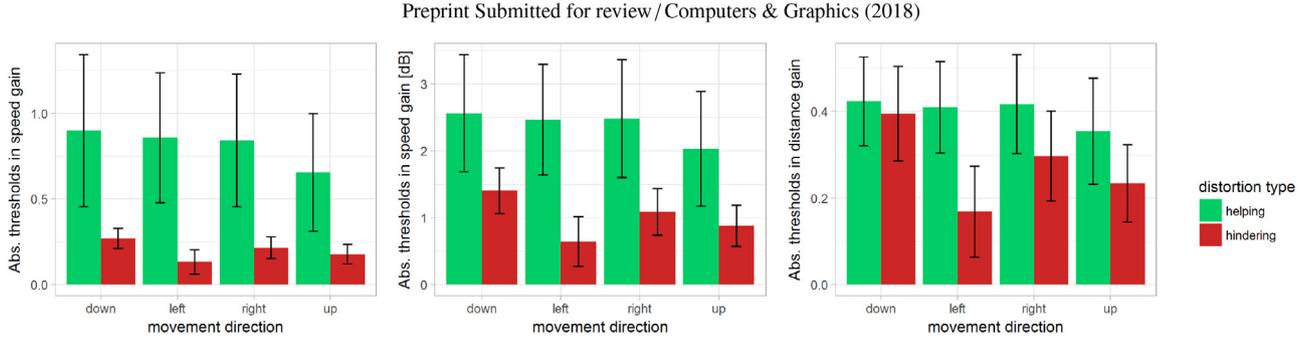


Fig. 7. Bar plots of the self-attribution thresholds for speed gain and distance gain (experiment 1). The difference between helping and hindering movement was significant in all directions and in all scales, except for the downward movement in distance gain scale. Error bars represent the standard deviation.

Table 3

Estimated self-attribution thresholds and Point of Subjective Equality (PSE) for distance gain scale (d_{gain} , Mean \pm Standard Deviation).

Direction	Threshold [d_{gain}] Decrease – increase	<i>t</i> -test <i>p</i> <	PSE [d_{gain}] Arithmetic mean	PSE [d_{gain}] Gaussian fit mean
Left	– .41 \pm .11 – + .17 \pm .10	.001	– .120 \pm .07	– .116
Right	– .42 \pm .11 – + .30 \pm .10	.004	– .060 \pm .08	– .070
Up	– .35 \pm .12 – + .24 \pm .09	.008	– .060 \pm .08	– .077
Down	– .42 \pm .10 – + .39 \pm .11	.343	– .014 \pm .06	– .013

combination of conditions. This left a total of 18 subjects for further analysis.

A summary of the thresholds of self-attribution is presented in Table 2. We present results in both, $speed_{gain_{dB}}$ and $speed_{gain}$ scales. The former is the measurement scale used in the experiment, while the latter is presented for comparison with the results reported in the related experiment described by Burns and Brooks [28].

In Fig. 7 we present absolute threshold values, comparing results for movement direction and the distortion type (helping or hindering). In spite of the use of the decibel scale, the variance of the helping and hindering results suggests that they are not compatible for direct comparison.

We tested variance across the levels of distortion type using an F-test of equality of variances for the different scales used to represent the thresholds. Both $speed_{gain}$ and $speed_{gain_{dB}}$ show a statistically significant difference when comparing the variance of the thresholds for the helping and hindering distortions ($F_{17} = .02$ $p < .001$ and $F_{17} = .12$ $p < .001$, respectively). Thus, we also examined the threshold results in the d_{gain} scale, which present similar variance across both levels of distortion type (failed to reject the equality of variances $F_{17} = .64$ $p > .35$).

These results suggest that d_{gain} is the most perceptually valid scale, and therefore the most reliable to estimate the Point of Subjective Equality (PSE) for each movement direction. balanced distribution of the helping and hindering distortions. Therefore we decided to compute PSE in this scale (the mean of both thresholds). Results are presented in Table 3, the PSE for movements

towards left, right and up, were found to be significantly different than 0. This implies that subjects found a distortion that made the reaching distance slightly shorter perceptually more correct than when no distortion was applied (i.e. higher self-attribution).

5. Experiment 2: Task difficulty

The second experiment acquires subject’s impressions on whether a given level of distortion makes the reaching task easier or harder to complete than it would be without any distortion. For instance, we suppose that by reducing or increasing the physical distance – relative to a virtual visual distance – that a participant has to move to complete a task, we are helping or hindering the completion of that task. However, the distortion might also cause a big mismatch between internal forward models predictions of sensory input and actual sensory input, requiring the subject to promptly correct an ongoing movement in order to comply with the distortion. Moreover, behavioral experiments have shown that the minimum delay needed for a visual or proprioceptive signal to influence an ongoing movement is around 80–100 ms [32]. Thus, if a movement is shortened too much it may become unpractical in terms of movement control mechanisms, potentially contradicting the assumption that such distortion is helping the user, and making the task easier.

The second objective of Experiment 2 is to verify if, when explicitly asked about task difficulty, subjects are capable of distinguishing movement distortions with more confidence than in Experiment 1.

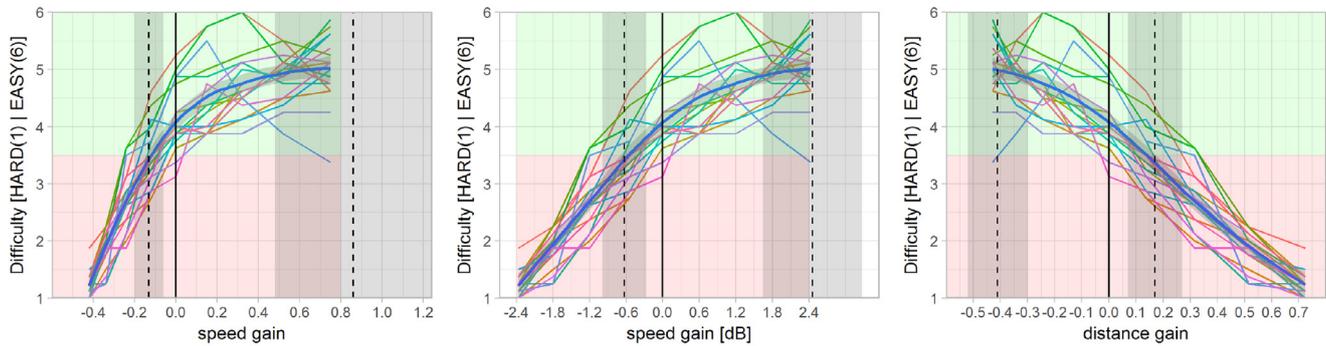


Fig. 8. Subjective evaluation of the difference in difficulty due to movement distortion; influence of speed gain and of distance gain (experiment 2). Note that in this experiment the subject only performed movements toward the left. The Self-attribution thresholds and their standard deviations from experiment 1 are marked by vertical dotted lines and a shaded grey area, respectively. The point where subjects become uncertain of whether the distortion was affecting difficulty coincides with the self-attribution threshold for hindering distortion. Colored lines represent individual subjects.

Experiment 2 followed a factorial within-subject design, with distortion intensity as the only independent variable (in $speed_{gain_{dB}}$, the same scale as experiment 1, with nine values ranging from -2.4dB to 2.4dB in steps of $.6\text{dB}$). In general lines, positive dB values represent distortions that we believe to help the subject, while negative dB values represent distortions that we believe to hinder the subject. The response variable was the difference between expected and felt difficulty. After each reaching the subject was asked: “Did the distortion made the task easier or harder?”. The answer was given in a forced choice six points scale (Fig. 5). Participants were led to believe that all the trials were distorted.

The experiment was divided into two short blocks, each with a total of 36 trials, four for each of the nine levels of distortion intensity. Each block took 3–5 min to complete. Movement direction was always towards the left. We did not needed to test other movement directions as Experiment 2 focus on comparing how subjects perceived the distortion when the context changes, i.e. when we explicitly ask about difficulty instead of self-attribution.

5.1. Results

For experiment 2, results are presented in Fig. 8. The blue line and the shaded region represents a LOESS fit (locally weighted regression) and its 95% confidence interval [33]. The vertical dashed lines represent the results of experiment 1 for the leftward movement for comparison. The green and red shaded areas highlight the “easier” and “harder” levels of difficulty available in the scale.

Overall, experiment 2 validated the expectation that our distortion model is able to help or hinder the completion of the task. Curiously, the point where subjects become uncertain of whether a distortion was affecting the difficulty of the task coincides with the self-attribution threshold for hindering distortion obtained in the first experiment. This overlap seems to suggest that, although subjects are able to identify a change in difficulty, they tend to self-attribute distorted movements as long as the distortion facilitates the completion of the task.

6. Discussion

6.1. Self-attribution vs. speed perception

The self-attribution thresholds obtained in experiment 1 are higher than the speed perception thresholds presented by Burns and Brooks [28]. This was the case especially for the helping distortion, which was more than twice bigger for two of the four movement directions. The higher tolerance highlights the effective difference between the experiments, namely: (i) unlike [28], our question is linked to the experience of self-attribution; and (ii) we

do not prime the subject to look for a specific physical feature of the distortion. Moreover, we also note that our task was target-directed, thus requiring a great level of attention and precision from the subject to be accomplished. Normally, one would expect discrepancies to become easier to spot as they interfere with the completion of the task. In addition, our setup presents the whole virtual body to the subject. Therefore, our results emphasize that our experiment is assessing a different construct than that presented by Burns and Brooks [28]. These differences are valuable in the context of agency and embodied interaction research, where we are not only concerned with the limits of perception, but also with the overall feeling of control of a given body.

6.2. Self-attribution and agency

The comparator mechanism suggests that, although it is not possible to have direct access to the sensory predictions made by the brain, when the mismatch of sensory input and prediction is high enough, one may become aware of the discrepancy [34,35]. Thus, below a certain threshold, the brain would typically monitor the movement execution and correct for sensorimotor discrepancies without the awareness of the subject [12,36]. But interestingly, when questioned about the means used to identify if a distortion did occur, subjects often reported using their subjective effort, e.g. comparing expected and dispensed efforts to complete the reaching task. This, as well as the improved similarity of perception thresholds and their variances in the d_{gain} scale, relates the awareness of distorted movements to the overall effort. This nuances the principle of a pure online comparator model, suggesting that the self-attribution of an action (or lack thereof) was often the result of a retrospective component of agency [37], and associates our results to the account of agency proposed by Synofzik et al. [38], in which a higher order – non-minimal – representation of the self and its current state and intentions can affect how one evaluates the ownership of actions.

Nonetheless, experiment 2 validates the notion that our distortion model manipulates the difficulty of the task. It also suggests that subjects are capable of perceiving the helping distortion below the assessed threshold interval when explicitly questioned about it. Therefore, what became apparent is that subjects are biased to self-attribute movements *as long as* the task becomes easier than its apparent difficulty (Table 3 and Fig. 8). A potential interpretation for our results is that of a self-serving bias, i.e. a distortion of a cognitive or perceptual process associated with the self-attribution of successful outcomes of actions as a means to maintain an elevated self-esteem [39].

6.3. Applications

Movement distortion can be used to manipulate the difficulty of a motor task, consequently modulating the engagement of the user and leveraging the challenge so that it matches the skills of the user and promotes the state of flow [40,41]. According to the user's engagement and their level of ability, an application designed for physical activity could redirect the virtual body movements in order to reduce or augment the effort necessary to complete a task. In particular, we envision its use in applications of motor rehabilitation after stroke where patients may experience reduced mobility and/or impaired fine control of movements [42]. Using embodied VR, patient's movements could be redirected to modulate the difficulty of the task, helping patients to achieve their goal while gradually increasing difficulty as they improve to produce a more engaging environment. Duke et al. [43] proposed an application with similar advantages, where a short range movement is mapped to a long-range movement in order to provide visual stimulation and a complete view of the action to the patient. We argue that an enhanced sense of agency and ownership of the virtual body can have an impact on how patients engage and perceive themselves as responsible for actions in the virtual environment. Alternatively, by requiring more effort from healthy subjects, one may propose applications that stimulate physical movement.

In addition to helping or hindering the completion of a task, spatiotemporal distortions can be used to prevent interpenetration with other elements of the VE [27,44], or to accommodate the visual surface of a virtual object into a passive haptics device of different shape [17,45]. The spatiotemporal distortion can also be expressed with respect to the subject's body to ensure a consistent self-contact [46]. Moreover, we believe that the investigation about tolerance to movement distortion can yield new venues to the development of motion capture hardware and animation software. The hardware used in the experiment is rated to present accuracy errors below 1 mm, which is above current consumer tracking solutions. However, the perception that the visual feedback can be severely altered without major effects to the self-attribution of movements may challenge the urgency for accurate absolute tracking in a range of full body applications in consumer VR. Notably, we argue that, for many applications, the main priority of motion sensors are neither precision in terms of absolute position nor preserving accurate movement dynamics, instead, it is to accurately track the proximity between limbs/end effectors, thus preserving visuo-tactile stimuli in situations where self-contact is present [46].

6.4. Limitations

The perception of hindering distortions across movement directions is not as uniform as for the helping distortion. Notably, the movement towards left was especially sensitive to the hindering distortion. We believe that this observation relates to the different bodily sensations accompanying movements. Notably, the movement towards left requires the full extension of the arm and involves self-contact between the forearm and the chest. Moreover, the upward and downward movements are influenced by gravity as visible in Table 4. Therefore, it appears that movements towards the right might be the less biased for the comparison of helping and hindering thresholds presented in Table 3.

Additionally, it is necessary to note that the measurement scale of the experiments ($speed_{gain_{dB}}$) is in $10 \cdot \log_{10}(speed_{gain} + 1)$. Thus, the conversion to d_{gain} and $speed_{gain}$ may result in additional bias. Moreover, we make the assumption that the threshold reflects the constant k in Weber Law, but when considering d_{gain} as the scale, users have only experienced a single standard stimulus (i.e. the movement distance d_{range} was constant). Therefore, it is not

Table 4

Potential bias according to distortion type and movement direction.

Direction	Distortion type	Potential bias
Left	Helping	–
	Hindering	Arm reach limits
Right	Helping	–
	Hindering	–
Up	Helping	Against gravity
	Hindering	Against gravity
Down	Helping	Toward gravity
	Hindering	Toward gravity

possible to reliably test whether this assumption holds. Moreover, the standard deviation of the thresholds range from .09 to .12, while the absolute thresholds range from .17 to .42. The relatively high standard deviation – as compared to the threshold values – may indicate significant inter-subject variability, i.e. subjects may experience different thresholds or interact in ways that make differences less or more evident. It is therefore recommended to be cautious when implementing this knowledge to an application. We note, however, that even adopting a conservative approach, such as subtracting a standard deviation from the threshold values, still allows for a wide range of distortions. In addition, one should pay attention to the tracking system used for a given application. Here we use professional tracking equipment, which yield very low intrinsic tracking error. When developing an application with a less reliable tracking system, it may be adequate to use more conservative distortion thresholds to compensate for equipment limitations.

7. Conclusion

In this paper, we explored the extent to which subjects tend to self-attribute distorted movements of their avatar in VR. We focused on the subgroup of goal-oriented movements. More specifically, we interfered by adjusting the effort required to complete a reaching task, consequently helping or hindering the movement. Our results show that subjects perform poorly in detecting discrepancies when the nature of the distortion is not made explicit, extending previous work on the subject. Additionally, we found that subjects are biased to self-attributing distorted movements that make the task easier. We extend these findings with a second experiment where subjects were explicitly asked about the distortion. Interestingly, we found that subjects self-attribute distorted actions in spite of being capable of perceiving a facilitation, this effect was not observed in the case of hindering distortion.

Our results extend to the context of immersive virtual reality the classical accounts on the sense of agency – the comparator model [35] and the notion of judgment of agency [47] – and support the view that a higher-order representation of the self and of its intentions can affect how one evaluates the ownership of actions [38]. These findings and the experience gained in implementing and testing a reliable movement distortion algorithm can be used for the design of novel guided interactions paradigms in VR, with potential applications for motor training and rehabilitation.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:[10.1016/j.cag.2018.09.001](https://doi.org/10.1016/j.cag.2018.09.001).

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