Rotating the Self Out of the Body Almost Preserves the Full Virtual Body Ownership Illusion

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Abstract

It has been shown that it is possible to induce a strong illusion that a virtual body (VB) is one's own body. However, the relative influence of a first person perspective view (1PP) of the VB and spatial coincidence of the real and VBs remains unclear. We demonstrate a method that permits separation of these two factors. It provides a 1PP view of a VB, supporting visuomotor synchrony between real and virtual body movements, but where the entire scene including the body is rotated 15º upwards through the axis connecting the eyes, so that the VB and real body are only coincident through this axis. In a within subjects study that compared this 15º rotation with a 0º rotation condition, participants reported only slightly diminished levels of perceived ownership of the VB in the rotated condition and did not detect the rotation of the scene. These results indicate that strong spatial coincidence of the virtual and real bodies is not necessary for a full-body ownership illusion. The rotation method used, similar to the effects of vertical prisms, did not produce significant negative side-effects, thus providing a useful methodology for further investigations of body ownership.

Keywords: body ownership, rubber hand illusion, full body-ownership illusion, virtual body ownership, first person perspective, third person perspective.

1. Introduction

Recent results have shown that it is possible to induce a strong illusion in people that a virtual body is their body. This line of research has its roots in the experiments of Botvinick and Cohen (1998), who demonstrated that it is possible to induce ownership over a rubber hand, known as the Rubber Hand Illusion (RHI). It has also been shown that this illusion of ownership can be produced using a virtual arm (Slater et al 2008). Since then various studies have demonstrated that it is possible to induce a full-body ownership illusion over a virtual body. The virtual body is experienced as one's own body for the duration of the experience, to the extent that people have physiological reactions to threats to that virtual body, for example (Ehrsson 2007; Maselli and Slater 2013; Petkova and Ehrsson 2008; Slater et al 2010). Further studies have established the flexibility of the full-body illusion, in that it is possible to induce it with arbitrary virtual bodies of the same sex (González-Franco et al 2010; Petkova and Ehrsson 2008), differently shaped bodies (Normand et al 2011; van der Hoort et al 2011), and even embody men in the virtual body of a girl (Slater et al 2010), females in a different raced virtual body (Peck et al 2013), and adults in a child virtual body (Banakou et al 2013).

The necessary and sufficient conditions required for induction of the full-body ownership illusion are not yet clear. Different conclusions have been drawn about the relative importance of several contributory factors. The most contested to date has been perspective position, in particular whether a full-body illusion can be induced in a third person perspective (3PP). Several studies have indicated that a full-body illusion can occur with respect to a distant body, seen from a 3PP, provided that additional reinforcement in the form of synchronous visuotactile information is provided (Aspell et al 2009; Lenggenhager et al 2009; Lenggenhager et al 2007). In other studies 3PP of the virtual body seems to break the illusion (Petkova and Ehrsson 2008; Petkova et al 2011b; Slater et al 2010), with a recent study also suggesting that ownership over a body seen from 1PP and 3PP are both supportable (Pomes and Slater 2013). In addition to perspective, additional factors may contribute to inducing or breaking the illusion: reinforcing synchronous visuotactile information (Petkova and Ehrsson 2008; Petkova et al 2011b), visuomotor synchrony (Banakou et al 2013; González-Franco et al 2010; Peck et al 2013; Sanchez-Vives et al 2010), visual appearance of the body (Haans et al 2008; Lenggenhager et al 2007; Tsakiris 2010). Current evidence suggests that visuomotor correlation is more potent in inducing the illusion compared to visuotactile (in the context of 1PP) (Kokkinara and Slater 2014).

A recent study by Maselli and Slater (2013) has sought to systematically investigate the relative importance of some of these factors. First person perspective (1PP) of the virtual body was found to robustly induce the full-body ownership illusion. As noted in their review, in nearly all cases of the full body illusion 1PP has been achieved by approximately co-locating the virtual body with the physical body. They conclude that in a static viewing condition, a high degree of spatial overlap between the physical and virtual body is sufficient to induce the illusion.

In this work we investigate whether this high degree of spatial overlap is required in addition to 1PP to induce the full body ownership illusion. As noted by Maselli and Slater (2013), the requirement of a high degree of overlap of the bodies is a stronger constraint than a 1PP of the body. This high degree of overlap generally implies that the virtual body is approximately aligned with and centred on the participant's own body with the origin of the visual and auditory 1PP located at the eyes of the virtual body's head. In existing experimental setups, the physical body has generally been in the same posture as the visually seen body, the exception being a case study by de la Pena et al. (2010), where the virtual body posture was quite different to that of the real body, although the effects of this were only reported anecdotally.

In these types of setup, three components are in close interplay: the egocentric viewpoint (1PP), the degree of spatial bodily overlap and the congruency of visuoproprioceptive cues. Petkova et al. (2011b) demonstrated a way of divorcing the bodily overlap from 1PP with only mild disturbances of the visuoproprioceptive cues. In that study participants, lying motionless on their back, viewed a mannequin body that was in the same static posture, but slanting upwards away from their own body, with the shoulders of the two bodies aligned. They reported that a full-body ownership illusion over the mannequin was induced by synchronous tactile feedback. The visual perspective was 1PP, with slight misalignment due to the rotation at the shoulder, in all conditions.

We present a method to create a full-body ownership illusion with 1PP over a virtual body that is not spatially coincident with the real body, while maintaining visuomotor synchrony and true 1PP. The real body movements are mapped in real-time onto corresponding movements of the virtual body. Thereby we can investigate the question of whether spatial coincidence is necessary in the full body illusion under free movement conditions. This is important as agency is considered an important factor in the induction and breaking of the ownership illusion (Dummer et al 2009; Kalckert and Ehrsson 2012; Kammers et al 2009; Riemer et al 2013). The fundamental meaning of 1PP is that there should be an egocentric viewpoint of the body thereby requiring only that the eyes of the virtual and real body be spatially coincident. We separate the requirements of 1PP and spatial coincidence of the full virtual and real bodies through application of a rotation to the entire virtual world, including the virtual body. The rotation was performed through the axis connecting the eyes, producing virtual prism glasses, cf. (Redding et al 2005). The effect is similar to the setup of Petkova et al. (2011b), but by localizing the rotation at the eye axis, the egocentric view of the body (1PP) was preserved. The visuoproprioceptive cues provided were nearly all congruent, but the virtual body was nonoverlapping with the actual body location. External views of the visual results of our manipulation are shown in Figure 1.

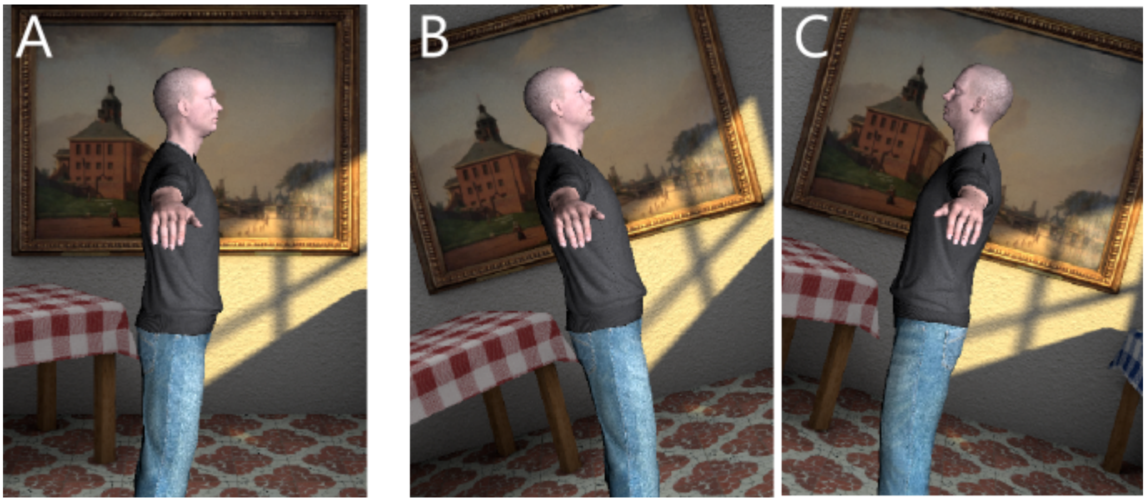

Figure 1 The effect of the rotation on the world. (A) shows the world with zero rotation. (B) shows the effect of a 15º rotation and (C) shows what happens when the participant rotates 180º on the vertical axis. Note the world is slanted in opposite directions in (B).

In this method the entire virtual environment and virtual body is simply rotated upwards about the axis connecting the eyes, common to both virtual and real bodies. The rotation also introduces a visual-vestibular mismatch, since the world is rotated up. A connection between the vestibular system and ownership has be suggested previously, but little research has addressed this issue (Lenggenhager et al 2006; Lopez et al 2008; Pfeiffer et al 2013). Our experiment seeks also to provide insight into whether the ownership illusion can be induced in the presence of visual-vestibular mismatch.

Physical rotations of the head on the sagittal axis (up and down rotations) are on the same axis as the manipulation and therefore present a completely stable world. However, physical rotations around the participant's vertical do cause some specific dynamic effects to the world stability. For instance, if the participant rotates 90° around the vertical from the initial orientation, the point ahead will be rotated up. In the initial orientation, that point would have been perfectly level. Rotating around 180° from the original orientation would cause the world to be rotated in exactly the opposite manner as in the initial orientation. This is demonstrated in Figure 1B-C. If we consider how the world is warped, it forms a conical vortex centred on the participant, specifically the mid-point between the eyes. This conical warp of the world exists in relation to the location of participant eyes, meaning movements also move the centre of the manipulation. The effect is only evident through participant translation and rotation and, as such, is a spatio-temporal effect rather than a spatial effect per se.

Given the spatio-temporal distortion of the virtual environment induced by the method used, adverse side-effects might be expected, i.e. simulator sickness (Stanney and Kennedy 2009).

Perception research that has induced perceptual mismatches using prisms, e.g. (Redding et al 2005; Rock et al 1966; Wallach 1987), has not reported on side-effects of such manipulations. The area of psychophysics dealing with vection has reported relevant studies that have also dealt with side-effects. The most relevant to our context are the studies dealing with circular vection. These studies typically present to the subjects simulated motions via moving points or lines in space, using projections or other technologies. The virtual space used in our experiment has strong lines (edges of the virtual room), which means if the participant looks around, similar vection cues may occur. The cues provided, if the person were to rotate and look up and down, may be similar to those in such studies as (Diels et al 2007; Palmisano et al 2007; Trutoiu et al 2009). In such vection studies, negative side effects were explored with stability tests; a decrease in stability with such motions was generally found. Some studies also report cases of "motion sickness" similar to simulator sickness (see Kennedy et al. (2010) for a discussion of differences). We, therefore, tested for adverse effects in the form of both simulator sickness symptoms and a loss in static postural stability.

To summarise: the major goal of our study was to examine the extent to which body ownership could be preserved notwithstanding our rotation manipulation, that effectively dislocates the virtual body from the real except where they coincide at the eyes and introduces a visuo-vestibular conflict. The second goal was to investigate whether the rotation manipulation might induce adverse side effects such as simulator sickness.

2. Material and methods

A single factor, within subjects experiment was designed with two conditions: Rotated and Normal. The Normal condition was an egocentric view of the body, where the real and virtual body were spatially coincident. The Rotated condition consisted of a 15° rotation around the axis joining the approximate centres of the participant's eyes (Figure 1B). The 15° rotation was selected through a combination of a psychophysical pilot experiment and expert experimentation, described in the online supplementary materials. All participants had full body visuomotor synchrony and received synchronous tactile feedback for reinforcement of the embodiment illusion.

Thirty one people participated in the experiment and the two conditions were presented in counter-balanced order. They were recruited from the campus of the University of Barcelona and our database of participants. The mean age was 27.3 (SD 7.1) and 18 were female. One participant had to be excluded from the analysis due to technical failure of the tracking system. The experiment was approved by the Bioethics Commission of University of Barcelona and performed in accordance with the Declaration of Helsinki. All participants gave informed written consent and were paid 10€.

2.1 Measures

Table 1 Questionnaires about body ownership and awareness of the manipulation.

Variable Name	**Question**
Set 1. After each of the two sessions	
(Q1) *mirror*	Even though the virtual body I saw did not look like me, I had the sensation that the virtual body I saw in the mirror was mine.
(Q2) *down*	Even though the virtual body I saw did not look like me, I had the sensation that the virtual body, that I saw when I looked down at myself, was mine.
(Q3) *body*	Even though the virtual body I saw did not look like me I had the sensation that the virtual body I saw was my body.
(Q4) *another*	I felt that the virtual body that I saw was someone else.
(Q5) *wrong*	Did you notice anything wrong with the environment? If so, what did you notice?

Set 2. After the end of both sessions and after set 1.

(Q6) *difference*	I noticed a difference between the two experiences.
(Q7) *diff-what*	If you noticed something wrong, what was it?
(Q8) *impression*	I had the impression something was different between the two experiences, but cannot specify exactly.

Set 3. After 2 and shown on a new screen

(Q9) *rotated*	The horizon was rotated up in one of the two sessions. Please identify which session you think you saw the world with the horizon rotated up.
(Q10) *confident*	How confident do you feel in your answer to the previous question?

Table notes: Q1-Q4, Q6,Q8 were scored on an anchored 5 point Likert scale with 1 as ‘Strongly Disagree’ and 5 as ‘Strongly Agree’.
Q5 was a yes/no answer with an open ended supplement.
Q7 was open-ended.
Q9 was binary forced choice with answer ‘first session’ or ‘second session’.
Q10 was scored on an anchored 5 point Likert scale with 1 as ‘Not at all/Guessed’ and 5 as ‘Very much so’.

In this experiment we were interested specifically in the subjective illusion of body ownership. As such, subjective measures elicited the level of body ownership as well as awareness of the manipulation. The questions and when they were administered are shown in Table 1. The questionnaires were administered on a computer display. The feeling of body ownership was elicited through the questions: *mirror*, *down*, *body*, and *another*, and asked immediately after each session. The open question *wrong* was also asked after each session to check for awareness of the manipulation. The questions *difference* and *diff-what* were asked only after the second session and after the previous questions. After the end of the second session and completion of the above questions, an additional screen page was displayed with the questions *rotated* and *confidence*.

To ascertain whether the manipulation caused any adverse effects, simulator sickness and postural stability measures were taken. Reviews of ‘simulator sickness’ and its measurement can be found in (Stanney and Kennedy 2009). A standard test for simulator sickness was used, the

Simulator Sickness Questionnaire (SSQ), and scored using the method laid out in Kennedy et al. (1993). The questionnaire was applied in a before/after exposure paradigm and was used comparatively.

Postural stability provided an objective measure of adverse effects (Akiduki et al 2003; Cobb 1999; Kelly et al 2008; Murata 2004; Takada et al 2009). We elected to use static postural stability tests using a force plate and a typical battery of tests: eyes closed both feet, eyes closed preferred leg, and eyes closed other leg. In these tests the subject is required to stand as quietly as possible in the specified posture for a length of time. The force plate measures the centre of pressure of the subject over time as the body sways. If the postural stability is affected by the exposures, the amount of body sway should increase. Tasks with the eyes closed were selected because they are more sensitive than the same tasks with eyes opened. A comparative paradigm of before/after exposures was used. Each trial was thirty seconds, with approximately fifteen seconds rest between trials. The order was always both legs, preferred leg, opposite leg.

2.2 Equipment and scenario

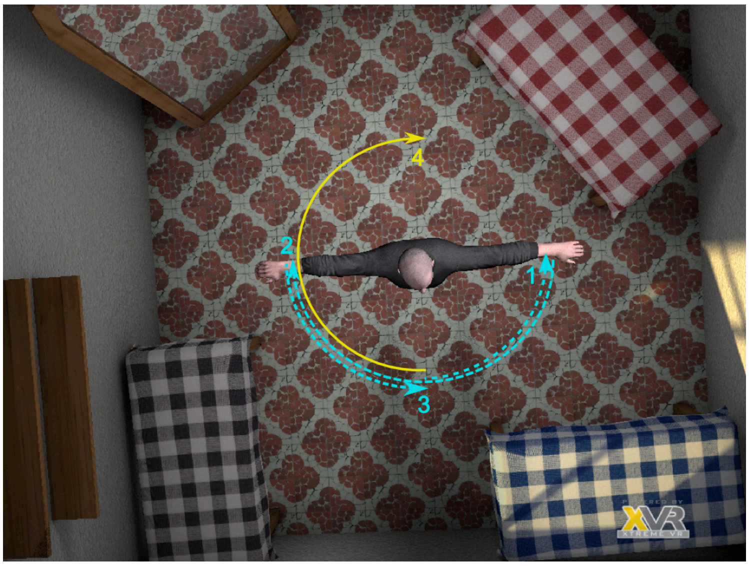

Figure 2 : The virtual environment used seen from above. The path of the ball for the following task is also shown at the approximate distance from the participant. The blue-green arrows demonstrate the path the ball took during the first following task, with the directional changes shown in order; the initial direction was randomized. The yellow path demonstrates the path followed in the second following task; the direction was always the opposite of the initial direction in the first.

The virtual environment was viewed via a stereo NVIS nVisor SX111 head-mounted display (HMD). It has dual SXGA displays with 76°H x 64°V field of view (FOV) per eye, totalling to a 111° horizontal FOV, and weighs 1.3kg. The displays were driven at 60Hz. Calibration was performed using the method proposed by Grechkin et al. (2010). Head tracking was performed by a 6-DOF Intersense IS-900 device. Full-body tracking was performed by Natural Point's

Optitrack optical tracking system. Twelve V100 infrared Optitrack cameras captured the tracking volume and body suits from Natural Point were used.

The virtual environment was implemented using the XVR system (Tecchia et al 2010) and the virtual human characters were loaded using the HALCA software system (Gillies and Spanlang 2010). The scene is shown from above in Figure 2. A full height virtual mirror was placed in one corner of the room and participants entered the VE facing towards it. The scene was rotated around the axis formed by the connection of the participant's eyes for the Rotated condition.

Synchronous tactile feedback was provided using the setup previously described (Spanlang et al 2010). Coin type vibrators of 10 mm diameter were placed on the skin of the participant using a sticky velcro strip. One was centred on the sternum (approximately located at the uppermost part of the gladiolus) and the other was placed just above the belly button. The vibrators operated at a rate speed of 9000 rpm and were controlled by an Arduino MEGA microcontroller, coupled to an Xbee Shield for wireless communication.

For the posture stability measurements, the Nintendo Wiiboard was used as a force plate. Clark et al. (2010) have shown that for stability analysis in repeated measures studies, the Wiiboard does not significantly differ from traditional force plates. Raw force measures at all four corners and Centre of Pressure (CoP) values were recorded. A custom program sent markers used to synchronize the signal to the start of stability tests and a special marker indicated if the participant fell.

2.3 Procedures

After completing a pre-study questionnaire, including the baseline SSQ, participants donned the tracking suit. The tracking system was calibrated; the vibrators were attached and connected the wireless controller was attached to the back of the tracking suit. The Wiiboard was introduced, and the procedure for the stability tests was explained. The participant performed the baseline stability tests. The procedure of the experiment was then fully explained. The HMD was put on the participant and calibrated. The first exposure was initiated, with the order of conditions randomized.

The scenario for each exposure was programmed to occur through a series of events (see also the video in the supplementary materials). An initial period of accommodation to the virtual environment started each block. The participant was asked to describe the scene in their first exposure and in the second to describe specific details (what they saw out the window, the time of day, contents of the painting) to avoid repetition. After the accommodation period, a virtual ball appeared in front of the participant. The participants were instructed to visually follow the virtual ball. During the tapping task they looked either directly or in the mirror. Either was allowed since extended periods of looking down to the body led to discomfort for some participants (see Section 4.3 in the discussion). Initially, the ball tapped and stroked the front of the participant for two minutes, with synchronous tactile feedback, with intervals determined by a pseudo-random generator. The tapping occurred at two positions, just above bellybutton and on the sternum, in a randomized order. Every two to seven seconds the position of tapping was selected anew. The movement between positions was in a line between the points. Tapping occurred with a one second period, with three to five taps performed at each selection of position.

After the tapping, the ball transitioned to a 30 second period of movement, where the participant visually followed the ball. The ball moved in a semicircle one meter in front of the participant, rotating 90° in one direction over 15 seconds; it then changed directions, rotating 180° over 30 seconds, before rotating back to the starting position over 15 seconds. The path of the ball is denoted in Figure 2 by the blue dashed arrows. Additionally, the ball was displaced vertically ±0.5m in a sinusoidal pattern with a period of 7.5 seconds. This assured the participant performed head movements through the spectrum of the manipulations effects. An additional two minutes of tapping was performed followed by another period of visual following of the ball. The ball pivoted 180° around the participant over 30 seconds, denoted by the yellow path in Figure 2. The exposure ended with the screen fading to black.

After completion of each exposure, the participant removed the HMD and the Wiiboard was reintroduced into the tracking area. The stability tests were performed again in the same order. They then completed the post-session questionnaire starting with the SSQ. The HMD was refit and the second exposure was initiated, this time with the other condition. Again, immediately after completion, the participant performed the stability tests and filled out the SSQ and post-session questionnaires. After completion, any questions were answered; they were thanked and paid for their participation.

2.4 Analysis

The stability data was analyzed following Prieto et al. (1996). They investigated a large number of transformations of stability data and determined four main clusters in the derived measures, each of which highlighted different aspects of postural stability. We used one CoP transformation for each class of stability measure plus the time each posture was held.

1. task time (till falling or end of trial)
2. mean velocity (MVELO)
3. Root Mean Square (RMS) of the resultant distance from the mean CoP.

4. 95% confidence circle area (AREA-CC) - an approximation of the area of a circle around the mean CoP whose size includes 95% of the distances from the mean CoP.
5. centroidal frequency (CFREQ)

The terminology used is derived from Prieto et al. (1996). Custom Matlab code was written to derive the values based on the description in that paper. The only modification was that CFREQ was calculated using Matlab's *pmtm* function, which uses Slepian tapers instead of the sinusoidal tapers used by Prieto et al.

We can think of the questionnaire scores affirming ownership as reflecting an underlying non-observable latent variable that we call 'body ownership'. Normally we could use factor analysis or principle components to estimate such a latent variable. However, here our observations are on an ordinal scale so such an approach may not be valid. Instead we use the technique of polychoric correlations, which assume that given a set of discrete ordinal scores there is a set of corresponding underlying continuous scores that follow a multivariate normal distribution and that correlations between the underlying scores can be estimated with maximum likelihood (Olsson, 1979). Once we have the correlation matrix we can compute principle components and the corresponding scores, which has been implemented in Stata (Kolenikov & Angeles, 2004).

The analysis of the data considered the data as panel data and was performed using the Stata 13 *xt** functions considering the inter-participant variation as random effects.

3. Results

3.1 Body Ownership Questions

Figure 3 shows the boxplots of the questionnaire scores over condition (Normal, Rotated) and the trial. If we consider the medians there is apparently no effect of trial, or of condition. Moreover the level of ownership judged by *mirror*, *down* and *body* is high (all medians are 4 out of 5) and for *another* the score is low (3 of the medians are 2 and one is 3). There is some evidence of a different range of values (compare Normal mirror with Rotated mirror in trial 1), but no apparent dramatic difference.

The boxplot data does not take into account the fact that this was a repeated measures experiment. Probit regression of the questionnaire scores based on the experimental design was carried out (using the 'panel data' functions of Stata 13, *xtoprobit* allowing for robust standard errors) with the results shown in Table 2. Probit regression was used rather than logistic since this uniformly gave smaller standard errors for the coefficient estimates.

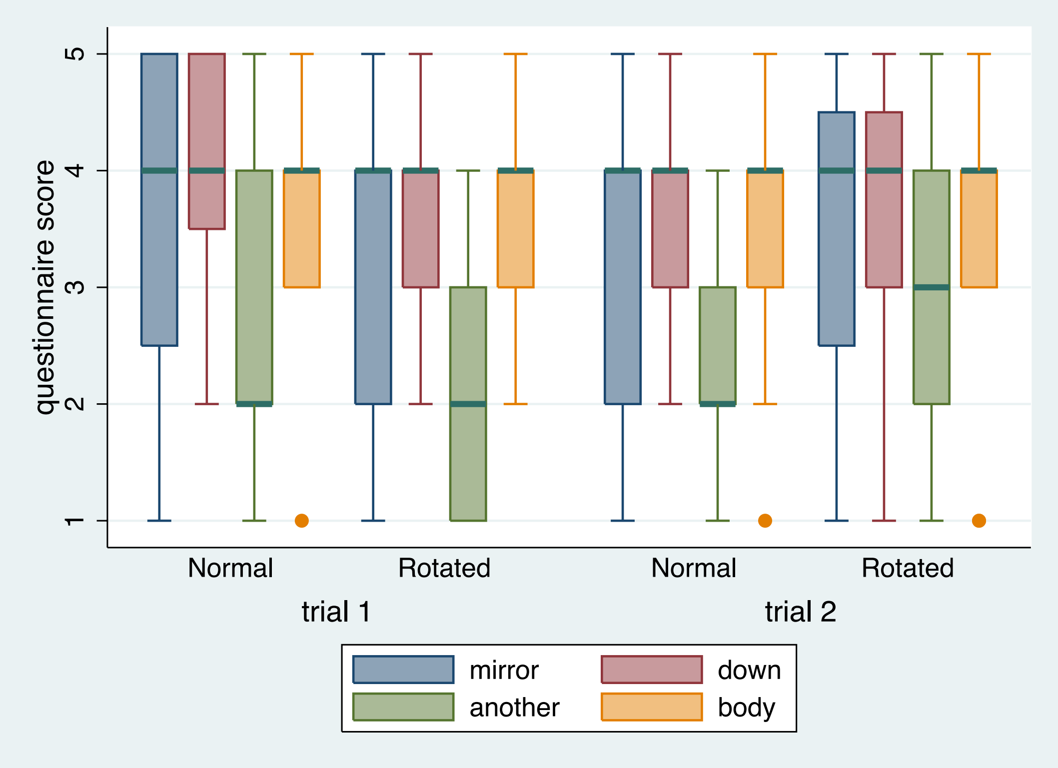

Figure 3 Box plots of the questionnaire data by condition and trial number. Responses were on anchored 5 point Likert scales with 1 as ‘Strongly Disagree’ and 5 as ‘Strongly Agree’. The thick green horizontal lines are the medians, the boxes are the interquartile (IQR) ranges, the whiskers extend to the highest or lowest data point within 1.5 * IQR. Values outside of this range are marked by single points.

Table 2 Probit Regression of Questionnaire Responses on Condition (Random Effects Model with Repeated Measures). Condition Normal = 0, Condition Rotated = 1.

Variable	Coefficient	S.E.	z-score	P (two-sided)
mirror	-0.69	0.30	-2.34	0.019
down	-0.62	0.47	-1.32	0.187
another	0.14	0.27	0.51	0.608
body	-0.42	0.27	-1.56	0.118

It is notable that for the three questions that affirm the body ownership illusion the coefficient is negative - i.e., the score tends to be less for the Rotated condition, whereas for the question *another* there is no association. However, there is only a significant effect for *mirror*.

For the principal components analysis based on polychoric correlations we used the three affirmative variables *mirror*, *down*, and *body*, and then checked the resulting PCA score variable (*Ownership*) against *another*. The polychoric correlations are shown in Table 3.

The PCA based on these three variables has first principle component accounting for 89% of the total variation, and we use the resulting score (*Ownership*) as representing the underlying ‘body ownership’ latent variable. This, of course, has high correlation with each of the three component variables (see row 4 of Table 3). As a check, it also has strong negative correlation with the control question *another* that was not used in the construction of the PCA score.

Table 3 Polychoric correlation matrix. Row 4 shows Pearson correlations of the resulting PCA score (*Ownership*) with the original questionnaire scores. Row 5 shows the regression coefficients of regression of mirror, down and body on the PCA score

	mirror	down	body	another
1. mirror	1			
2. down	0.89	1		
3. body	0.83	0.80	1	
4. Correlations with *Ownership*	0.92	0.92	0.89	-0.54 (P < 0.00005)
5. Regression coefficient of *Ownership*	0.77	0.56	0.60	

In order to obtain some idea as to the scale of the latent variable *Ownership*, the final row of Table 3 shows the regression coefficients of the three affirmative questionnaire scores on body ownership. Hence a unit increase of 2 units in *Ownership* is equivalent to about a 1.5 increase in *mirror*, and just over a unit increase in each of *down* and *body*.

Now a repeated measures random effects regression of *Ownership* on condition results in a significant main effect (z = -2.16, P = 0.030), with the regression coefficient of -0.26 ± 0.12 (S.E.). In other words the change from Normal to Rotated condition would result in a very small decrease in subjective body ownership scores (row 5 of Table 3). The residual errors of the fit are compatible with normality, Shapiro-Wilk test P = 0.96.

Participants were asked about their perceptions of the experience with two questions. The forced choice question *rotated* responses (17 correct) were globally not different than random ($\chi^2(1)$=0. 45, p=.70) and not significantly different by order of conditions ($\chi^2(1)$=.78, p=.38). Considering only the participants who reported being confident >=3 (n=16) in their selections, the responses are also random and no different than the uncertain participants ($\chi^2(1)$=1.17, p=.28). This is also true when using >= 4 (n=6) as a cut point for confidence level, where three answered correctly and three incorrectly. The question *impression* showed a strong relationship with the latent variable *Ownership*.

Table 4 Random effects regression for the latent variable Ownership.

Term	Coeff	S.E.	z	P (two-sided)
Const.	-0.65	0.48	-1.34	0.179
Condition (Rotated=1)	0.14	0.20	0.67	0.500
impression	0.38	0.21	1.82	0.069
Interaction: condition.impression	-0.21	0.09	-2.36	0.018

The question *impression* was included in the random effects repeated measures regression for *Ownership* and the resultant fit can be seen in Table 4. The within subjects residual errors were compatible with normality (Shapiro-Wilk test P=0.52). From the demographic variables recorded prior to the experiment we can add age, gender, and previous VR experience to the regression. However, none of these are significant.

If we examine the coefficients of condition and the interaction (condition.impression) we can see that in the Normal condition the relationship between *Ownership* and impression is not significant (coeff = 0.38). However, for the Rotated condition (i.e., now taking into account the interaction term) there is a negative relationship between impression and *Ownership* - the more that participants had 'the impression something was different between the two experiences' the less the *Ownership*. However, in the forced choice test, where participants were told that one of the trials had been rotated, their answers matched what would be expected by chance.

Hence, we would conclude that there was a slight reduction of the sensation of body ownership in the Rotated condition. Moreover, this is associated with the impression that something was different between the two conditions.

3.2 Adverse Side Effects

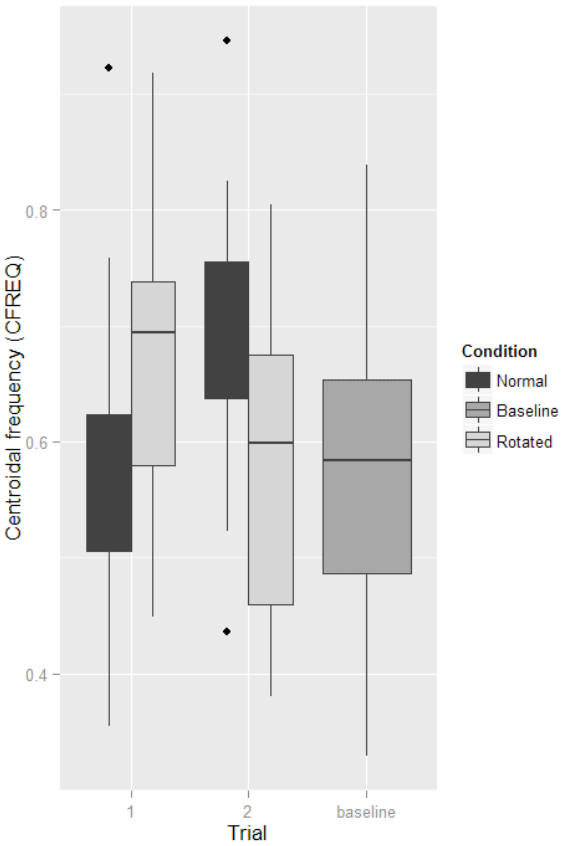

Figure 4 Box plot of the participant stability on the measure of Centroidal Frequency on the Preferred Leg Eyes Closed task. Demonstrates the interaction effect, which was most pronounce in this task.

An analysis of adverse side effects showed only a limited influence of the Rotated condition. The repeated measures random effects regression of the SSQ difference to baseline on condition showed no significant differences by condition, P > 0.3. Two factor RM ANOVA analyses on the stability measures found no significant main effects by condition or order for any measure. Significant interaction terms were found for two of the preferred leg, eyes closed measures, CFreq (F(1,76)=7.8, p<.01), MVelo (F(1,76)=4, p<.05) and trends existed for AreaCC (F(1,76)=3.5, p=.07) and RMS (F(1,76)=3.8, p=.06). Figure 4 illustrates this effect. In the other leg eyes closed task similar trends existed for RMS (F(1,76)=2.9, p=.09) and MVelo (F(1,76)=3.4, p=.07) measures.

4. Discussion

The main contribution of this research is to demonstrate a method for separating out 1PP and spatial coincidence of the virtual and real bodies, where full-body movement is possible. The results of our experiment indicate that complete spatial coincidence of the bodies is not necessary for induction of the full-body illusion when there is egocentric viewpoint, visuomotor synchrony, and synchronous visuotactile stimulation. In this experiment we do not separate out the relative influences of these two types of reinforcing stimulation.

Our work supports and extends the findings of Petkova et al. (2011b) in a number of ways. They used a mannequin placed at a 30° angle rotated up from the real reclining body. They showed induction of the body ownership illusion in this perspective, and attack the mannequin body in the lower abdominal region with a knife. The mannequin was collocated at the shoulders in Petkova et al. This created an offset of the body that was slightly unnatural, though they do not report on whether this was noticed nor if it had any effect. Our solution rotates the body through the eye axis, so it does not produce such offsets.

Most importantly, our solution provides full body visuomotor contingencies, where the movements of the real body result in corresponding movements of the virtual body, with freedom of movement, and therefore agency with respect to the virtual body. Movement is known to update the proprioceptive senses (Banakou et al 2013; Llobera et al 2013; Peck et al 2013; Tsakiris et al 2005; Tsakiris et al 2006), whereas in Petkova et al.'s setup the subject had to be static; this would allow the proprioceptive quality to degrade over time which may have contributed to their ability to induce the illusion in the rotated setup. Thereby, we extend the findings of Petkova et al. by showing that it is possible to robustly induce the full-body ownership illusion when there is repeated updating of visuotactile and continuous visuomotor stimulation. Furthermore, agency, at least over a body part like the hand, has been shown to be a powerful factor in the ownership illusion (Dummer et al 2009; Kammers et al 2009; Riemer et al 2013). The relationship between agency and ownership of body parts is not completely clear, though recent evidence from Kalckert and Ehrsson (2012) provides evidence for a double disassociation in the RHI context. This relationship in full-body conditions is not yet clear and our setup may provide a unique platform for its exploration. Combined, these differences permit control of the various other components of embodiment, while maintaining 1PP. This makes it possible to investigate the influence of bodily location and perspective independently in the full body illusion and the minimal phenomenal self (Blanke and Metzinger 2008).

Overlap of the physical and virtual bodies may be an important factor in several findings to date. (Ehrsson 2007; Petkova et al 2011b) have used threat measures to show achievement of the full-body illusion in the 1PP. However, when a virtual body is co-located with the real body, any responses may be because the physical body occupies the same space as the virtual body, rather than being due to the illusionary body. Hence a threat to the virtual body is also a threat to the real one. In (Petkova et al 2011b), where there is a spatial separation between physical and virtual bodies in the 1PP, the knife threat to the lower abdominal region used may be perceived as a threat also to the physical body, which appears to be approximately 30 cm away from attacked point in their setup, and, therefore, within peri-personal space. A significant difference between SCR responses was found for synchronous vs. asynchronous visuotactile feedback. However, it is not clear from the data presented whether this is directly attributable to ownership or some other process.

We believe that one of the most important aspects of the utility of our setup is that the egocentric view of the body provided is nearly perfect even though the virtual body is not spatially coincident with the real one, and the virtual body moves synchronously with the real. The only systematic discrepancy is with respect to the fact that the virtual environment rotation leads to the adjustment of the head rotation, even though this does not appear to be consciously noticed by participants. This causes a static proprioceptive mismatch between seen orientation and actual orientation of the head, as well as the spatial positions of the other body parts. However, movements of the participant, including the head, are mapped one to one of the seen virtual body, which is likely the most important of the proprioceptive cues for induction of the body ownership illusion (Walsh et al 2011). Because of this rotation, the vestibular cues are also non-congruent with the visual stimulus, which we discuss more below.

Indications were found that our method did cause a very small reduction in the ownership illusion. Looking at the regression results of the latent variable *Ownership*, we see that the more that participants had the impression that something was different between the two conditions, the more likely it was that they would give a lower score in the Rotated condition compared to Normal. However, after seeing the Normal condition first, response levels for the Rotated condition remained flat, no matter what their impression had been. Hence, we conclude that there was some reduction of the sensation of body ownership in the Rotated condition. Moreover, this reduction was associated with the impression that something was different between the two conditions. Since participants were quite unable to say what was wrong - even when told that one of the worlds had been rotated they could not differentiate between the two conditions - this suggests that this happened at an unconscious level.

There are two possible interpretations as to why this small degradation of the ownership might have occurred that we will discuss in subsequent sections. It may indicate that the lack of spatial coincidence between the real and virtual body slightly decreases the full-body ownership illusion. However, an alternative reason may be that the method we employed also creates a visual-vestibular conflict (the vertical of the real body subject to gravity compared to the rotated virtual body and world). Finally, we discuss the manipulation itself and its impact on the participant.

4.1 Bodily Location

One of the fundamental concepts involved in embodiment is self-localization, i.e. where the person identifies themselves to be (Blanke and Metzinger 2008; De Vignemont 2011; Kilteni et al 2012). Outside of clinical conditions, spatial localization is normally within the physical body. Yet, creating perceptions that the body parts are located outside of the confines of the physical body has been shown repeatedly in the RHI and related illusions. While ownership of displaced body parts can be easily demonstrated, there is a fundamental difference between displacing a single limb and the whole body (Petkova et al 2011a). It has been shown that non-clinical participants can experience a condition where, to some extent, they self-localize outside of their own physical body through the induction of Out-of-Body-Experience illusions (Aspell et al 2009; Ehrsson 2007; Lenggenhager et al 2007; Petkova and Ehrsson 2008). In our experimental setup, participant responses indicated that they associated strongly with the virtual body, which was not aligned with their own and, therefore, also spatially offset. Informal spontaneous responses during the experiment and from post-session comments indicated that the touch of the ball was felt to be in the virtual body, supporting the view that the participants localized into the virtual body.

The small reduction of the full-body ownership illusion found in the Rotated condition might be an indication that the location of body, particularly the torso, modulates the illusion. The out of body illusions above generally report illusion ratings that are lower than those reported here, based on a broad interpretation of the endpoints and medians of the response in their respective scales. This would seem to support the hypothesis that with increasing body separation the illusion diminishes. However, the vestibular conflict is a possible confound, so it is not yet possible to attribute the change to the collocation of the body.

4.2 Vestibular Conflict

The influence of vestibular conflicts in the full body ownership illusion has not been much addressed to date (Pfeiffer et al 2013). Yet it has been proposed as an important part of embodiment and the body ownership illusion (Lenggenhager et al 2006; Lopez et al 2008). It has been noted in various places that both embodiment and vestibular processing are related to the temporal parietal junction (Barra et al 2012; Lopez et al 2008). In our experiment the main conflict could be considered to be visual-vestibular in nature, as not only the body, but the entire environment, was rotated. This creates a conflict of 15° between the visually seen vertical and the felt vertical. Moreover, this conflict is dynamic, changing with any rotation of the head.

Pfeiffer et al. provide evidence that a strong visual-vestibular conflict (180°) diminished the ownership feelings in comparison to a lesser conflict (90°) in an OBE scenario. Our results indicate this diminishing effect of ownership illusion may also exist when the 1PP viewpoint is collocated with the body. It also provides evidence that at smaller degrees of conflict ownership feelings can be high, nearly matching those without a conflict. Additionally, because the conflict was dynamic in our setup, these ownership scores indicate a general robustness to small scale conflicts.

Our study differs from previous experiments in the manner of presenting the conflict. In our study the visual-vestibular conflict was created by presenting a full environment. The small, largely barren virtual room provided strong vertical and horizontal cues. By looking at these strong lines at the edge of the visual field it is possible to detect the rotation during head rotations in the horizontal plane. The room, therefore, provided strong cues to the participants to the manipulation. An environment with less pronounced horizontal lines would make the manipulation much harder to detect. At the same time the room may have provided clues that contributed to the manipulation not being detected. The participant had the feeling that they were standing orthogonally to the floor and could see visual cues that confirmed this because the virtual body was parallel to vertical. A recent study by Barra et al. (2012) indicates that mental processes contribute to the sense of verticality. Their results suggest that spatial representations, which are strongly present in our scenario, modulate internal models of verticality. Moreover they find that body awareness modulates those same internal models of verticality. In our study we have manipulated both the body orientation as well as spatial cues of verticality congruently. Our results seem to support their finding. However, because we manipulated both the spatial component and the perceived body orientation congruently it is not possible to speculate on the relative contributions of each in our data.

Pfeiffer et al. (2013) investigated the effect of individual differences in processing of visual-vestibular mismatch. Although the influence they found on perspective is not relevant to our research due to differences in the setups, the methodology may provide insight into our results. Two different processing strategies can be identified: those that are visual field dependent and those that are visual field independent. These differences may explain the variable *impression* that was an important covariate in our analysis. We would suspect that those who are more visual field independent i.e. do not rely as heavily on visual cues in making judgments of verticality, would be more likely to have the impression that something was different between the conditions. Given the strong cues of verticality in our experimental scenario those with visual field dependence would be unlikely to detect the manipulation. If this were the case it would provide a good correlating variable or even a way to adjust the maximal rotation based on individual differences.

Lenggenhager et al. (2006) proposed the induction of a similar visual-vestibular conflict as our experiment induces, but by means of transcranial magnetic stimulation (TMS). Our method requires only the presentation of a virtual environment to induce this illusion, providing a good platform for future investigations. Additionally, both methods could potentially be combined, providing a method to isolate the effects of bodily alignment and vestibular conflict.

Rotational manipulations similar to ours have been used in other contexts, which provide insight into its applicability. Participants have been shown to be blind to dynamic rotational scaling in single axes when wearing a Head Mounted Display (HMD). The most common of these is a manipulation of the rotation through the vertical axis of the participant. This has been done as part of the paradigm referred to as 'redirected walking,' where a mismatch between physical rotations and perceived visual rotations were introduced in order to change the heading of the participant in the physical space (Engel et al 2008; Jerald et al 2008; Peck et al 2009). These studies have performed psychophysical based studies to determine the amount of disparity possible, without the participant noting the manipulation. Although the amount of acceptable positive gain varied, it was generally between 7.7% and 35%. In a related set of work, Bolte et al. (2010) looked at the perception in roll and pitch axes (the two orthogonal axes to the vertical axis used in redirected walking). They found that both pitch and roll could be augmented by 30% and 44% respectively. However, movement was restricted to head rotations in the axis of manipulation.

Several studies have investigated changing the horizon artificially in order to investigate known deficits in distance perception in Virtual Reality (VR), i.e. 'distance compression phenomena' (Kuhl et al 2009; Messing and Durgin 2005; Williams et al 2009). The methods used were the same as our proposed work, though with restricted movement and without a virtual body. These works all find no significant effect of pitching the world between ±5.7° and 11.5° on distance perception. In contrast, experiments using prisms in the real world have found adaptation effects (Ooi et al 2001; Thompson et al 2007). The method of pitching the environment is similar to our method, but those studies all restricted head and body movements.

Related work grounded in the physical world has shown that adaptations to prism glass can be induced and occurs rather quickly with conditions similar to those we propose. Wallach (1987) provides a review of early literature and theory on how the perceived environment becomes stable. Redding et al. (2005) provide a more recent review. Most research focuses on lateral displacements of the visual field. Wallach does note that earlier work avoided the use of the more extreme prisms, because “inadvertent tilting of the head causes tilting of the visual field that nauseates the subject.” He also notes that ‘nodding’ motions were “more sharply represented” and theorizes that is because of the gravity reference. Recent work has looked at ‘base up’ prisms for their effect on the horizon and depth perception (Ooi et al 2001; Thompson et al 2007), as discussed above. An adaptation effect was found, causing distance perceptions to be modified. The subjects walked forward in those experiments, and the authors do not report on any adverse side effects.

4.3 Impact of Manipulation Method

The angle of manipulation used in the experiment was 15°. The relative size of this rotation has to be considered. In the supplementary materials we present a small pilot study that explored the limits of awareness of the manipulation, which indicated that larger manipulations were not noticed, but seemed to induce simulator sickness. The average maximal cervical extension in the sagittal plane (looking up) for the 20-29 age group is approximately 80° in unconstrained conditions (Youdas et al 1992). By biasing the entire environment “up” 15°, we have already taken a decent portion of the unconstrained range of motion, just to achieve level viewing. When the comfortable range and the addition of the HMD is considered, 15° is already a fairly large manipulation.

The manipulation also has a potential benefit on the converse side. The average maximal unconstrained flexion (looking down) in the 20-29 age group is 54° (Youdas et al 1992). By rotating the world up 15°, participants are able to see further in this direction. This is particularly important in a setting such as ours. The current generation of HMDs has a limited vertical field of view, 64° in our HMD. Using the classical tactile reinforcement method, as we have done here, requires the participants to look down at the body, causing extreme flexion under the external constraints, i.e. the weight of the HMD. This makes extended downward looking stressful on the neck, something we have heard from participants in various studies. By rotating the world up 15° we reduce the flexion required to see the torso and, thereby, make it less stressful.

The method employed here has two limitations that may limit the method’s applicability outside of experimental studies. If the participant were to turn their head to one side and then look down, the world and body would be tilted up. In this case the virtual body would appear to be tilted up 15° in that direction; for instance, rotating the head to the left and looking down at the body, it would appear to slant up to the left. However, when looking down approximately to the front this tilt is not noticeable. The other limitation would be perceivable if the participant were to tilt their head; the world would ‘rock’ along the eye axis, producing a pendulum-like visual effect. It is important to note that in this study the participants were unconstrained in their movement and these conditions never occurred at such a level as to make the manipulation obvious. This may, however, be due to the weight of the HMD used, which could have discouraged such movements. The strong cues of the room walls and visual changes on movement may provide enough information to force an assumption of a stable world, even though the environment was intrinsically unstable during the forced motion. This interpretation is at least partially supported by Rock et al. (1966), who found that room cues changed adaptation with vertical prism effects over a dark room and abstract light points.

It is interesting to note that the 15° upward rotation was not noted on initial entry to the environment (nor larger rotation of 25° in a pilot presented in the Supplementary Materials). Prism effects seem to be noticed very quickly by healthy subjects, although the literature does not specifically address effects with vertical offset prisms. This blindness to the manipulation may be an factor in our results, as Michel et al. (2007) have shown prism adaptation is more complete when the participant is unaware of the manipulation. The direction of gravity should have provided a strong cue (Wallach 1987), which would lead one to suspect that the participant would detect the manipulation. We believe two factors may contribute to this blindness. The calibration screens shown initially may have provided enough time for the strong cues of verticality of the laboratory setting to be negated. Individuals who process visual-vestibular signals as visual field dependent are likely to have simply accepted the visual cues. The more important factor may be the weight of the HMD. Particularly for the individuals that are visual field independent, neck proprioception has been shown to influence perception of vertical (Golomer et al 2005). We suspect that because of the weight, the proprioceptive sense of the rotation of the head may be degraded to the point that the deviation is not noticed.

It was somewhat surprising that very limited adverse side-effects of the experience were found, given the literature. Two participants did comment in the open questions about related feelings. After the first session in the Normal condition a participant commented, “once I moved a bit fast and felt a bit dizzy, losing my balance” (the participant did not fall). The other, after the Rotated condition in the second session, commented that they felt more tired than before. Indications of a subtle effect on the stability of the participants were found in the analysis in the form of interaction effects, particular in the task of standing on the preferred leg. Figure 4 illustrates this with the centroidal frequency measure, where the effect was most pronounced. It appears that the exposure to the Rotated condition in the first session tended to induce some instability, but if the exposure was in the second only minimal changes in instability were induced. We also see that the stability improves on the second exposure to the Normal condition. This pattern emerges in most of the measures and mirrors the subjective ownership findings discussed above.

It is important also to consider that we found no effects of Simulator Sickness. The VR literature indicates that elevated occurrences of simulator sickness should be found even without manipulation and the prevailing ideas indicate any modifications to the viewpoint have a high potential for such negative effects. Following Stanney and Kennedy (2009) one would expect 70-90% of participants to experience some mild symptoms and 5% should have experienced effects significant enough to warrant discontinuing the experiment during the exposure. None of our subjects reported any severe symptoms and none stopped. Individual participants indicated some elevation of sickness symptoms, in particular dizziness, but no more so than in any other experiment that uses our setup. Often this was even in the Normal condition. In addition, the mean SSQ score delta pre to first exposure was 0.6 (SD 8.3) and after both exposures 3.0 (SD 13.3). Here we see limited evidence of sickness, even after two exposures of 6-7 minutes, including the Rotated condition. This may be due to improved technologies or differences in the tasks, or it may be because unlike the standard measures, in our experiment participants had a virtual body. Much of the simulator sickness research is based in long exposures to aircraft simulations by military personnel, which may not be indicative of scenarios like ours, and with technology from the 80’s and 90’s. Our results are more in line with those reported by Bouchard et al. (2009), who found 80% of participants had no or only slight indications of simulator sickness.

Conflict of interest statement

The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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