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The exposure to body size distortions affects allocentric distance perception in extra-personal space

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Previous research demonstrated that body size distortions induced by body illusion can influence spatial perception in near space. We investigated whether manipulating body size through a Full-Body Illusion-like paradigm influences allocentric distance perception in extra-personal space. Participants estimated the distance between landmarks in far space before and after a body illusion with standard or big bodies in anatomical (i.e., virtual and actual legs were aligned) or non-anatomical orientation (i.e., virtual legs were rotated by 45 degrees). We analysed space perception via Multidimensional Scaling for landmark configuration and distance misestimation. Embodiment occurred with bodies in anatomical orientation, while exposure to bigger bodies increased perceived distance, regardless of the presence of the embodiment. However, no significant changes emerged in the perception of landmark configuration. Findings indicated that, in extra-personal space, the distance perception between objects, rather than their shape configuration, is scaled based on a metric reference related to a seen body.

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1. Introduction

Our body is the means through which we engage with the external world. Our body's perception is mediated by cerebral representations of its size, shape, and movements, facilitating effective interactions with the surrounding environment (de Vignemont et al., 2007; Longo et al., 2010). Body representation is highly malleable and plastic to adapt to structural and contextual body changes (e.g., during the transition from

Abbreviations: MDS, Multidimensional Scaling; SDT, Space Distance Task; PD, Procrustes Distance.

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infancy to adulthood or during pregnancy). Moreover, body perception can be experimentally altered through body illusions by inducing embodiment over an artificial or virtual body part (e.g., Rubber Hand Illusion; Botvinick & Cohen, 1998) or an entire body (e.g., Full Body Illusion; Petkova & Ehrsson, 2008). Accordingly, the properties of the artificial or virtual body are processed similarly to those of one's own body (de Vignemont, 2011). For instance, during the Full Body Illusion (FBI), ownership feelings towards the artificial/virtual body are typically evoked by ensuring congruence between the tactile sensations perceived on one's own body and the touch on the artificial body, which is seen from a first-person perspective (Ehrsson, 2007; Lenggenhager et al., 2007).

Previous works showed that the representation underlying tactile and proprioceptive information about the body is distorted (Longo, 2015; Stone et al., 2018; Tosi et al., 2022). An asymmetric distortion of body metric perception of the legs has been previously shown, where a higher underestimation in proximo-distal distances rather than in the medio-lateral body axis was proved (Tosi & Romano, 2020). Similar results were observed for other body segments (Longo, 2015; Stone et al., 2018), suggesting that humans represent their limbs as shorter than they actually are. These studies are particularly relevant because such internal representations of the body can change as a result of body illusions (Serino et al., 2020; van der Hoort et al., 2011). In a previous work from our laboratory (Tosi et al., 2022), we employed a Full-Body paradigm and a Body Distance Task, adapted from previous works (Longo et al., 2015; Longo & Golubova, 2017; Longo & Haggard, 2012), to investigate whether body illusions affect the metric representation of the body. We found an underestimation along the proximo-distal body axis when fake legs resemble the participants' and are presented from an anatomical viewpoint. However, participants recalibrated their perception of body size after resized (i.e., short or long) bodies were presented. Since the body is also known to serve as a fundamental reference in the visuospatial perception of the surrounding environment (Proffitt & Linkenauger, 2013), distortions in body perception through visual and body illusion can alter space perception (Mancini et al., 2011; van der Hoort et al., 2011). Specifically, body illusions have proven to affect object size perception (Banakou et al., 2013; Linkenauger et al., 2010; van der Hoort et al., 2011), as well as motor planning (Marino et al., 2010; Tosi et al., 2020). Crucially to the present study, many studies found a relationship between body representations and peri-personal space (Holmes & Spence, 2004), defined as the space immediately surrounding our bodies (Rizzolatti et al., 1997). Arm length seems to influence the extent of the near space (Longo & Lourenco, 2007). Thus, altering the perceived size of the limb affects the distance perception of nearby objects (Linkenauger et al., 2015). Moreover, peri-personal space perception appears scaled to the perceived body characteristics (Proffitt & Linkenauger, 2013).

Despite the large body of work related to peri-personal space, there are still relatively few studies that have investigated extra-personal space (Proffitt et al., 2003; Fini et al., 2015), defined as the area surrounding the body beyond the reach of the arm (Vallar & Maravita, 2009). Proffitt and colleagues related physical effort to space perception. For instance, wearing a heavy backpack increases egocentric distance estimation of objects and geographical slant judgment (Proffitt et al., 1995, 2003). Therefore, distance perception can be influenced by action intentions or motor potentialities. Previous work found that the same Full-Body Illusion-like paradigm can also alter body affordances (Tosi et al., 2020). In particular, we demonstrated that participants imagined walking faster after the illusion elicited by long legs, compared to when seeing standard legs. This result proves that altered body representation could affect how individuals perceive their interaction with the surrounding space. Taken together, these studies support the idea that our body serves as a crucial frame of reference in our interactions with the environment (Mancini et al., 2011; Tosi et al., 2020; van der Hoort et al., 2011), influencing how we perceive spatial surroundings. Since an altered body representation has been proved to alter different spatial properties of the environment, it is possible that one's body representation in terms of body metrics and motor potentialities may also affect allocentric distance perception. For instance, Clark et al. (2016) demonstrated that increasing the level of physical exertion leads to an increase in the estimation of the length of a line, suggesting that body representation modulations can indeed shape allocentric space perception. However, it remains unclear if a change in the perceived body morphology, without an explicit manipulation of action potentialities, can affect extra-personal space perception and allocentric distance in far space. We specifically tackled this literature gap by extending the line of evidence from our research group. We have already shown that body size perception is distorted (Tosi & Romano, 2020) and, crucially, can be manipulated through body illusions (Tosi et al., 2022). We also demonstrated that it is possible to influence how individuals perceive their interaction with their spatial surroundings by addressing egocentric distances (Tosi et al., 2020). The present work analyses the portion of space away from our body and the surroundings, the so-called extra-personal space or far space. It evaluates whether manipulation of body representation can influence the perception of allocentric distances in far space, just as it does on the body. We employed a Full-Body Illusion-like paradigm that allows a modification of body metric perception (Tosi et al., 2022) to investigate the relationship between body and extra-personal space perception. We first hypothesised to induce perceptual delusion of embodying other bodies with different sizes. Since the body works as a fundamental reference in space processing (Holmes & Spence, 2004), we hypothesised that manipulating body size could also influence the perception of distance between landmarks in far space, rescaling distance estimation according to body metric.

We addressed distance perception in extra-personal space by considering both the misestimation of distances between landmarks (error in distance estimation; Stone et al., 2018) and landmarks' global configuration (using Multidimensional Scaling—MDS; Longo & Golubova, 2017). Both misestimation and MDS were developed for the analysis of perceptual spaces (Aznar-Casanova et al., 2006; Stone et al., 2018); they are complementary indices that provide slightly different information about distance perception and focus on global configuration (MDS) and local directional biases of the estimate (misestimation; Tosi & Romano, 2020). Specifically, MDS is a technique used to create perceptual maps based on patterns of distance estimations, which reconstruct the spatial structure of a set of

items using a pairwise distances matrix (Cox, 2001; Everitt, 1997; Shepard, 1980). In particular, given pairwise distances between landmarks, MDS extracts coordinates for each landmark in a bi-dimensional space. Then, Procrustes Alignment (PA; Goodall, 1991; Rohlf & Slice, 1990) superimposes spatial configurations of homologous landmarks by translating, scaling, and rotating them (Longo & Golubova, 2017). This procedure removes all the non-shape differences (Bookstein, 1991) and provides a dissimilarity index between the two configurations, called the Procrustes Distance. These methods have been deeply employed to map the underlying structure of different perceptual spaces, such as visual space (Aznar-Casanova et al., 2006) or to extract the geometry of tactile space (Longo & Golubova, 2017; Tosi & Romano, 2020). Procrustes Distance is a measure of global shape dissimilarity that does not distinguish between different types of distortions. To evaluate the accuracy of the participants' perception, we also employed misestimation to have a measure of length judgment errors, independently of the shape of the grid. Specifically, misestimation additionally measures a directional bias in length estimation, being a complementary index to the Procrustes Distance (Tosi & Romano, 2020).

2. Methods

2.1. Participants

We recruited 24 healthy volunteers (14 females, mean age 22.71 ± 1.90 years, range 18–26 years; mean education 14.71 ± 2.35 years, range 8–16 years) through the Research Participation System (SONA) of the Psychology Department of the University of Milano-Bicocca. Gender was considered as a spectrum, recognizing the diverse identities and expressions people use to define and present their gender (Coen & Banister, 2012). All participants had normal or corrected-to-normal vision and were unfamiliar with the objective of the experiment. To calculate the a priori sample size of participants to be included in the study, we conducted a power analysis with G*power 3.1.9.2, as pre-registered. We selected a repeated measure within factors ANOVA 2 × 2 design. The analysis revealed that to obtain a power of .80, with alpha set at .05 and effect size at f = .25 (medium size, corresponding to partial $\eta^2 = .06$), we needed to test 24 participants. Previous results from our lab with similar experimental designs (Tosi et al., 2020, 2022) revealed large effect sizes for the difference between experimental and control conditions (partial η^2 between .18 and .30). Considering these effect size values, the a-priori power analysis for a main effect in a 2 × 2 rmANOVA design revealed a sample size between 7 and 12 subjects. We decided on a conservative solution and included 24 participants, assuming a medium effect size. The local Ethics Committee of the University of Milano-Bicocca (Commissione per la Valutazione della Ricerca, Dipartimento di Psicologia) approved the study on the 17th January 2018 (protocol number: RM-2018-119-Tosi Maravita). The investigation was conducted according to the ethical standards of the Declaration of Helsinki (World Medical World Health Organization, 1996). Informed consent was obtained from all participants included in the study. The experimenter explained to the participants the general aim of the study and the procedure before collecting the informed consent. At the end of the experimental sessions, the experimenter also described the specific scope of the study.

2.2. Procedure

Participants underwent two testing sessions on two days, with a washout week. At the beginning of the first session, participants performed a Space Distance Task (SDT), during which they were asked to estimate the distance between landmarks in far space. Distance estimation was requested both in meters between landmarks and in the number of steps needed to cover the distance between them. We collected this data as a baseline measure to control for the individual's natural ability in distance estimation.

Then, in each session, the body illusion was induced with different body sizes. As soon as the illusion phase was completed, participants were required to perform the same SDT to investigate the potential influence of the body illusion on distance perception in extra-personal space. The illusion induction and the SDT occurred in a virtual environment within the HMD. The SDT began immediately after the illusion phase was completed and took approximately 3 min, ensuring the persistence of illusion effects during participants' distance evaluations (see Abdulkarim et al., 2021 for embodiment duration and Tosi et al., 2022 for similar experimental design).

After each condition, following the SDT, we administered a questionnaire to evaluate the subjective experience of embodiment over the fake bodies.

At the end of the second session, we also recorded the number of steps each participant needed to walk a 5-m distance.

2.3. Tasks

2.3.1. Body illusion paradigm

Participants sat in an armchair, keeping their arms behind the back of the chair. During the procedure, participants wore Head-Mounted Displays (HMDs—Samsung Gear VR 2016; Samsung Electronics, field of view = 101°) in which they saw pre-recorded videos of two artificial bodies receiving tactile stimulation with a stick. Videos were recorded with a 360° camera (Samsung Gear 360 2017-features: CMOS 8.4 MP ×2 /F2.2 lens; video recording resolution: 360° Dual Lens: up to 4096 × 2048, 24fps) so that the participant could explore the environment during the video presentation visually. Indeed, the 360° videos were recorded in the same room where the experiment was performed and from the exact position of the participant's viewpoint, providing an immersive, realistic, and ecological context. During the experiment, participants were asked to look towards their legs and lower abdomen to increase the focus on the fake body.

Two artificial bodies were adopted. The artificial bodies were different for the length of the legs: a standard pair (108 cm, as shown in Fig. 1a and b) and an elongated pair, roughly two times longer (203 cm, as shown in Fig. 1c and d). In each video, participants saw one of the two artificial bodies from a first-person perspective, touched by a wooden stick for 120 s. Touches were delivered on the upper left leg for 2 min at

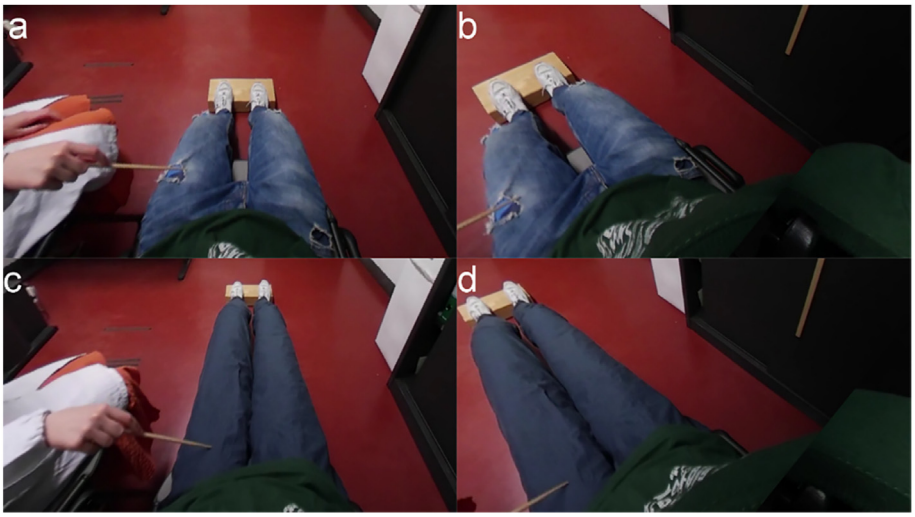

Fig. 1 – Body illusion paradigm.
Note. The figure shows four frames extracted from the videos used to induce the body illusion. (a) Standard size legs showed in the anatomical orientation. (b) Standard size legs showed in the non-anatomical orientation. (c) Long size legs showed in the anatomical orientation. (d) Long size legs showed in the non-anatomical orientation.

1 Hz. During this period, the experimenter touched the participant's left leg simultaneously and in the corresponding location, generating a synchronous visuotactile stimulation. During the video presentation, participants heard white noise to avoid interference from outside the lab room.

Participants underwent two conditions of leg orientation. The 0° rotation provided videos of bodies seen from an anatomical viewpoint (Fig. 1a and c). This one was our experimental condition for which we expected to induce embodiment. In the 0° rotation, participants saw the mannequin legs holding the same posture and orientation as their real legs when they looked down. In the second condition, we provided the same videos from a 45° counter-clockwise rotated angle (Fig. 1b and d). With this arrangement, when volunteers looked down, they saw two legs that were not aligned with their bodies, resulting in a non-anatomically compatible viewpoint. We used this non-anatomical orientation as a control condition for which we did not expect to induce embodiment (Guterstam et al., 2011; Pavani et al., 2000; Romano et al., 2016; Tosi et al., 2020, 2022).

By crossing size and orientation variables, we obtained four conditions: standard anatomical, standard non-anatomical, long anatomical, and long non-anatomical. In a counterbalanced order, we administered the Standard and Long conditions in two different testing sessions held on two different days interleaved by one week.

2.3.2. *Embodiment questionnaire*

At the end of each condition, we administered a questionnaire to evaluate the embodiment of the artificial legs presented in the videos (Tosi & Romano, 2023). Participants rated their agreement on 16 questions on a seven-point Likert scale (−3 to +3). Six items of the questionnaire were designed to capture the three components of the general experience of embodiment (Longo et al., 2008): the sense of ownership (items Q1 and Q2), the sense of agency (items Q3 and Q4 reversed), and the sense of co-location (items Q5 and Q6). We averaged participants' responses to these six items to evaluate the occurrence of the embodiment as pre-registered. The complete questionnaire is reported in Table 1.

2.3.3. *Space distance task (SDT)*

Participants underwent a Space Distance Task at the beginning of the procedure and after each condition of the body illusion. We modified the task from previous works (Longo et al., 2015; Longo & Golubova, 2017; Longo & Haggard, 2012; Tosi et al., 2022; Tosi & Romano, 2020) so that it can be administered in the extra-personal space rather than on the body. For this task, we selected a well-known environment: the square facing the main entrance of the University of Milano-Bicocca, with four environmental landmarks (maple trees), as shown in Fig. 2a. We specifically chose this setting because all participants were familiar with it, so that the task did not rely solely on visual perception but also on participants' previous knowledge of the space. This choice helps minimizing potential variability in distance estimation arising from differences in spatial familiarity. Additionally, using a known environment allowed us to explore the effects of the bodily illusion in a context where participants' prior knowledge might attenuate the effects. Therefore, any effects of the bodily illusion observed under these conditions would be considered as a lower bound of the potential effect, providing robust evidence. Participants were presented with a 360° picture of the same environment from a first-person perspective (Fig. 2b and c). Photographs were taken with a 360° camera (Samsung Gear 360 2017-features: CMOS 8.4 MP ×2/F2.2 lens; resolution: 360° Dual Lens: up to 4096 × 2048, 15 megapixels) from the very exact position of the participant's viewpoint, providing an immersive, realistic, and ecological context. In this way, participants could visually explore the environment. During each trial, two landmarks were highlighted for the entire duration of the stimulus presentation (as shown in

Table 1 – Statements and components of the Embodiment questionnaire.

COMPONENT		ID	QUESTION
Embodiment	**Ownership**	Q1	Did it seem like you were looking directly at your own legs?
		Q2	Did it seem like the legs in the video belonged to you?
	Agency	Q3	Did it seem like you could have moved the legs in the video if you had wanted?
		Q4	Did it seem like you were not in control of the legs in the video?
	Co-location	Q5	Did it seem like the legs in the video were in the location where your legs were?
		Q6	Did it seem like the touch you felt was caused by the stick touching the legs in the video?
Disembodiment		Q8	Did it seem like you could have moved your legs if you had wanted?
		Q9	Did it seem like your legs were out of your control?
		Q10	Did it seem like you couldn't really tell where your legs were?
		Q12	Did it seem like your own legs became "fake"?
Control		Q7	Did it seem like your legs had disappeared?
		Q11	Did it seem like the experience of your legs was less vivid than normal?
		Q13	Did it seem like you had four legs?
		Q16	Did you find that experience enjoyable?
Size		Q14	Did it seem like the stick was smaller, bigger or the same as the real one?
		Q15	Did it seem like the legs in the video were smaller, bigger or the same as your own?

Fig. 2b and c), and participants were asked to verbally estimate the distance between them. For each pair of landmarks, we asked participants to evaluate the distance in meters and to indicate the number of steps they would need to walk from one landmark to the other. There were four possible landmarks and six possible stimulus pairs. Each pair was presented four times for a total of 24 stimuli pairs. This repetition allowed for a direct comparison of estimations between conditions. However, we recognized that repeating the same pairs might lead some participants to recall their previous responses. To address this, we monitored participants' response patterns during data analysis and excluded those who displayed no variance, taking under control potential reliance on memory rather than perceptual re-evaluation. The task took approximately 3 min, which is less than the reported duration of the sense of ownership (Abdulkarim et al., 2021)

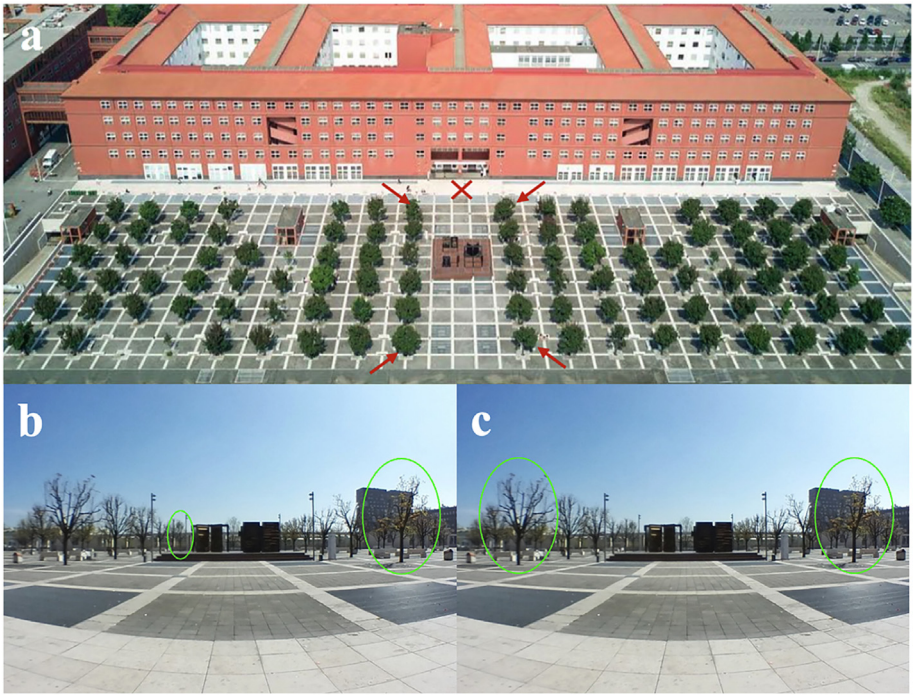

Fig. 2 – Space distance task.
Note. (a) Shows the well-known space and the environmental landmarks selected for the task (the four trees indicated by a red arrow); the X shows the participants' viewpoint. (b) Shows the 360° image of the same environment from the participants' perspective with one of the obliquus trials of the Space Distance Task, during which we asked participants to evaluate the distance between the two highlighted stimuli (c) Shows the transversal trial of the same Space Distance Task.

Table 2 – Real matrix distances and coordinates.

	A	B	C	D	x-coordinate	y-coordinate
A	.0	20.0	40.0	44.7	−19.994	9.988
B	20.0	.0	44.7	40.0	−19.994	−9.988
C	40.0	44.7	.0	20.0	19.994	9.988
D	44.7	40.0	20.0	.0	19.994	−9.988

Note. The left part of the table shows the pairwise distances between landmarks in the real environment; the right part shows the bi-dimensional coordinates obtained from the MDS.

and less than a similar task used to investigate body metric perception after the same body illusion (Tosi et al., 2022).

2.4. *Measures*

2.4.1. *SDT-responses in meters*

We analysed participants' responses in meters with two methods. First, we used Multidimensional Scaling (MSD) and Procrustes Alignment to evaluate the shape of the grid based on the distances between landmarks (Longo, 2015; Longo & Morcom, 2016; Tosi & Romano, 2020). Second, we calculated the percentage of error estimation for each pair of stimuli to assess how accurately participants perceived the distance between landmarks (misestimation; Stone et al., 2018; Tosi & Romano, 2020).

2.4.1.1. Global configuration perception. MDS is a technique that identifies the underlying spatial structure of a set of items by analysing the matrix of pairwise distances between them (Cox, 2001; Everitt, 1997; Shepard, 1980). We used MDS to determine the coordinates of each point on the actual grid (see Fig. 2a and Table 2 for the distance in meters between the landmarks and their coordinates) and the perceived locations of the grid points reported by each participant in a bi-dimensional space. This allowed us to reconstruct a perceptual representation of the grid for each participant in each condition. Specifically, we averaged the distances reported under the two presentation orders. This resulted in a symmetric matrix representing the pairwise perceived distances between grid points, with zeros on the diagonal. We then applied Multidimensional Scaling (MDS) to this matrix, transforming the four-dimensional data into coordinates in a two-dimensional space. We based this transformation on the eigenvalues of each dimension, as shown in Supplemental Materials, Table S1. The first two dimensions accounted for a significant portion of the variance (99.93%), with the first dimension explaining 67.71% and the second dimension explaining 32.22%. For each subject and in each condition, a perceptual configuration of the grid was reconstructed using these two dimensions, as depicted in Fig. 3.

To examine the shape of the perceived grids, we created multiple distorted versions of the real grid by stretching the x-coordinates and y-coordinates of the grid points. The coordinates were multiplied by a stretch parameter ranging from .33 (reducing the distance between two points to one-third of the original length) to 3 (increasing the distance to three times the original length), with a resolution of .0005 units in logarithmic space, producing 4415 different grids on each coordinate. These distorted grids were then compared to the perceptual configurations of the participants using Procrustes Alignment, which measures the dissimilarity between the grids (i.e., the Procrustes Distance—PD).

Procrustes Alignment superimposes two grids and eliminates any differences that don't affect their overall shape (Bookstein, 1991). The Procrustes Distance is calculated as the square root of the residual sum of squared distances between corresponding landmarks, which remains unaffected by Procrustes Alignment. For each participant and coordinate (x or y), we obtained 4415 dissimilarity indices (PD) from the

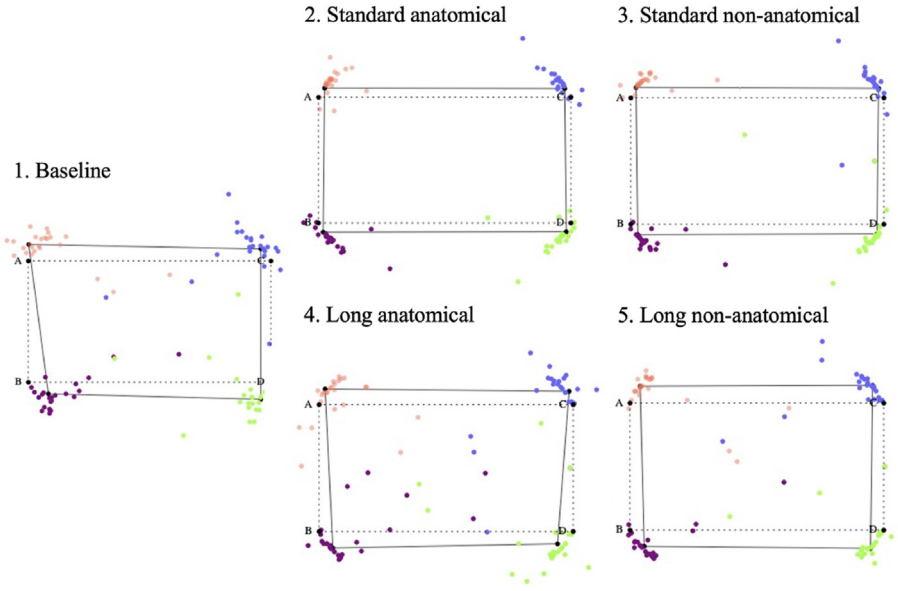

Fig. 3 – Results of the Multidimensional Scaling for the different conditions (responses in meters). Note. The solid line represents the subjects' averaged configuration based on their responses in meters; the dashed line represents the actual grid. We characterised participant's perceived location of each point with different colours (different grayscale).

stretched grid of points. The PD ranges from zero (identical shapes) to one (no shared spatial structure). We determined the stretch of the actual grid that minimised PD, considering both x-axis and y-axis stretches. This identified the stretched configuration most similar to the participant's perception. We calculated the stretch minimising PD for both the baseline and each condition (standard anatomical, standard non-anatomical, long anatomical, and long non-anatomical) to determine the most likely perceived shape.

2.4.1.2. Distances misestimation. Procrustes Distance is a measure of global shape dissimilarity that does not distinguish between different types of distortions. To evaluate the accuracy of the participants' perception, the percentage of perceived misestimation was computed for each pair of stimuli using the following formula:

$$\%\ misestimation = \frac{(perceived\ \ distance - actual\ distance)}{actual\ distance} * 100$$

Since the misestimation additionally measures a directional bias in length estimation, it represents a complementary index to the Procrustes Distance (see for more details on the complementarity of misestimation and global shape dissimilarity; Tosi & Romano, 2020). As for the Procrustes Distance, we calculated the percentage of Misestimation for the baseline and each condition considering the size (standard/long) and the orientation (anatomical/non-anatomical) of the legs presented during the body illusion.

2.4.2. SDT-responses in steps

At the end of the experimental procedure, we assessed the number of steps necessary to walk five meters. Then, we computed the actual number of steps participants would have needed to walk from each landmark to the others. Finally, we calculated the percentage of misestimation for each pair of landmarks in the baseline and each condition according to the size (standard/long) and the orientation (anatomical/non-anatomical) of the legs presented during the body illusion.

3. Data analysis

We conducted the analyses with R 3.4.2 (R Development Core Team, 2016). We used the package *stats* (*cmdscale* function) to run MDS. PD has been calculated with the package *vegan* (function *Procrustes*). Misestimation percentages have been calculated using an ad hoc formula in R. For Bayesian *t*-tests, we used the *BayesFactor* package, considering the default priors (scale = $\sqrt{2}/2$, mu = 0).

3.1. Embodiment questionnaire

As pre-registered, to assess if the body illusion can induce embodiment over bodies with different sizes, we ran a within-subjects 2(size) * 2(orientation) repeated measure ANOVA (rmANOVA) on the averaged responses for the embodiment score. Significant effects were interpreted by inspecting 95% Confidence Intervals. We focused on the embodiment score because it constitutes the primary component of the embodiment questionnaire that was the focus of our manipulation. The analyses on the other questionnaire factors are reported in the Supplemental Materials, Table S2.

3.2. SDT—response in meters

3.2.1. Global configuration perception

The stretches that minimised PD have been log-transformed to improve the fit with normal distribution for the inferential statistic. In addition to the pre-registered analyses, we performed a series of Bayesian independent one-sample *t*-tests on the stretch that minimised PD of each condition. To assess if there was any distortion in the perceived metric of the space, we compared the stretch to 0, corresponding to the logarithm of 1, a value indicating that the participant's grid resembles the real one. We chose a Bayesian approach because it allows us to test evidence for both alternative and null hypotheses compared with the frequentist approach. Given the mixed results of a previous study (Tosi et al., 2022), we decided to assess evidence favouring both hypotheses.

Then, as pre-registered, we ran a within-subjects 2(size) * 2(orientation) rmANCOVA with the baseline as a covariate variable. This analysis was intended to evaluate any effect of the body illusion conditions on the perceived shape of the grid, as assessed in meters. We used the stretch that minimised the Procrustes Distances as a dependent variable; significant effects were interpreted by inspecting 95% Confidence Intervals.

3.2.2. Length distance misestimation

Before running the analyses, we checked for the presence of outliers, considering all estimates in each condition using the boxplot method as implemented in the R function *identify_outliers* (*rstatix* package). Additionally, we removed participants who showed no variance in their responses (standard deviation = 0) within each direction of the landmark pairs (longitudinal/transversal/obliquus), irrespective of the specific stimuli or the session.

We analysed the responses given in meters by running a Linear Mixed Model (LMM) with the misestimation as the dependent variable. We considered the direction of the landmark pairs (longitudinal/transversal/obliquus) as a fixed effect factor to investigate differences in distance estimations based on stimulus type. We set random slope and intercept across participants and stimuli to control for both participant-level and stimulus-level variability. We interpreted significant effects by inspecting 95% Confidence Intervals. We utilised marginal R^2 (R^2_m) to convey the proportion of explained variance attributed to the fixed effect and conditional R^2 (R^2_c) to represent the proportion of variance explained by both the fixed and random effects within the model. We computed R^2_m and R^2_c using the R function *r.squaredGLMM* (*MuMIn* package). LMM was chosen for its greater flexibility compared to standard rmANOVA, as it allows us to enhance statistical power by accounting for both participant- and stimulus-level variability. This analysis represents a slight deviation from our preregistration. In the preregistration, we introduced the analyses based on prior work regarding body size perception following the same body illusion (Tosi & Romano, 2020). In line with the previous work, the initial proposal included an analysis considering both the direction (longitudinal/

transversal/obliquus) and distance (short/medium/long) of the stimuli pairs. However, in the current study, the two factors convey the same meaning (longitudinal = medium distance; transversal = short distance; obliquus = long distance). Therefore, we opted to include only one factor in our analysis. Moreover, deviating from the pre-registration, we included stimulus as a random effect.

In addition to the pre-registered analyses, we performed an LMM to evaluate whether the body illusion conditions affected the responses given in meters. Again, misestimation was considered as the dependent variable. Fixed effects were size (standard/long) and orientation (anatomical/non-anatomical) as factors and baseline as the covariate. We set random intercept across participants and stimuli to control for both participant-level and stimulus-level variability. Significant effects were interpreted by inspecting 95% Confidence Intervals.

3.3. SDT—response in steps

Before running the analyses, we checked for the presence of outliers, considering all estimates in each condition using the boxplot method as implemented in the R function *identify_outliers* (*rstatix* package). Additionally, we removed participants who showed no variance in their responses (standard deviation = 0) within each direction of the landmark pairs (longitudinal/transversal/obliquus) irrespective of the specific stimuli or the session.

As pre-registered, we analysed the responses in steps by running a Linear Mixed Model (LMM) with the misestimation as the dependent variable. We considered size (standard/long) and orientation (anatomical/non-anatomical) as fixed factors and baseline as the covariate, to evaluate whether the body illusion conditions affected the responses given in steps. We set random intercept across participants and stimuli to control for both participant-level and stimulus-level variability. Significant effects were interpreted by inspecting 95% Confidence Intervals. R^2_m and R^2_c were reported to express the variance explained by the model. This analysis was pre-registered to assess whether the body illusion conditions affected the responses in the number of steps.

3.4. Correlation

In addition to the pre-registered analysis, we extracted the LMM models' random slope on the responses in meters and steps. We used these variables to measure the individual differences in distance estimation independently by the body illusion effects. We performed a correlation analysis between the random effects to evaluate the coherence between the responses given in meters and the number of steps.

4. Results

4.1. Embodiment questionnaire

The 2(size) * 2(orientation) repeated measure ANOVA resulted in significant main effects of orientation ($F(1,23) = 16.60$, $P \leq .001$, partial $\eta^2 = .42$). Both the standard (CI: [.54; 1.22]) and the long legs (CI: [.41; 1.25]) presented in an anatomical orientation induced a stronger embodiment as compared to the non-anatomical orientation in the standard (95% CI: [−.56; .49]) and long (95% CI: [−.63; .37]) legs (Fig. 4). The main effect of size and the interaction between size and orientation were not significant ($P > .4$). The results obtained from the other factors of the questionnaire are reported in Table S2 (see Supplemental Material).

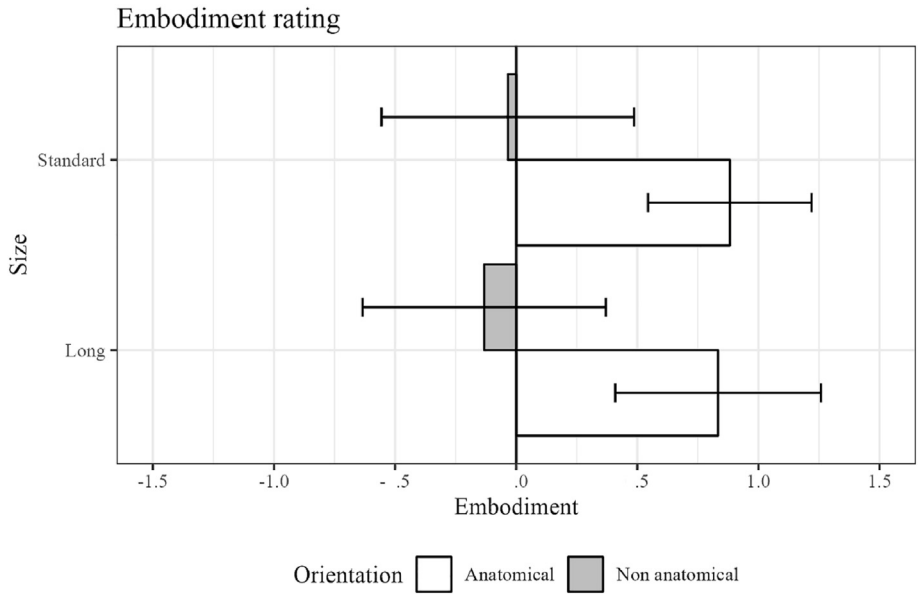

Fig. 4 – Embodiment questionnaire results.
Note. The figure shows the results of the within-subjects 2 (size) x 2 (orientation) repeated measure ANOVA on the averaged answers to embodiment statements. Grey and white columns display Non-anatomical and Anatomical conditions, respectively. Error bars indicate 95% confidence interval limits.

Table 3 – Results of the Bayesian one-sample *t*-tests ran on the stretch that minimised the Procrustes Distance for each condition.

	Mean PD (log)	Median effect size	95% CI lower	95% CI upper	BF_{10}	BF_{10} error (%)
Baseline	−.129	−.12	−.23	−.02	1.33	±.02%
Long anatomical	−.179	−.16	−.37	.05	.71	±.03%
Long non-anatomical	−.071	−.06	−.27	.15	.26	±.02%
Standard anatomical	−.072	−.06	−.22	−.09	.30	±.03%
Standard non-anatomical	−.146	−.13	−.28	.03	.83	±.02%

Note. The table shows the Procrustes Distance (PD) Mean after log transformation, the median of the effect size, the effect size credible interval (CI), the Bayes Factor$_{10}$ (BF_{10}, showing the probability of the alternative hypothesis compared to the null), and its error (%).

4.2. *SDT—response in meters*

4.2.1. *Global configuration perception*

The Bayesian one-sample t-tests showed anecdotal to moderate evidence in favour of the null hypothesis that the stretches that minimised the Procrustes Distance are equal to 0 for all the body illusion conditions (see Table 3). These results suggested that the perceived grid did not differ from the actual grid of the targets in all conditions (Fig. 3). On the contrary, we found anecdotal evidence favouring the alternative hypothesis in the baseline condition, suggesting a possible shape difference between the perceived grid and the real one before the illusion. However, the 2(size) * 2(orientation) ANCOVA did not show any significant effect (all $P > .3$), discarding the possibility that the body illusion has a significant influence on the perception of the global configuration of landmarks in far space.

4.2.2. *Length distance misestimation*

Participants who showed no variance in their responses (IDs: 1, 10, 17, and 24) were excluded from the analysis. For completeness, analyses including these participants are provided in the supplementary materials (see Tables S5 and S6). Additionally, four outliers participants (IDs: 7, 8, 9, and 20) and three other extreme estimations trials were removed from the dataset. Notably, the final sample size remains larger ($N = 16$) than the one estimated with the power analysis based on previous studies effect size ($N = 7–12$), thus keeping the study properly powered.

The LMM revealed a significant main effect of direction ($F(2,174) = 10.98$, $P < .0001$). Participants generally underestimated the distances between landmarks, as shown by the negative values in all three directions. Moreover, distance estimation exhibits a gradient of underestimation according to the direction: progressing from the longitudinal direction, which manifested the most pronounced underestimation (95% CI: [−67.3; −36.6]), to the oblique direction (95% CI: [−60.7; −30.1]), and ultimately to the transversal direction, which exhibited the slightest degree of underestimation (95% CI: [−57.2; −26.6]). Considering the overall model, random and fixed effects explained 77.19% of the variance, while fixed effects explained 1.54%.

Moreover, the additional analysis regarding the effect the body illusion on the meters misestimations revealed a significant main effect of Size ($F(1,1305) = 47.41$, $P < .0001$) and Orientation ($F(1,1305) = 6.99$, $P < .01$), as shown in Fig. 5a. The

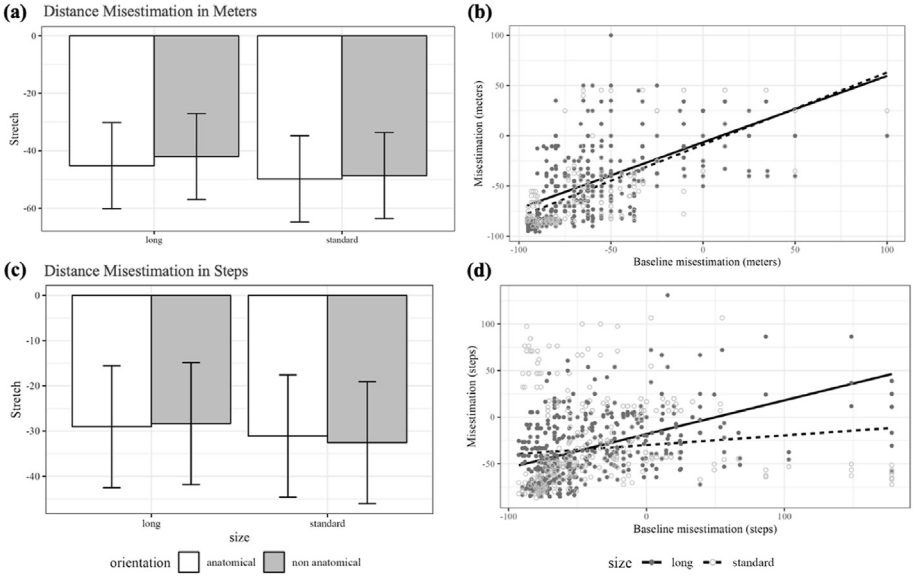

Fig. 5 – Misestimations Results.
Note. (a) Results of the 2(Size)*2(Orientation) ANOVA on distance estimations in meters. The covariate Baseline was kept constant at a value of −33.5. (b) Interaction effect between Baseline and Size. (c) 2(Size)*2(Orientation) ANOVA on distance estimations in steps. The covariate Baseline was kept constant at a value of −33.5. (d) Interaction effect between Baseline and Size. Error bars display 95% confidence interval limits.

estimation made after the videos with the long legs was more precise (95% CI: [−58.6; −28.6]) rather than after the videos with the standard legs (95% CI: [−64.2; −34.3]). Moreover, participants tend to underestimate more when the legs are in the anatomical orientation (95% CI [−62.5; −32.5]) than the non-anatomical ones (95% CI [−60.3; −30.4]). A significant interaction between the legs' size and the baseline ($F(1,1305) = 5.85$, $P < .05$) also emerged (Fig. 5b). The relationship between the misestimation before and after the illusion seemed to be slightly more attenuated in the long leg size condition compared to the standard one. Considering the overall model, 77.42% of the variance was explained by random and fixed effects, while 1.05% of the variance was explained by fixed effects. See Supplementary Materials for additional details on the effect of the body illusion on misestimation in meters (Table S3).

4.3. *Response in steps*

Participants who showed no variance in their responses (IDs: 1 and 17) were excluded from the analysis. For completeness, analyses including these participants are provided in the supplementary materials (see Table S7). Additionally, three outlier participants (subjects IDs: 2, 7, and 20) and two extreme estimation trials were removed. The LMM revealed a significant main effect of size ($F(1, 1403) = 10.11$, $P < .01$). We also found a main effect of the covariate baseline ($F(1,1403) = 20.85$, $P \leq .0001$) and an interaction between size and baseline ($F(1, 1403) = 143.34$, $P \leq .0001$). No additional effects reached statistical significance ($P > .05$). See Supplementary Materials for additional details on the effect of the body illusion on misestimation in steps (Table S4).

As shown in Fig. 5c, the estimations made after the videos with the long legs were more precise (95% CI: [−42.10; −15.30]) than after the videos with the standard legs (95% CI: [−45.20; −18.40]). Moreover, the level of estimation accuracy remained constant before and after the bodily illusion: those participants who were more accurate in their estimates before the body illusion were also more accurate afterwards. However, the relationship between the misestimation before and after the illusion seemed to be attenuated in the standard leg size condition compared to the long one (Fig. 5d). Thus, estimations in steps appear to be more influenced by the illusion compared to those in meters, probably because they depend more on body representation. At the same time, estimations in meters remain more stable, showing a stronger correlation between pre- and post-illusion conditions. Considering the overall model, 68.80% of the variance was explained by random and fixed effects, while 4.91% of the variance was explained by fixed effects.

4.4. *Correlation*

The correlation analysis revealed a positive correlation between the estimation in steps and meters ($r(13) = .59$, $P < .05$), suggesting an accordance between measures.

5. Discussion

Our body is a fundamental reference in the visuospatial processing of the surrounding space (van der Hoort et al., 2011). In the present work, we investigated the relationship between body size and the perception of extra-personal space distance. We employed a Full-Body Illusion-like paradigm that modifies body metric perception (Tosi et al., 2022). We hypothesised that the illusory manipulation of body size could influence the distance perception between landmarks in far space. A space distance task (SDT) modified from previous studies on body perception (Longo, 2015; Longo & Morcom, 2016; Tosi & Romano, 2020) was implemented to assess the perception of distances in far space. We tackled extra-personal space perception with a twofold approach. On the one hand, we analysed the shape perception of landmark configuration through Multidimensional Scaling (MDS). On the other hand, we assessed the perceptive misestimation in terms of distance in meters and steps needed to cover the spread. MDS and misestimation are complementary approaches focusing on global configuration and length estimation. At the end of each condition, we evaluated the subjective experience of embodiment induced by the Full-Body Illusion with different body sizes through a questionnaire. Results revealed that exposure to bigger bodies increased perceived distance, regardless of the presence of the embodiment. However, no significant changes emerged in the perception of landmark configuration.

Specifically, both the standard legs and the long ones presented in an anatomical orientation induced a stronger embodiment sensation than when presented in the non-anatomical orientation. This result is consistent with previous studies and confirms that it is possible to induce the embodiment of a fake body when presented from a first-person perspective and in an anatomical position. Specifically, we generated illusory ownership over artificial legs holding both realistic and unrealistic bigger sizes (Romano et al., 2016; Tosi et al., 2020; van der Hoort et al., 2011).

Considering the effect of body illusion on the distance estimation task, we found that embodying a body of a bigger size led to perceiving objects as closer. Specifically, participants who tend to underestimate the number of steps needed to walk a certain distance at the baseline showed the same pattern after the videos and were scarcely influenced by the body illusion. On the contrary, people who overestimated the number of steps at the baseline showed a higher overestimation after the video with the long legs than the standard legs. Therefore, after exposure to longer legs, participants tended to perceive distances between the landmarks as longer. Compared to estimations in steps, estimations in meters appear more stable, showing a stronger correlation between pre- and post-illusion conditions and being less influenced by the illusion effect. It is possible that when participants estimate distances in steps, there is a

stronger and more direct involvement of body representation, compared to the more abstract and indirect estimation of distance in meter. This is the reason why the correlation between estimations in steps made before and after the illusions was more influenced by the legs' size presented. Moreover, regarding the response given in meters, our results revealed a general underestimation of distances, consistent with prior studies that investigated distance estimation using virtual reality setups (Creem-Regehr et al., 2023; Kelly, 2022). This finding seems to parallel the proximo-distal underestimation typical of body perception (Longo, 2015; Longo & Morcom, 2016; Stone et al., 2018; Tosi & Romano, 2020). However, alternative explanations are possible. On the one hand, this result may be due to the greater difficulty of depth perception in virtual reality. Indeed, transverse estimation may be less affected by depth processing in virtual reality, unlike in oblique and especially longitudinal distance estimation. Moreover, the longitudinal direction corresponded to the longest distance between landmarks, and the transversal direction matched the shortest distance. Our results could be explained by a generalised effect of increasing underestimation with longer distances, as shown by previous findings (Tosi et al., 2020).

Our findings may initially seem contradictory to prior studies' results, which indicated that embodying a body of a bigger size led to perceiving objects as closer to the body (D'Angelo et al., 2019; Linkenauger et al., 2013; van der Hoort et al., 2011) and reduced the perceived time needed to reach an object (Tosi et al., 2020). However, the present study specifically examined allocentric distance (i.e., the distance between two objects in space) rather than egocentric (i.e., an object's distance from one's own body), as explored in most prior research. Clark et al. (2016) focused on allocentric distance perception and showed that increasing the level of physical exertion leads to an increase in the estimation of the length of a line. Our result could align with Clark's result, as the longer legs could have enhanced the perceived physical effort needed to walk. Additionally, it is plausible that this effect is not primarily related to the embodiment effect, as indicated by the lack of an interaction effect between the size and orientation of the body during the illusion. Instead, it may be attributed to a perceptual mechanism of visual capture (i.e., the higher influence of visual inputs over proprioception and tactile sensation; Pavani et al., 2000; Romano et al., 2013; Tosi et al., 2018), independent of the legs' orientation and embodiment. Compared to the previous literature, the different result could be attributed to a more relevant role of embodiment for egocentric distance estimations than allocentric distance estimation in far space. In extra-personal space, for allocentric distance estimation, it is possible that what is important is not one's own body size but a general body reference according to which the world is scaled. Thus, the visual exposure to long legs may serve as a perceptual metric reference upon which allocentric distances are rescaled. If I use the body as a reference to perceive distances, when I am exposed to longer legs, I assume everything else is bigger and rescale distances accordingly. Consequently, an overestimation of distances might emerge as an implicit mechanism following exposure to stretched stimuli. In this sense, the long legs are not used as an internal metric for distance estimation, but rather as an external reference that alters the perceived scale of the surrounding environment. Specifically, exposure to very long legs may lead participants to underestimate the size of their real legs, which could influence their subsequent distance estimations. This underestimation of real leg size could lead participants to estimate a larger number of steps and meters to cover the same physical distance. Our results cannot disambiguate whether these spatial rescaling mechanisms are specific to the exposure of large bodily stimuli, or a generic large stimulus used as a reference in distance estimation. Future directions may address the rescaling hypothesis by using different perspectives (i.e., third-person perspective) or reference stimuli. This effect would be present both in estimations that directly involve one's body representation during distance estimation, such as estimating the number of steps required to cover a distance, and in more indirect and less body-centred estimations, such as distance estimations in meters. In fact, we found similar results when analysing the perceived distances in meters, and the two estimation measures were consistent, as evidenced by their positive correlation. Therefore, our findings suggest that allocentric distance estimation between two objects in extra-personal space is scaled based on a metric reference related to a seen body. Based on this hypothesis, visual exposure to a large body, observed from a third-person perspective, could rescale the perception of the surrounding environment.

At the same time, the global configuration of landmarks in far space seems not to be influenced by body illusion. Participants seemed to perceive the configuration of extra-personal space accurately, as no distortion emerged in the perceived configuration of points compared to the actual landmark configuration. Previous research robustly supported that humans possess a distorted body map to perceive tactile stimuli (Longo, 2015; Longo & Morcom, 2016; Stone et al., 2018; Tosi et al., 2022; Tosi & Romano, 2020). The representations of the hand and leg seem to exhibit significant distortions, leading to an underestimation of proximal-distal distances compared to mediolateral distance estimates (Longo, 2015; Longo & Morcom, 2016; Tosi & Romano, 2020). Moreover, Tosi et al. (2022) found that body illusion can modulate these perceptual biases. When participants were exposed to a fake body with bigger or smaller legs, the distortion was reduced due to a recalibration of body size perception. However, the current findings suggest that the body illusion did not have a corresponding effect on the perception of extra-personal space configuration. Consequently, participants could estimate the overall spatial configuration accurately and maintain these precise estimations regardless of illusory changes in body size. The discrepancy between the results of the present study and our previous findings suggests that the mechanisms underlying bodily shape perception and spatial shape perception may be distinct.

The present work cannot disambiguate if the rescaling affects egocentric distances in extra-personal space as well. Future studies could benefit from including an egocentric condition to directly compare egocentric and allocentric spatial rescaling following body illusions.

As a potential limitation of the present study, we acknowledge that the use of a familiar environment and the

repetition of the same distance pairs in our task may have influenced the results. Using a more complex and unfamiliar environment could reduce reliance on visual memory and offer further insights into how body manipulation affects spatial processing. Furthermore, assessing participants' sense of presence in the virtual scenario could provide additional insights.

6. Conclusions

The results of this study confirm that it is possible to induce the embodiment of a fake body holding either standard or longer legs when presented from a first-person perspective and in an anatomical position. Moreover, visual exposure to long legs seems to influence both the estimations of distances in meters and the number of steps. Indeed, the long legs condition increased the perceived distance in meters and the number of steps participants imagined they would need to walk between the landmarks. Our findings suggest that the perception of distance between objects in the far space is scaled in relation to a metric reference associated with a seen body. We expect our results to generalise to the real world; however, perceptive differences between the real world and virtual reality exist (e.g., greater difficulty of depth perception in virtual reality). Perceptual differences may constrain the generality of our results.

CRediT authorship contribution statement

Giorgia Tosi: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Francesca Frisco:** Writing – review & editing, Writing – original draft, Visualization, Methodology. **Angelo Maravita:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Daniele Romano:** Writing – review & editing, Methodology, Conceptualization.

Data availability

The present work, including hypotheses, design, sampling and analysis plan were preregistered on the Open Science Framework (OSF) platform at the following link: https://doi.org/10.17605/OSF.IO/85ZVG.

Data and analysis scripts of the experiments are available at the OSF at the following link: https://osf.io/9rtm8/?view_only=f26796d89cdb44fc826717eb86a61774.

Ethics approval

The local Ethics Committee of the University of Milano-Bicocca (Commissione per la Valutazione della Ricerca, Dipartimento di Psicologia) approved the study on the 17th January 2018 (RM-2018-119-Tosi Maravita).

Declaration of competing interest

The authors declare that they have no known conflicts of interest to disclose.

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During the preparation of this work the author(s) used Gemini in order to improve English writing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2025.01.004.

REFERENCES

Abdulkarim, Z., Hayatou, Z., & Ehrsson, H. H. (2021). Sustained rubber hand illusion after the end of visuotactile stimulation with a similar time course for the reduction of subjective ownership and proprioceptive drift. *Experimental Brain Research, 239*(12), 3471–3486.

Aznar-Casanova, J. A., Matsushima, E. H., Ribeiro-Filho, N. P., & Da Silva, J. A. (2006). One-dimensional and multidimensional studies of the exocentric distance estimates in frontoparallel plane, virtual space, and outdoor open field. *The Spanish Journal of Psychology, 9*(2), 273–284.

Banakou, D., Groten, R., & Slater, M. (2013). Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences, 110*(31), 12846–12851. https://doi.org/10.1073/pnas.1306779110

Bookstein, F. L. (1991). *Morphometric tools for landmark data*. Cambridge University Press. https://doi.org/10.1017/CBO9780511573064

Botvinick, M., & Cohen, J. (1998). Rubber hands' feel' touch that eyes see. *Nature, 391*(6669), 756. https://doi.org/10.1038/35784

Clark, E. V., Ward, N. S., & Kuppuswamy, A. (2016). Prior physical exertion modulates allocentric distance perception: A demonstration of task-irrelevant cross-modal transfer. *Experimental Brain Research, 234*, 2363–2367. https://doi.org/10.1007/s00221-016-4641-5

Coen, S., & Banister, E. (2012). *What a difference sex and gender make: A gender, sex and health research casebook*. CIHR Institute of Gender and Health.

Cox, T. F. (2001). Multidimensional scaling used in multivariate statistical process control. *Journal of Applied Statistics, 28*(3–4), 365–378. https://doi.org/10.1080/026647601200

Creem-Regehr, S. H., Stefanucci, J. K., & Bodenheimer, B. (2023). Perceiving distance in virtual reality: Theoretical insights from

contemporary technologies. *Philosophical Transactions of the Royal Society B, 378*(1869), Article 20210456. https://doi.org/10.1098/rstb.2021.0456

D'Angelo, M., di Pellegrino, G., & Frassinetti, F. (2019). The illusion of having a tall or short body differently modulates interpersonal and peripersonal space. *Behavioural Brain Research, 375*, Article 112146. https://doi.org/10.1016/j.bbr.2019.112146

de Vignemont, F. (2011). Embodiment, ownership and disownership. *Consciousness and Cognition, 20*(1), 82–93. https://doi.org/10.1016/j.concog.2010.09.004

De Vignemont, F., Tsakiris, M., & Haggard, P. (2007). Body mereology. In G. Knoblich, I. Thornton, M. Grosjean, & M. Shiffrar (Eds.), *The body from inside out* (pp. 147–170). Oxford University Press.

Ehrsson, H. H. (2007). The experimental induction of out-of-body experiences. *Science, 317*(5841), 1048. https://doi.org/10.1126/science.1142175

Everitt, B. (1997). *The analysis of proximity data, 4*. Arnold Publishers.

Fini, C., Brass, M., & Committeri, G. (2015). Social scaling of extrapersonal space: Target objects are judged as closer when the reference frame is a human agent with available movement potentialities. *Cognition, 134*, 50–56. https://doi.org/10.1016/j.cognition.2014.08.014

Goodall, C. (1991). Procrustes methods in the statistical analysis of shape. *Journal of the Royal Statistical Society: Series B (Methodological), 53*(2), 285–321.

Guterstam, A., Petkova, V. I., & Ehrsson, H. H. (2011). The illusion of owning a third arm. *Plos One, 6*(2), Article e17208. https://doi.org/10.1371/journal.pone.0017208

Holmes, N. P., & Spence, C. (2004). The body schema and multisensory representation (s) of peripersonal space. *Cognitive Processing, 5*(2), 1–21. https://doi.org/10.1007/s10339-004-0013-3

Kelly, J. W. (2022). Distance perception in virtual reality: A meta-analysis of the effect of head-mounted display characteristics. *IEEE Trans. Vis. Comput. Graph*, 1–13. https://doi.org/10.1109/TVCG.2022.3196606

Lenggenhager, B., Tadi, T., Metzinger, T., & Blanke, O. (2007). Video ergo sum: Manipulating bodily self-consciousness. *Science, 317*(5841), 1095–1099. https://doi.org/10.1126/science.1143439

Linkenauger, S. A., Bülthoff, H. H., & Mohler, B. J. (2015). Virtual arm′ s reach influences perceived distances but only after experience reaching. *Neuropsychologia, 70*, 393–401. https://doi.org/10.1016/j.neuropsychologia.2014.10.034

Linkenauger, S. A., Leyrer, M., Bülthoff, H. H., & Mohler, B. J. (2013). Welcome to wonderland: The influence of the size and shape of a virtual hand on the perceived size and shape of virtual objects. *Plos One, 8*(7), Article e68594. https://doi.org/10.1371/journal.pone.0068594

Linkenauger, S. A., Ramenzoni, V., & Proffitt, D. R. (2010). Illusory shrinkage and growth: Body-based rescaling affects the perception of size. *Psychological Science, 21*(9), 1318–1325. https://doi.org/10.1177/0956797610380700

Longo, M. R. (2015). Implicit and explicit body representations. *European Psychologist, 20*(1), 6–15. https://doi.org/10.1027/1016-9040/a000198

Longo, M. R., Azañón, E., & Haggard, P. (2010). More than skin deep: Body representation beyond primary somatosensory cortex. *Neuropsychologia, 48*(3), 655–668. https://doi.org/10.1016/j.neuropsychologia.2009.08.022

Longo, M. R., & Golubova, O. (2017). Mapping the internal geometry of tactile space. *Journal of Experimental Psychology: Human Perception and Performance, 43*(10), 1815–1827. https://doi.org/10.1037/xhp0000434

Longo, M. R., & Haggard, P. (2012). A 2.5-D representation of the human hand. *Journal of Experimental Psychology: Human Perception and Performance, 38*(1), 9–13. https://doi.org/10.1037/a0025428

Longo, M. R., & Lourenco, S. F. (2007). Space perception and body morphology: Extent of near space scales with arm length. *Experimental Brain Research, 177*, 285–290. https://doi.org/10.1007/s00221-007-0855-x

Longo, M. R., Mancini, F., & Haggard, P. (2015). Implicit body representations and tactile spatial remapping. *Acta Psychologica, 160*, 77–87. https://doi.org/10.1016/j.actpsy.2015.07.002

Longo, M. R., & Morcom, R. (2016). No correlation between distorted body representations underlying tactile distance perception and position sense. *Frontiers in Human Neuroscience, 10*, 1–8. https://doi.org/10.3389/fnhum.2016.00593. November.

Longo, M. R., Schüür, F., Kammers, M. P. M., Tsakiris, M., & Haggard, P. (2008). What is embodiment? A psychometric approach. *Cognition, 107*(3), 978–998. https://doi.org/10.1016/j.cognition.2007.12.004

Mancini, F., Longo, M. R. R., Kammers, M. P. M. P. M., & Haggard, P. (2011). Visual distortion of body size modulates pain perception. *Psychological Science, 22*(3), 325–330. https://doi.org/10.1177/0956797611398496

Marino, B. F. M., Stucchi, N., Nava, E., Haggard, P., & Maravita, A. (2010). Distorting the visual size of the hand affects hand pre-shaping during grasping. *Experimental Brain Research, 202*(2), 499–505. https://doi.org/10.1007/s00221-009-2143-4

Pavani, F., Spence, C., & Driver, J. (2000). Visual capture of touch: Out-of-the-Body experiences with rubber gloves. *Psychological Science, 11*(5), 353–359. https://doi.org/10.1111/1467-9280.00270

Petkova, V. I., & Ehrsson, H. H. (2008). If I were you: Perceptual illusion of body swapping. *Plos One, 3*(12), Article e3832. https://doi.org/10.1371/journal.pone.0003832

Proffitt, D. R., Bhalla, M., Gossweiler, R., & Midgett, J. (1995). Perceiving geographical slant. *Psychonomic bulletin & review, 2*, 409–428. https://doi.org/10.3758/BF03210980

Proffitt, D. R., & Linkenauger, S. A. (2013). Perception viewed as a phenotypic expression. *Action science: Foundations of an emerging discipline, 171*. https://doi.org/10.7551/mitpress/9780262018555.003.0007

Proffitt, D. R., Stefanucci, J., Banton, T., & Epstein, W. (2003). The role of effort in perceiving distance. *Psychological Science, 14*, 106–112. https://doi.org/10.1111/1467-9280.t01-1-01427

R Development Core Team. (2016). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing.

Rizzolatti, G., Fadiga, L., Fogassi, L., & Gallese, V. (1997). The space around us. *Science, 277*(5323), 190–191. https://doi.org/10.1126/science.277.5323.190

Rohlf, F. J., & Slice, D. (1990). Extensions of the Procrustes method for the optimal superimposition of landmarks. *Systematic Biology, 39*(1), 40–59. https://doi.org/10.2307/2992207. March 1990.

Romano, D., Bottini, G., & Maravita, A. (2013). Perceptual effects of the mirror box training in normal subjects. *Restorative neurology and neuroscience, 31*(4), 373–386. https://doi.org/10.3233/RNN-120273

Romano, D., Llobera, J., & Blanke, O. (2016). Size and viewpoint of an embodied virtual body affect processing of painful stimuli. *The Journal of Pain, 17*(3), 350–358. https://doi.org/10.1016/j.jpain.2015.11.005

Serino, S., Scarpina, F., Chirico, A., Dakanalis, A., Di Lernia, D., Colombo, D., Catallo, V., Pedroli, V., & Riva, G. (2020). Gulliver's virtual travels: Active embodiment in extreme body sizes for modulating our body representations. *Cognitive Processing, 21*, 509–520. https://doi.org/10.1007/s10339-020-00977-5

Shepard, R. N. (1980). Multidimensional scaling, tree-fitting, and clustering. *Science, 210*(4468), 390–398. https://doi.org/10.1126/science.210.4468.390

Stone, K. D., Keizer, A., & Dijkerman, H. C. (2018). The influence of vision, touch, and proprioception on body representation of the lower limbs. *Acta Psychologica, 185*, 22–32. https://doi.org/10.1016/j.actpsy.2018.01.007

Tosi, G., Maravita, A., & Romano, D. (2022). I am the metre: The representation of one's body size affects the perception of tactile distances on the body. *Quarterly Journal of Experimental Psychology, 75*(4), 583–597. https://doi.org/10.1177/1747021821104448

Tosi, G., Parmar, J., Dhillon, I., Maravita, A., & Iaria, G. (2020). Body illusion and affordances: The influence of body representation on a walking imagery task in virtual reality. *Experimental Brain Research, 238*, 2125–2136. https://doi.org/10.1007/s00221-020-05874-z

Tosi, G., & Romano, D. (2020). The longer the reference, the shorter the legs: How response modality affects body perception. *Attention, Perception, & Psychophysics, 82*, 3737–3749. https://doi.org/10.3758/s13414-020-02074-3

Tosi, G., & Romano, D. (2023). The network of the subjective experience in embodiment phenomena. *Psychological Research, 87*(4), 1043–1056. https://doi.org/10.1007/s00426-022-01714-7

Tosi, G., Romano, D., & Maravita, A. (2018). Mirror box training in hemiplegic stroke patients affects body representation. *Frontiers in Human Neuroscience, 11*, 617.

Vallar, G., & Maravita, A. (2009). Personal and extra-personal spatial perception. *Handbook of neuroscience for the behavioral sciences, 1*, 322–336. https://doi.org/10.1002/9780470478509.neubb001016

van der Hoort, B., Guterstam, A., & Ehrsson, H. H. (2011). Being barbie: The size of one's own body determines the perceived size of the world. *Plos One, 6*(5). https://doi.org/10.1371/journal.pone.0020195

World Health Organization. (1996). *Guidelines for the promotion of human rights of persons with mental disorders (No. WHO/MNH/MND/95.4)*. World Health Organization.