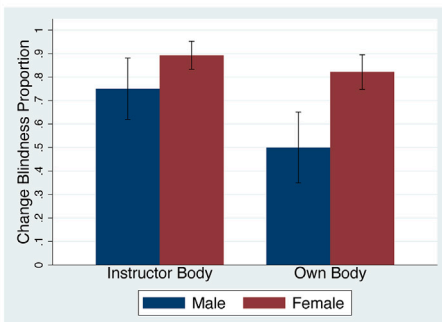


Article

Imperceptible body transformation in virtual reality: Saliency of self representation

40 participants entered a virtual reality to take part in a Qi Gong lesson. They had a virtual body that they saw also in a mirror, and that moved synchronously with their movements. They followed the instructions of the Qi Gong teacher. During the 8 minutes of the scenario both their own and the instructor faces changed.



The overall proportion of change blindness (CB) was high. There was less CB for their own virtual body compared to the virtual body of the instructor.

Women showed more CB than men, but contrary to men, the more they looked towards their own virtual body the less the change blindness.

We propose that CB occurs here because participants rely largely on internal perceptual models, with the VR providing basic evidential cues about where they are and what is happening. The lower CB with respect to the own body may be due to the saliency of self-representation.

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Highlights

Change blindness occurs in virtual reality even under continuous observation

Participants' virtual bodies incur more change blindness than another virtual body

There is more change blindness for female virtual bodies than for males

The more that women look at their virtual bodies the less the change blindness

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Article

Imperceptible body transformation in virtual reality: Saliency of self representation

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SUMMARY

Change blindness (CB) is the perceptual phenomenon whereby people are blind to dramatic changes in their visual environment. In virtual reality (VR) a person's body can be substituted by a life-sized virtual one that moves synchronously with their real body movements as their self-representation. We consider whether CB occurs in VR, and whether there are differences in the case of changes to their own virtual body compared with the body of another. Forty people took part in a Qi Gong lesson in VR led by a virtual instructor. During the lesson both their own and the instructor's face dramatically changed in appearance. Overall, 73% and 85% did not notice the changes to their own and instructor's face respectively. People make iconic inferences about their visual surroundings without sampling detail, and reduced CB in the case of their own body may be a marker for self-representation.

INTRODUCTION

Change blindness (CB) is the perceptual phenomenon whereby people fail to notice dramatic changes in their visual environment. CB has been shown to occur in real-life events, where, for example, in one experiment people were talking with a person who was surreptitiously swapped with another in the midst of the conversation, and more than half did not report the change.¹ Typically, CB is demonstrated with images on a screen using a variety of different types of stimuli, usually with some disruption between changes including where there are image changes during saccades.^{2–4} CB has also been shown to occur in Virtual reality (VR) with respect to objects in a scene (e.g., a church spire)⁵ and a recent study has systematically explored the conditions under which it occurs.⁶ As well as displaying any type of scenario, VR delivered via a head-tracked wide field-of-view head-mounted display and tracking devices affords virtual embodiment. When participants in VR look down toward their real body, they see a life-sized virtual body spatially coincident with it, if this has been programmed. Moreover, if their body movements are tracked in real-time then these can be mapped to corresponding and synchronous movements of their virtual body. Repeated studies have shown that first-person perspective (1PP) over a life-sized virtual body that apparently substitutes their own body representation, together with synchrony and correspondence between their real body movements and the movements of their virtual body, results in the strong perceptual illusion of ownership over the virtual body.^{7–9}

A pilot experiment with 25 people found that CB occurred with respect to their virtual body representation, where the face of the virtual body dramatically changed over a 10-min period. Twenty-one participants did not notice the change, and many were visibly shocked when this was pointed out to them (reported by H.Pehlivan in “Virtual Embodiment: The experience of ownership of a transforming virtual body” MSc, University of Copenhagen, 2018). However, from this experiment, it was not clear whether there was any special status for their own body representation or whether this would have occurred to the same extent with the representations of others in the scenario. The goal of the experiment described in this article was to test the impact of such self-representation on CB and to compare the extent of CB for the self-representation compared to the representation of another. Our hypothesis was that due to the special status of the self-representation, changes to their own virtual body would be more noticeable than changes to the body of another. In the experimental study reported here participants in VR could see the virtual body that represented themselves by looking down toward their real body, and also in a virtual mirror. They could also see and interact with the virtual body corresponding to another character in the scenario. The experiment was set up so that participants looked toward both bodies an approximately equal amount of time. Both bodies, especially the faces, gradually transformed over an 8-min period toward quite different appearances. Moreover, our question was whether change blindness would occur in a situation where participants were looking specifically at the two virtual bodies where change was occurring. If the degree of CB would be different between their own body representation and the other body, in particular, if there were less likelihood of CB with respect to their

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Figure 1. The scenario for the Qi Gong

- (A) A participant with a female body that she sees in the mirror in front and follows the movements of the instructor standing to the left.
 (B) A participant with a male body and male instructor.
 (C) The participant looks down toward herself and sees her life-sized virtual body that visually substitutes her real body. The feet are surrounded by weights in order to discourage the participant from moving her feet.
 (D) A male participant looks directly toward his reflection in the mirror.

own body representation, then this would be an important marker of virtual embodiment, i.e., that the representation of the self in the scene has a special status compared to other scene components.

Typically, in CB studies there is an intervening event (a disruption) between the pre- and post-change images. This disruption may be internal (for example, a saccade or blink) or caused externally (for example, a blank screen between the two images on a computer display or some temporary visual obstruction in physical reality). In movies, for example, there can be mistakes when the film is composed from shots of the same scene taken at different times, so that accidental and significant incorrect changes in the scene between cuts are frequent, but the vast majority of the viewers do not notice.¹⁰ Even in physical reality the changes can be dramatic. For example as mentioned earlier, Simons and Levin¹ carried out an experiment with 15 pedestrians who were engaged in conversation by a target confederate. Two other confederates carried a plank between the two, during which time the target confederate was rapidly swapped with another person, and then the conversation continued. Eight of the 15 participants did not notice the change in one condition, and 8 out of 12 did not notice the change in another similar condition.

It has been shown that a visual disruption between changes is not necessary. Simons et al.¹¹ carried out an experiment where the changes were gradually introduced by morphing between two computer images, and therefore in the absence of any discontinuity. The extent of CB was the same between the gradual and a disruption condition (about 40% of participants in each case) showing that a disruption is not necessary for CB to occur and even though participants were continuously looking at the area of the change. In another condition that involved changes of colors between images, there was greater CB in the gradual change condition (69%) compared to a disruption condition (59%). David et al.¹² further showed that when gradual change is applied to human facial expressions there is a high degree of CB. Only 15% of participants noticed the change, three times less than those who noticed the change under a disruption condition.

The experiment reported here used gradual change with respect to two life-sized virtual bodies in VR but where only the faces changed. One body was embodied by the participant, and the other was a virtual human character that interacted with the participant. The scenario (Figure 1) was a Qi Gong teaching session where the participant had to follow the movements of a virtual instructor to carry out various body

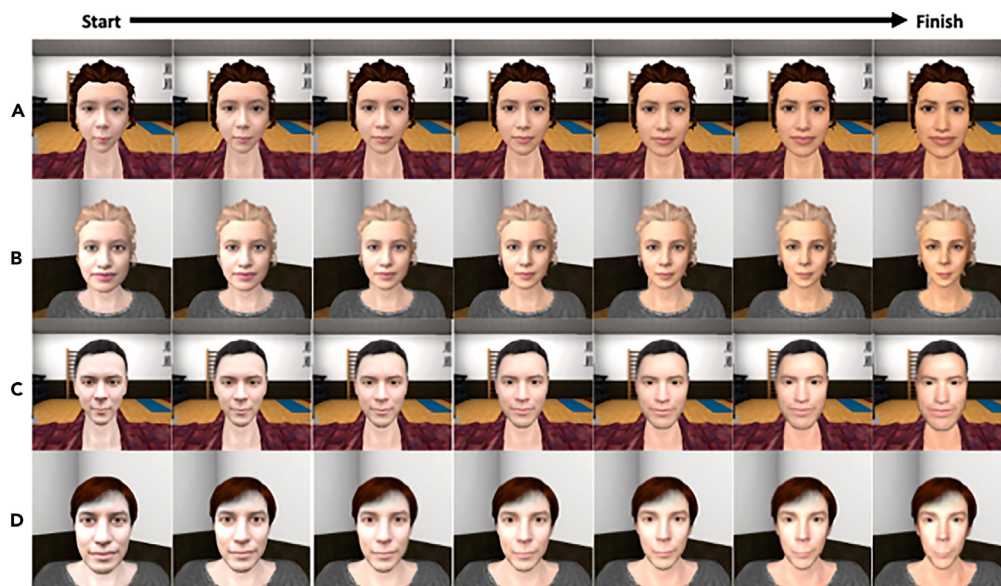


Figure 2. Evolution of the faces over time from left to right
(A–D) (A) The self for female (B) The instructor for female (C) The self for male (D) The instructor for male.

movements. The participants saw via a wide field-of-view head-tracked head-mounted display (see [STAR Methods](#)) a sex-matched life-sized virtual body when looking down toward themselves and in a virtual mirror directly in front of them. The virtual instructor was standing 45° to their left and the distances from the participant's viewpoint were the same to both bodies (Methods). The instructor explained and demonstrated a sequence of Qi Gong movements and the participants were asked to copy these. The instructor told the participants when they should look toward him- or herself, and when they should look in the mirror at themselves. The participants held a 6 degrees of freedom tracked controller in each hand, so that when they moved their arms the virtual arms moved synchronously and correspondingly. Gradually over the 8-min of the Qi Gong lesson the faces of both the self-representation body and the instructor morphed into quite different forms ([Figure 2](#)). [Video S1](#) illustrates the scenario.

At the end of the session, the participants completed a questionnaire which included an assessment of CB. The initial and final appearances of the face of the self and instructor bodies were depicted, and the participants were asked whether they had seen this change or not. An example is shown in [Figure 3](#) for the case of the female instructor. CB is indicated by answering “No, I did not notice this change” to the question.

In order to test whether the changes in the faces were perceptually equivalent across all 4 sets we carried out an online survey where participants were asked to compare pairs of faces from the scenario ($n = 106$). For each of the 4 sets of faces pairs were chosen that were a measured number of frames apart, ranging from 0 (i.e., the same face) to the maximum number of frames that separated the faces (i.e., the first appearance to the last appearance of the face). Respondents were asked to rate the degree of difference between the faces in each pair on a scale of 0 (the same face) to 10 (a completely different face). The results showed that the level of changes across the 4 sets of faces were judged as being the same. Full methods and results are given in [Figures S1](#) and [S2](#), [Table S1](#), and [Data S1](#).

The Qi Gong experiment was carried out with 40 participants recruited from the University of Barcelona campus. There were 12 who identified as male, 27 as female and 1 preferred not to say. However, each participant chose a virtual body for self-representation at the start of the VR session, and all chose according to their reported gender and the one who preferred not to say chose the female avatar. Their mean \pm SD age was 25 ± 8 , ranging from 18 to 55. However, the age distribution follows a reversed exponential distribution pattern (J-shape) with 15% of participants over 30, and 5% over 40.

RESULTS

Descriptive results

The demographic characteristics of the sample are shown in [Tables S2–S6](#). [Table 1](#) shows the basic results for CB.

It can be seen that the overwhelming proportion of participants did not notice the change in the body of the instructor nor in their own body. However, there does seem to be an important difference between those with the male and those with the female body, with the male body participants less likely to report CB, although the more detailed analysis below qualifies this. Also, CB was lower for their own virtual body compared with the instructor body.

Below you can see an image of the instructor at the beginning of the Qi-Gong session on the left, and at the end of the session on the right.



Did you notice this change in the appearance of the instructor during the course of the Qi Gong lesson?

- No, I did not notice this change
- Yes, I did notice this change

Figure 3. The change blindness questions

The questionnaire after the VR exposure included 2 questions as above – for the self-representation and for the instructor body. This figure only shows the female instructor case. The others are shown in Figure 2 as the first and last images of each row.

Analysis of the basic results

Suppose the number of participants is n and y of them do not notice the change (CB). Then by independence between the participants y has a binomial distribution with parameters n , the number of trials, and θ the probability of CB, i.e.,

$$y \sim \text{binomial}(n, \theta)$$

with probability distribution:

$$f(y|\theta) \propto \theta^y (1 - \theta)^{n-y}, y = 0, 1, \dots, n$$

To make inferences about θ we can use Bayes' Theorem. Although there is a lot of prior evidence about θ from previous studies, here we will assume that we do not know anything about $\theta \in [0, 1]$ and therefore use the uniform distribution on the unit interval as the prior for θ : all values in the range 0–1 are equally likely. Then by Bayes' Theorem the posterior distribution is:

$$g(\theta|y) \propto \theta^y (1 - \theta)^{n-y}, 0 < \theta < 1$$

which is the Beta distribution $\text{Beta}(y + 1, n - y + 1)$. From this posterior distribution we can make any inferences of interest about the value of θ .

Figure 4 shows the posterior distributions of θ , the probability of CB. For their own virtual body, the instructor body and overall, there is clear evidence of CB. In each case the probability density is located at greater values for females than for males. Table 2 summarizes the posterior distributions where it can be seen that CB occurs, with the lowest probability being 0.5, for the male own body. All other 80% credible intervals are greater than, and do not overlap this one. It is also clear from Table 2 that the probability of CB is substantially lower in the case of their own body compared to the instructor body. For example, the probability of CB being at least 0.8 is approximately 7 times greater overall for the instructor body compared to the own body, 36 times higher in the case of the male body, and 1.6 times higher in the case of the female body (which in any case is the highest).

Comparison of the own body posterior distributions of θ with the instructor body distributions are shown in Figure 5. The probability densities of own body distributions are to the left of the instructor body in each case, though most pronounced in the case of the male body, and least in the female body. By pseudo random sampling 100,000 pairs of observations for each case (female, male, overall) and counting the number of times that the instructor value is greater than the own body value, we can find the probabilities that θ for the instructor is greater

Table 1. The number who reported that they did not notice the change (CB) by role and gender

	Male (n = 12)	Female (n = 28)	Total (n = 40)
Instructor body	9 (75%)	25 (89%)	34 (85%)
Own body	6 (50%)	23 (82%)	29 (73%)

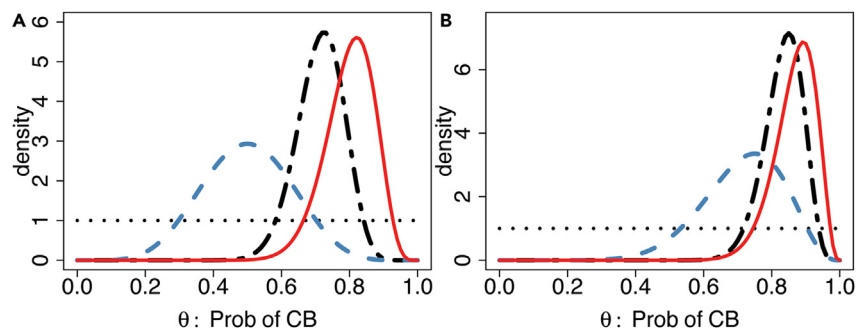


Figure 4. Posterior distributions for θ

(A and B) (A) the own body (B) instructor body. In each case the dotted line is the prior distribution, the black dash-dot curve is overall, the blue long-dash curve is for those embodied in the male body, and the red solid curve is for those embodied in the female body.

than θ for the own body. The results are shown in Table 3, further indicating that the probability of CB is greater for the instructor body than the own body.

Taking into account gaze directions age and sex

The above analysis does not include the possibility that results may have been influenced by the proportions of time that the participants looked toward the instructor body and their own, thereby directing attention more to one body rather than another. The amounts of time that participants looked toward their own body and toward the instructor body were recorded based on head gaze direction. While the overall mean amount of time looking toward the instructor (211 ± 58.6 SD s) was hardly different from the mean overall time looking toward the self (213 ± 58.7 s) this masks the variability among the participants. Let *lookob* (*look at own body*) be the proportion of time that participants looked toward their own virtual body in the mirror after the exercises had started. The mean \pm SD proportion of time is 0.50 ± 0.14 , the minimum is 0.25 and the maximum is 0.77. With this variability it is possible that the differential proportions of time among the participants affected the results.

In order to assess the influence of this proportion of time, the influence of the sex of the virtual body and age, we use a Bernoulli logit model. Let $y_{ins,i}$ be a binary response variable that indicates CB in the case of the instructor, i.e., $y_{ins,i} = 1$ for no change reported and 0 when a change was reported, for the i th individual ($i = 1, 2, \dots, n = 40$). Similarly, $y_{own,i}$ for the own body. In the case of the instructor,

$$P(y_{ins,i} = 1) = \theta_{ins,i}$$

$$P(y_{ins,i} = 0) = 1 - \theta_{ins,i} \quad \text{(Equation 1)}$$

where $\theta_{ins,i}$ is the probability of the i th individual not reporting the change in the instructor body (CB). To relate $\theta_{ins,i}$ to the variables *sex*, *age*, and *lookob* we use the linear predictor:

$$\eta_{ins,i} = \beta_{ins,0} + \beta_{ins,1}sex_i + \beta_{ins,2}lage_i + \beta_{ins,3}lookob_i + \beta_{ins,4}(lookob_i \times sex_i) \quad \text{(Equation 2)}$$

where $sex_i = 0$ if the i th individual has a male virtual body, and $sex_i = 1$ for a female body. age_i is the age of the i th individual and $lage_i = \log(age_i)$. The log was used because there were outlying values in age that affected the goodness of fit of the model (e.g., the median age is 22, but the maximum is 55). The variable *lookob* _{i} is the proportion of time that the i th individual looked toward their own virtual body rather than that of the instructor. We include the interaction term to allow for the possibility that the time looking at the self has a different influence on CB depending on whether the participant had the male or female body.

Table 2. Summaries of the posterior distributions of θ showing the mean, standard deviation, two probabilities of interest and the 80% and 95% equal-tail credible intervals

	Mean	SD	$P(\theta > 0.5)$	$P(\theta > 0.8)$	80% CI	95% CI
Own body overall	0.714	0.069	0.998	0.102	0.657–0.774	0.571–0.839
Own body male	0.500	0.129	0.500	0.007	0.387–0.613	0.251–0.749
Own body female	0.800	0.072	1.000	0.537	0.741–0.863	0.642–0.920
Instructor overall	0.833	0.057	1.000	0.739	0.787–0.883	0.708–0.928
Instructor male	0.714	0.117	0.954	0.253	0.616–0.818	0.462–0.909
Instructor female	0.867	0.061	1.000	0.860	0.818–0.920	0.726–0.961

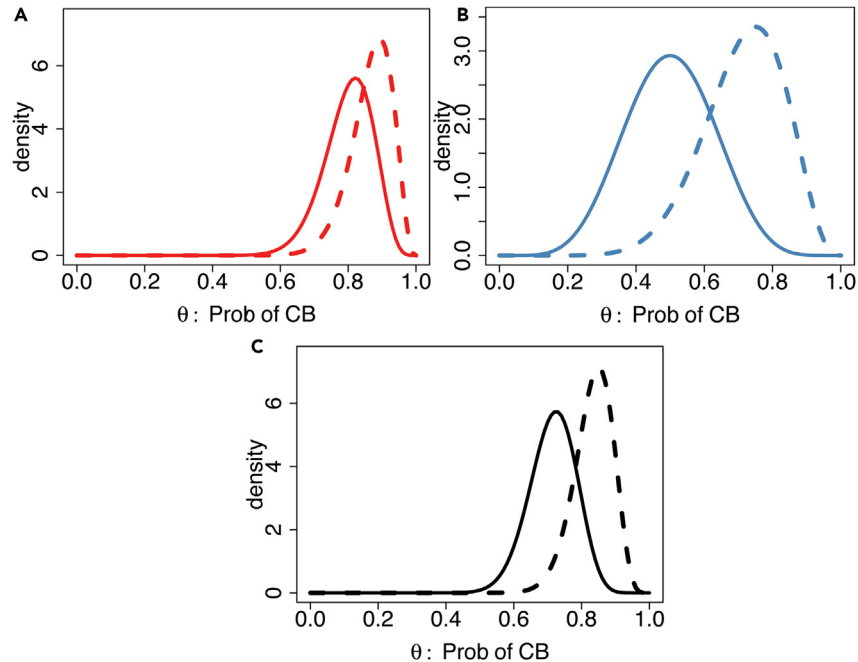


Figure 5. Posterior distributions of θ for own body (solid line) and instructor body (dashed line)
(A–C) (A) Female body (B) Male body (C) Overall.

In the Bernoulli logit model, the relationship between (1) and (2) is through the logit link, i.e.,

$$\log\left(\frac{\theta_{ins,i}}{1 - \theta_{ins,i}}\right) = \eta_{ins,i} \quad \text{(Equation 3)}$$

or equivalently,

$$\theta_{ins,i} = \frac{1}{1 + \exp(-\eta_{ins,i})}$$

This also guarantees that $\theta_{ins,i}$ is in the range 0–1 for all possible values of $\eta_{ins,i}$. The interpretation of $\beta_{ins,j}$ is that it is the change in log-odds of CB compared to no CB for a unit change in the corresponding variable, for all else held constant. Substituting “own” for “ins” in Equations 1–3, the same model is derived for $y_{own,i}$.

Let the prior distributions for the β parameters be normal (mean = 0, SD = 10), which results in prior 95% credible intervals ± 20 . These are wide intervals corresponding to weakly informative priors.¹³ The posterior distributions are summarized in Table 4. Notice that the posterior 95% credible intervals are considerably narrower than the prior intervals.

From Table 4 age has no influence on CB in the case of the own body but is associated with an increase in CB for the instructor body (Prob = 0.950). For those with the female body the more that they looked toward their own body representation the lower the change blindness (Prob = $1 - 0.016 = 0.984$). However, this is not the case for the instructor body (Prob = $1 - 0.347 = 0.653$). For the instructor body there is some evidence in favor of there being more change blindness for the female body (prob = 0.791).

Figure 6 shows the histograms of the sampled posterior distributions of the probability of CB for the own body θ_{own} and the instructor body θ_{ins} over all participants. The histograms are well-fitted by Beta distributions. This shows that the probability of CB is generally greater for the instructor compared to the own body. These results take into account variations in age, sex of the virtual body and the proportion of time looking toward the own body. The breakdown across the conditions is given in Table 5 which shows that the probability of CB is greater for the instructor body than the own body, even considering variations in the amount of time looking toward the own body.

Table 3. Posterior probability that θ for the instructor body is greater than for the own body

Condition	Probability θ instructor > θ own body
Overall	0.909
Female body	0.768
Male Body	0.887

Table 4. Summaries of the posterior distributions showing the mean, SD, 95% credible interval

Parameter	Coefficient of	Mean	SD	2.5%tile	97.5%tile	Prob >0
Own body						
$\beta_{own,0}$		-3.16	4.85	-12.75	6.44	0.251
$\beta_{own,1}$	sex	7.74	3.06	1.76	13.73	0.995
$\beta_{own,2}$	lage	0.59	1.44	-2.24	3.50	0.664
$\beta_{own,3}$	lookob	2.16	4.80	-7.09	11.61	0.675
$\beta_{own,4}$	sex × lookob	-11.35	5.29	-21.73	-1.10	0.016
Instructor body						
$\beta_{ins,0}$		-8.72	6.40	-21.67	3.09	0.082
$\beta_{ins,1}$	sex	2.54	3.20	-3.87	8.93	0.791
$\beta_{ins,2}$	lage	3.23	2.02	-0.46	7.38	0.950
$\beta_{ins,3}$	lookob	-0.65	5.08	-11.05	8.69	0.454
$\beta_{ins,4}$	sex × lookob	-2.21	5.71	-13.55	9.21	0.347

Prob>0 is the probability of the parameter being positive.

DISCUSSION

Using a gradual change paradigm where participants observed two different virtual human characters in VR, one their own virtual body and the other that of an instructor, our results indicate that CB occurred, with the minimum level being 50% among those observing their embodied male virtual body. The overall CB level was 85% for the instructor body and 73% for the own body representation. A Bayesian statistical model shows that these results have strong support, in comparison to a prior probability distribution for equal probability of all possible proportions of CB. A second more comprehensive statistical model allowed for variations in CB as a function of the sex of the virtual body (which corresponded to the declared gender of all participants except for one), age, and the proportion of time gaze was directed to the own virtual body in the mirror compared to the instructor body, including an interaction term between sex and proportion of time. This found that, other things being equal, age was associated with increased CB in the case of the instructor body only, and that the proportion of time looking at the own body was associated with a decrease in CB. This was especially pronounced in the case of the female body. Critically, CB is less for the own body than the instructor body in both analyses. First, we consider the result for age, then the differing effects for the male and female bodies, and finally the implications for virtual embodiment.

Age is associated with an increase in the likelihood of CB, and an indication of cognitive decline, especially notable as an extreme example, for patients with Alzheimer.¹⁴ An important practical concern is whether CB with age also influences potential dangers during driving, and it has been found that CB increases with age in traffic scenarios.¹⁵ However, while CB has been found to be positively correlated with age, the effect could be explained by older adults making more eye movements than younger adults, and fixating longer, and also the eye scan path

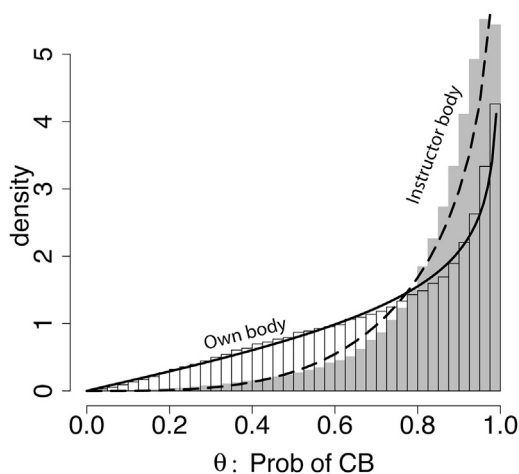


Figure 6. Histograms of the posterior distributions for θ_{own} and θ_{ins} (the probability of CB)

The instructor body distribution is the solid gray histogram, and the own body distribution is the lined histogram.

Table 5. Posterior probability that CB for the instructor body is greater than for the own body taking into account variations in age, sex, and proportion of time looking toward the own body

Condition	$P(\theta_{ins} > \theta_{own})$
Overall	0.676
Female body	0.608
Male body	0.833

returns more frequently to the salient points.¹⁶ It should be noted though that studies typically use a disruption between changes (e.g., a blank screen) which is different from the gradual change method that we have used. Our results are more nuanced. Table 4 shows strong evidence that greater age is associated with an increase in CB for the instructor body, but the evidence of this is weaker for the own body.

There are mixed results in the literature concerning differing levels of CB between women and men. For example, while no difference in CB was found between the sexes, Fitzgerald et al.¹⁷ found that women were more likely to exhibit CB in the context of a driving simulator while engaged in conversation with a male passenger.¹⁸ However, the authors argued that this did not imply that women were more likely to exhibit CB in general, because of the nature of the particular task. Note that the results may also be influenced through differing responses to distraction – in this case it was a conversation, in our case it was the attempt to follow the Qi Gong movements. Amado et al.¹⁹ reported that change detection of facial expressions of males toward angry faces resulted in less CB than all other transitions (fearful and neutral expressions), but not for female faces. Successive faces were separated by a blank screen. By repeating the experiment with the photographs of faces upside down it was found this result no longer held, meaning that it was the expression itself that was important not the actual feature changes. This study tested both men and women as participants but there were no differences between them. Davies and Hine²⁰ used a burglary video where the burglar changed halfway through. Half the participants were told to look for a change and the other half not. Half of the participants were women. The results were that overall, 35/40 did not detect the change in the no advanced warning condition (incidental) and 14 out of 40 in the advanced warning (intentional) condition. There were no differences between men and women in the incidental condition, but in the attentional condition women were more likely to detect the change than men.

The results from our experiment strongly indicate (Table 4) that the more that those with the female body looked toward themselves the less the CB, whereas the opposite was the case for those with the male body. There were no similar effects for the instructor body. In support of this an fMRI study by Burke et al.²¹ found that when people observe their own body or that of another, for women their own body is more salient, but for men the other body is more salient.

Moreno-Briseño et al.²² reported gender differences in motor learning between men and women with men doing better in a throwing accuracy task. Similar results were also reported by Gromeier et al.,²³ and Pereira et al.²⁴ found evidence of gender differences in motor learning across age. It therefore remains possible that a different type of task, or no task at all other than observation, might result in similar levels of CB between women and men.

The method we have adopted consists of gradual change to the virtual bodies, rather than changes separated by a disruption such as a blank screen, which is the usual paradigm. Simons et al.¹¹ found that CB does occur when changes are gradual, even when participants were instructed to deliberately look out for changes. Another gradual change study reported by David et al.¹² used a paradigm similar to ours since participants were required to observe faces, although on a screen rather than in VR. It was found that detection rates were lower for gradual changes compared to changes between a disruption, even though participants had been instructed to look for changes. Moreover, the rate of detection was 15% in the gradual change conditions, which is the same as we found for the participants overall with respect to the instructor body (Table 1).

Our results show that the probability of CB is lower for the own body than the instructor body in the raw data (Figure 5), and when taking into account the proportion of gaze time toward the different bodies (Figure 6). Bodily self-consciousness is enabled through body-centered perception and multisensory integration of synchronous proprioceptive and visual or tactile cues in peripersonal space.^{25–27} This has been shown multiple times with respect to a virtual body seen from 1PP in VR that visually substitutes the real body, for example.^{7,28–31} It is known, moreover, that virtual embodiment can influence perceptual processing. Manipulation of the size of the virtual body, in particular making it smaller, has been shown to lead to an overestimation of object sizes^{8,32,33} with a generalization by Van der Hoort and Ehrsson.³⁴

Although, of course, everyone knows that the virtual body is not *really* their body, it nevertheless has important implications. Rensink et al.³⁵ found that CB occurs less with attention, and that when there are no changes in the scene due to motion then interest is required to detect change. Kelley et al.³⁶ also found that high interest changes were less likely to exhibit CB. For participants their own body representation – which they saw from 1PP (e.g., seeing their arms move in front of them as they carried out the exercises, or seeing their virtual body when looking down toward their real body) and also reflected in the virtual mirror – may have been the most salient and meaningful feature in the scene, i.e., it represented themselves. Recall that for women their own body is more salient than that of others (compared to men) and specifically for women the more they paid attention to their virtual body the less the CB, which was not the case for men. Our conclusion is that a reduction of CB with respect to the virtual body compared to another body is due to the self-representation generated by this multisensory integration and thereby to the greater importance of the virtual body in the scenario. The importance of the body is also indicated by studies that show that when the rubber hand in the rubber hand illusion³⁷ or the virtual body is threatened there are arousal and brain activation responses that correspond to this.^{38–40} Moreover, Fusaro et al.⁴¹ found higher arousal (as measured by skin conductance responses)

when participants saw an embodied hand from 1PP, over which there was body ownership, penetrated by a needle compared with third person perspective (3PP) with low body ownership. Similarly Slater et al.⁷ showed that greater heart rate deceleration was found when participants observed a virtual body being attacked that they had experienced from 1PP compared with 3PP. Since the self-representation is so salient, participants are more likely to notice changes to it compared to other scene features, even the body representations of others. There is of course still a high degree of CB with their own body representation, but it is less than CB with respect to the instructor body.

The meta study of Gibbs et al.⁴² examined a number of factors found to influence CB. Their findings indicate that distraction and divided attention through requiring participants to undertake an unrelated task increased the amount of CB. In the case of our experiment, attention was focused on the Qi Gong task, and therefore not divided in the sense that participants were concentrating only on this. Nevertheless, the fact that they were required to watch body movements to follow the instructions means that it was less likely that they would notice changes in the faces. The meta study also reported that participants were more likely to detect changes in famous faces rather than unfamiliar ones. In our studies the face of their own body did not look like their real face (except by chance) so cannot be said to be more “famous.” However, the multisensory integration of their virtual body would likely have made their own virtual face more important than that of the instructor. Overall, the meta study concluded that “Increasing attention, the saliency of the object change and spatial violations significantly reduced CB.” There were no spatial violations in our study, but these conclusions otherwise are in concordance with our finding that CB was reduced for the own body in comparison with the instructor body.

Noton and Stark⁴³ argued that our perception is top down driven, based on experimental evidence that our eye scan paths can be different when looking at the same object depending on our *expectation* of what that object is (for example, when observing ambiguous figures). Following from this Stark⁴⁴ argued that virtual reality works “because reality is virtual.” The process of perception in physical reality involves the interpretation of an entire scene based on a tiny amount of visual sampling: our eyes rest on a few salient points in a scene, we quickly settle to a set of scan paths over the scene with small variation, and just from that limited sampling we already have the illusion that we have a model of the whole scene (which is impossible based on empirical evidence of low entropy eye scan paths). In this view perception is heavily based on our internal models, with sensory data providing cues as to the type of scene being perceived. It is argued that the same happens with perception in VR – we see a few salient points, and from these and based on prior knowledge we automatically perceive an entire scene utilizing pre-existing internal models, which is one reason why there can be a strong illusion of presence in a virtual scene irrespective of its level of visual realism.⁴⁵ In this view CB can be argued to occur because the region of change had never been fully visually sampled. Even when observing faces, participants may scan over the face and the perceptual system infers “this is a face” without sampling particular details, so that changes leave the inference “this is a face” invariant notwithstanding even substantial changes. This is especially the case in our gradual change scenario where from one moment to the next the face hardly changes. We do not have direct evidence for this interpretation, which would require eye scan paths to be recorded.

In conclusion our results show that CB occurs in VR following^{5,6} - in particular when participants are observing and interacting with virtual human bodies that gradually transform, one body representing an instructor and the other the participants themselves. CB with respect to the instructor body increased with age. Furthermore, women in the sample exhibited CB more than men, but the more that they looked toward their own body the less the CB. CB was less with respect to the own body representation compared to the instructor. We propose that CB in this scenario occurs because participants rely largely on internal perceptual models with the VR providing basic evidential cues about where they are and what is happening – “This is a gym,” “This is a person,” “This is a face” - and therefore are unaware of detailed changes in those overall representations. The lower CB with respect to their own body is due to the saliency of the self-representation compared to the rest of the scenario.

Limitations of the study

Simons⁴ pointed out that change is detected more often in areas of attention but not in marginal interest areas. Our study required people to look at the critical areas where the changes occurred, i.e., at the instructor and their own body – such observation was inherent in the task, and participants were not informed that there would be changes. However, it is possible that participants focused more on the body rather than the faces, which were the areas of the most profound change. Further research, employing eye tracking, is needed in order to address this question. Very recently a new generation of high quality and relatively low-cost head-mounted displays with eye tracking built in as a basic facility have come onto the market, so such a future study will be feasible.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.isci.2023.107938>.

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AUTHOR CONTRIBUTIONS

Original idea of gradual change to virtual bodies: HPJ.

Conceptualization: MS.

Experimental design: MS.

Writing original draft: MS.

Image extraction and analysis: JG.

Writing – review and editing: All authors.

Implementation of program: FMV.

Supervision: MS, KH.

Experimental study: GS, FMV.

DECLARATION OF INTERESTS

MS is a founder of the spin-off company Virtual Bodyworks S.L., Spain, which concentrates on the use of virtual reality to encourage DEI. FMV currently works at the Universitat Pompeu Fabra, in Barcelona, Spain. HPJ currently works at the company Jobindex A/S in Copenhagen, Denmark.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Raw data	This paper	https://doi.org/10.17632/d9kdb8tyc7.1
Software and algorithms		
R and Stan programs and data	This paper	https://www.kaggle.com/code/melslater/body-transformation-code
Unity3D version 2020.2.6f1	Unity Technologies	https://unity.com/releases/editor/whats-new/2020.2.6
Reallusion Character Creator 3	Reallusion	https://www.reallusion.com
QuickVR library	Oliva et al. ⁴⁶	https://github.com/eventlab-projects/com.quickvr.quickbase
Stan	Stan Development Team	https://mc-stan.org
The R interface to Stan (rstan)	Stan Development Team	https://mc-stan.org/users/interfaces/rstan
The R Project for Statistical Computing	The R Foundation	https://www.r-project.org
RStudio	Posit	https://posit.co/download/rstudio-desktop/
R Package MASS	Venables and Ripley ⁴⁷	https://cran.r-project.org/web/packages/MASS/index.html
Stata	Stata Corp LLC	https://www.stata.com
Other		
Quest 2 head-mounted display	Meta	https://www.meta.com/es/en/quest/products/quest-2/
Qualtrics Survey Tool	Qualtrics	https://www.qualtrics.com
Blend shape lerpig	Unity Forum Discussion	https://forum.unity.com/threads/lerpig-between-an-old-and-new-blendshape-value.437509/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Mel Slater (melslater@ub.edu).

Materials availability

There are no materials associated with this paper.

Data and code availability

- Data from this experimental study have been deposited at Mendeley and are publicly available as of the date of publication. The DOI is listed in the [key resources table](#).
- All original code has been deposited at Kaggle and is publicly available as of the date of publication. The URL is listed in the [key resources table](#).
- Any additional information required to reanalyze the data reported in this paper is available from the [lead contact](#) upon request.

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

Study participants

The experiment was carried out with 40 participants recruited from the University of Barcelona campus. There were 12 who identified as male, 27 as female and 1 preferred not to say. However, each participant chose a virtual body for self-representation at the start of the VR session, and all chose according to their reported gender and the one who preferred not to say chose the female avatar. Their mean \pm SD age was

25 ± 8 , ranging from 18 to 55. However, the age distribution follows a reversed exponential distribution pattern (J-shape) with 15% of participants over 30, and 5% over 40. The demographic characteristics of the sample are shown in Tables S2–S6.

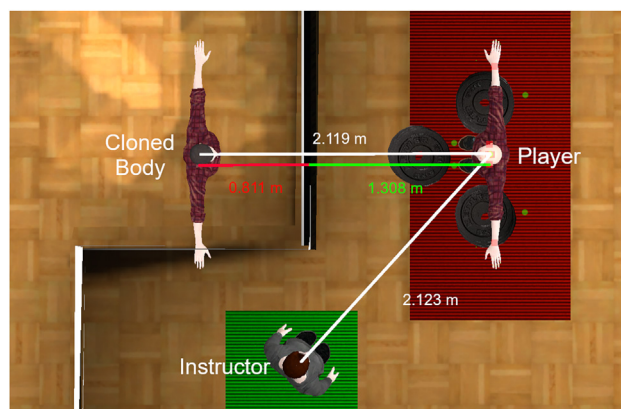
METHOD DETAILS

Ethics approval

Ethics approval for the study was granted by the Comissió de Bioètica, Universitat de Barcelona (IRB00003099), and all participants gave written and informed consent. They were compensated with 10 euros for their trouble and time.

Experimental design

A top-down view of the scenario is shown in Figure. During the course of the scenario, which lasted 8 minutes, the virtual instructor explained to the participant some ideas behind Qi Gong, and demonstrated movements that the participant should follow. The participant was embodied in a virtual body that could be seen directly from first person perspective when looking towards themselves and in a virtual mirror. The instructor was standing about 45 degrees to the left of the participant. The distances to the reflected body of the participant and to the instructor were the same. The participants were asked by the instructor to sometimes look towards him- or herself and sometimes in the mirror towards themselves. The amount of time that they looked towards each body was recorded and used as a covariate in the analysis.



A top-down view of the scenario

“Player” is the virtual body representation of the participant, and the “Cloned Body” is the mirror reflection. The Instructor body is shown to be at an angle of 45° to the line joining the participant body and its reflection. The distances from the reflected body and the instructor body are the same, but that the mirror reflection is not the same distance behind the mirror as the participant in front of it.

The questionnaire was administered using Qualtrics (see [key resources table](#)). After completing the questionnaire participants could read a further information sheet that explained the scientific question behind the study. Participants were paid 10 euros for their participation.

The participants were recruited from our database. They were sent a recruitment email which invited them to participate in the study. If they agreed to take part, they signed a consent form. Participants gave written and informed consent.

Materials

Participants donned a Quest 2 head-mounted display (see [key resources table](#)). This is a stand-alone headset with no cables or computer needed. It has 1832×1920 resolution per eye, 90Hz refresh rate and weighs 503g. The program was implemented using Unity3D (see [key resources table](#)) version 2020.2.6f1 for the virtual environment creation, and Reallusion’s Character Creator 3 software (see [key resources table](#)) was used for 3D avatar creation (see [key resources table](#)). The head gaze directions were recorded as a 3-dimensional vector of the participant’s head rotation every 0.5 seconds. The cut-off to determine whether the participant was looking at their own body or at the instructor’s body was defined as 245.5 degrees in the Y-dimension of the rotation vector. 221 degrees represented looking directly at the instructor body, while 270 degrees represented looking directly at the participant’s own body.

Implementation

The implementation was carried out using the QuickVR library⁴⁶ (see [key resources table](#)) which is built on top of Unity3D. QuickVR was useful especially for implementation of embodiment including inverse kinematics to estimate virtual upper body movements of the self-representation based on the head tracking data from the Quest and the hand tracking afforded by the controllers. The morphing of the characters was carried out by first creating the Start and End versions using Character Creator 3, and then an interpolation of both the textures and the geometry between these two was derived and rendered using Unity as the scenario progressed. For the texture, this was a simple fade of the

Albedo and Normal maps from each of the two extreme characters. For the geometry, we generated a new blendshape for the Start character based on the vertex information from the End character. Then we simply animated blendshape lerping (see [key resources table](#)).

QUANTIFICATION AND STATISTICAL ANALYSIS

The details of the statistical analyses are described in the main text. Two analyses were carried out to determine the probability of CB. The first analysis was based on the number of participants out of the 40 who failed to report the change for the own body and the instructor body. The second analysis allowed for variations in age, sex of the virtual body, and proportion of time looking towards the own body as covariates.

We used the Stan probabilistic programming language⁴⁸ (see [key resources table](#)) through the R interface (see [key resources table](#)) to derive numerical approximations to the posterior distributions. Stan was executed with 2000 iterations and 4 chains and converged with all $R_{hat} = 1$ indicating that the 4 chains mixed.

Bayesian methods were used as a matter of preference to null hypothesis significance testing (NHST), but also because for each method there were two response variables and multiple queries. With NHST, as soon as more than one statistical test is carried out overall significance is affected, and the only recourse is use to ad hoc methods such as Bonferroni corrections. With Bayesian analysis both response variables are treated in one overall model, and multiple inferences can be drawn from the joint posterior distributions of the parameter of interest, without diminishing their validity.

The `fitdistr` function (see [key resources table](#)) from the R package MASS⁴⁷ was used to fit the Beta distributions shown in [Figure 6](#).

To test the predictive ability of the model we used the 'leave one out' (loo) method.⁴⁹ This theoretically involves leaving out each data point in turn, then fitting the model with the remaining data, and estimating the one left out. This results in an 'out-of-sample' estimate of fit, summarized by an information based statistic (ELPD, expected log pointwise predictive density). This procedure showed no problems with the model: 'pareto k estimates' were <0.7 indicating no convergence problems for any individual, and also there was no overfitting.

All the code for statistical analysis is available see the [key resources table](#) and [supplemental information](#) for further details ([Data S1](#)).