Visual self-motion feedback affects the sense of self in virtual reality

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Abstract

We assessed how self-motion affects the visual representation of the self. We constructed a novel virtual reality experiment that systematically varied an avatar's motion and also biological sex. Participants were presented with pairs of avatars that visually represented the participant ("self avatar"), or another person ("opposite avatar"). Avatar motion either corresponded with the participant's motion, or was decoupled from the participant's motion. The results show that participants identified with i) "self avatars" over "opposite avatars", ii) avatars moving congruently with self-motion over incongruent motion, and importantly iii) identification with the "opposite avatar" over the "self avatar" when the opposite avatar's motion was congruent with self-motion. Our results suggest that both self-motion and biological sex are relevant to the body schema and body image and that congruent bottom-up visual feedback of self-motion is particularly important for the sense of self and capable of overriding top-down self-identification factors such as biological sex.

Introduction

Humans have the conscious experience of having a sense of self (Gallagher, 2000). In the last twenty years, there has been a rise in experimental research on bodily self-consciousness and the sense of self (Blanke et al., 2015). At the same time there has been a rise in the use of virtual reality (VR), which has enabled researchers to manipulate visual feedback of the self, using virtual avatars in order to assess vision's role on the body schema (Maravita and Iriki, 2004) as well as body image (Mölbart et al., 2018). Although there is no consensus among researchers of these terms, body schema is generally regarded as an unconscious, bottom-up, dynamic representation, relying on proprioceptive information from the muscles, joints, and skin during self-motion (Gallagher, 2000). On the other hand, the body image is a more conscious, top down, cognitive representation, incorporating semantic knowledge of the body and one's identity including biological sex (Longo et al., 2008). An interesting research question arises then: to what extent does visual self-motion feedback and biological sex identification affect the sense of self in virtual reality?

Previous experiments such as the rubber hand illusion (Tsakiris and Haggard, 2005; Ehrsson et al., 2005; Suzuki, K et al., 2013) and whole-body illusions (Aglioti and Candidi, 2011; Petkova and Ehrsson, 2008; Blanke and Metzinger, 2009) have demonstrated that vision can powerfully change the representation of the self where ownership can even be induced over a body of a different race, age, or gender (Petkova and Ehrsson, 2008; Maister et al., 2014). Here, it is the temporal coupling of synchronous touch and vision of being touched that enables one to feel

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embodiment and a sense of agency over another body or body part. Similarly information about self-motion from proprioception and the vestibular system has also been shown to contribute to high-level bodily perception, such as the sense of body ownership (Lopez, 2015). It has also been suggested that the interaction between vestibular and bodily somatosensations is a form of self-representation, which is important to link the spatial description of one's own body to the spatial description of the outside world (Ferrè & Haggard, 2015). Further, out-of-body experiences, in which patients localise the self outside their own body and experience seeing their body from a disembodied location, have been attributed to failures in integrating multisensory bodily information due to conflicting visual and vestibular information (Kaliuzhna et al., 2015). Finally, while experiments have recently shown that bodily self-consciousness may arise from the integration of multisensory signals in fronto-parietal and temporo-parietal regions of the brain (Blanke et al. 2015), much more work remains to be done to determine the plasticity of human bodily self-consciousness.

Self-motion is critical to how we identify sensory experiences related to the body with our identity. Indeed self-recognition among humans, as well as other species (Gallup, 1970; Reiss and Marino, 2001; Ari and D'Agostino, 2016) and perhaps even machines (Hart and Scassellati, 2012), is conventionally identified by the understanding that actively exploring one's own mirror reflection enables us to recognize that the reflected image of oneself does not represent another individual but oneself. Like a mirror, VR's interactive computer interface that immerses the user in a synthetic 3-dimensional environment can give the user the illusion of

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identifying with the visual representation of the body and "being" in that virtual setting through a sense of "presence" (Sanchez-Vives & Slater, 2005). VR technology is uniquely capable of being used to assess human self-awareness by presenting the user with an avatar representation of their self. Here resemblance of the artificial body to a human body improves embodiment into the avatar (Maselli and Slater, 2013), and the feeling of presence in the virtual world (Eastin, 2006).

Here we sought to assess the role of self-motion and the sense of self by presenting participants with pairs of mirrored avatars that visually represent their self, or another person. Self-motion was manipulated by assigning one of the avatars to move 1:1 with participant movement using motion tracking, or alternatively by adding different motions to participant movement to present realistic but decoupled motion. Through various combinations of avatar pairs and motion applied to each avatar, we assess the hypothesis that participants' judgements of their sense of self will be influenced by both visual self-motion and biological sex of encountered avatars.

Materials & Methods

Participants

Nine participants (7 males; 24-54 years; average age: 27.2 years; average height: 173.5cm SD = 5.09cm) participated in the experiment. All participants were Korean and visiting the Games Institute at the University of Waterloo as part of a workshop series on gaming. All consent materials and instructions were translated into Korean. A Korean translator familiar with the experiment was available at all

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times to ensure that participants understood experimental instructions. Participants had normal/corrected to normal vision and had no known neurological disorders. The experiment was approved by the University of Waterloo's Research Ethics Committee, which complies with the Declaration of Helsinki.

Avatar creation

As recent research suggests that the customization of avatars increases the extent to which people feel connected to their avatars (Lim and Reeves, 2009), participants in our experiment created their own avatars. In the first stage of the experiment, participants had thirty minutes to create a computer-generated avatar that they felt most represented their self using Adobe Fuse Creative Cloud (<https://helpx.adobe.com/creative-cloud/how-to/create-3d-character-adobe-fuse.html>; Figure 1). This software enabled participants to rapidly assemble a 3D character from more than 20 base characters and further customize it into a unique character with different weight, height, skin tones, and texture to their satisfaction. A mirror was provided for each participant for reference and experimenters as well as the translator were available to technically assist participants when needed. All participants reported that they were satisfied with their avatars within the thirty-minute creation period. After participants created their "self" avatars, the experimenters created "other" avatars that were of the opposite biological sex of each participant by swapping each body segment while closely matching size. The clothing used on the other-avatar was matched as close as possible to the clothing

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on the self-avatar, but some were more different than others depending on the initial clothing selected by each participant (Figure 2).

Figure 1: Participants had thirty minutes to work with Adobe Fuse software to create an avatar that they felt most closely represented their self. Participants were provided a mirror for reference. Following completion, the experimenter swapped all body components with those of the opposite sex of the participant in consultation with the translator but not the participants themselves (lower right). Written informed consent was obtained from the individuals for the publication of this image. Note however that these individuals have faces obscured for this preprint.

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Figure 2: Avatars created by each of the nine participants ("self"), and avatars that were created in the image of the opposite sex ("other") by the experimenter.

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141 *Equipment*

142 Participants were fitted with the HTC VIVE virtual reality head mounted
 143 display (VRHMD; Figure 3). The HTC Vive uses an organic light-emitting diode
 144 display and provides a combined resolution of 2160x1200 (1080x1200 per eye)
 145 with a refresh rate of 90 Hz and a field of view of about 110 degrees. The VRHMD
 146 weighs about 555 grams and was connected by link box that supplied power, HDMI
 147 1.4, and USB connection to a PC that generated an environment that was rendered
 148 by a high-end graphics card (NVIDIA GTX1070). Two stationary reference cameras
 149 were used to track the participant's head while they moved within the virtual
 150 environment (Figure 4; <https://www.htcvive.com>). The Microsoft Kinect One (v2)
 151 motion capture camera (<https://developer.microsoft.com/en-us/windows/kinect>)
 152 was used to capture movement of the participants' whole-body motion. The Kinect
 153 is a motion sensing device used for video game interaction and computer interfacing
 154 that performs body pose tracking based on an infrared time of flight camera. Its SDK
 155 contains drivers and an API, which allows accurate body pose inference, in the form
 156 of an animated skeleton, and scripts exemplifying application development that
 157 enabled us to animate the avatars used in the experiment. The VRHMD was
 158 equipped with a Leap Motion controller (Figure 4: <https://www.leapmotion.com>)
 159 mounted to the front to capture high-resolution hand and finger movement tracking.
 160 The Leap Motion controller is a small (7.5 × 2.5 × 1.2 cm) sensor using 3 high-
 161 powered infrared LEDs and two high-resolution cameras for hand tracking. Its SDK
 162 uses undisclosed algorithms based on stereo images to track two hand skeletal
 163 models that we integrated with body tracking from the Kinect.

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Figure 3: Avatars created in Adobe Fuse were imported into the virtual environment using the Unreal Engine 4 by the experimenter (upper left). Participants were equipped with the HTC VIVE head mounted display (upper right), which was equipped with the Leap Motion camera (lower left). Participants were given instructions in Korean by a translator and trained to indicate whether they preferred the avatar on the left or right by raising their corresponding left or right hand (lower right). Written informed consent was obtained from the individuals for the publication of this image. Note however that these individuals have faces obscured for this preprint.

A game engine (Unreal Engine 4, <https://www.unrealengine.com>) was leveraged for its built-in rendering, simulation, and networking capabilities, while

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the processing of inputs listed above that captured self-motion were accomplished by using plugins to the game engine. "Self" and "other" avatars created with Adobe Fuse were transferred into Mixamo software (<https://mixamo.com>) which enabled animation of avatars (Figure 4) while also allowing us to subtly decouple self-motion from true 1:1 motion by averaging true 1:1 motion with subtle animation of a "breathing idle" animated character.

Figure 4: Experimental equipment (upper left) and design (right). Normal 1:1 self-motion was captured through combination of the HTC VIVE inertial measurement units, HTC VIVE cameras, Leap Motion camera, and Microsoft Kinect camera. On each trial, participants were presented with two avatars (lower left) rendered two virtual meters in front of them, one of which always had normal 1:1 motion and the other with "decoupled motion". Decoupled motion was generated by averaging normal 1:1 motion with an "idle pose" avatar available from Mixamo and imported into the Unreal Engine 4 virtual environment. Written informed consent was obtained from the individual for the publication of this image.

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192

193 *Task*

194 On each trial, participants were exposed to a simple virtual reality scene
 195 with 3D depth information that placed two avatars at a constant distance of two
 196 virtual meters in front of the observer in depth and were located one virtual meter
 197 to the left and right of the observer's straight-ahead. The two avatars could both be
 198 the "self" or "other" avatar, or one of each, with either 1:1 or decoupled motion
 199 applied to them. Eight conditions made up from these arrangements were each
 200 repeated ten times using the method of constant stimuli for a total of 80 trials (Table
 201 in Figure 4). Participants were encouraged by the experimenter to move around and
 202 interact with the avatars for ten seconds after which instructions on the screen
 203 prompted the participants to indicate whether the avatar to their left or their right
 204 most represented their self using their corresponding left or right hand with an "ok"
 205 gesture that was recorded and coded as a left or right judgement. Following the
 206 experiment we asked participants to report their cybersickness level that were
 207 collected using a quick verbal report (Fast Motion Sickness scale, FMS; Keshavaraz &
 208 Hecht, 2011). FMS scores are measured as a verbal response to the following
 209 question: "On a scale from 0-20 with 0 being no sickness and 20 being severe
 210 sickness, how do you feel?"

211

212 *Analysis*

213 Probabilities of selecting one avatar type versus another were averaged over
 214 20 trials per condition (%self normal vs. %self decoupled; %other normal vs. other

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decoupled; %self normal vs. other decoupled; %self decoupled vs. other normal). As the dataset failed Shapiro-Wilk tests for normality and Bayesian statistics can handle outliers by describing the data as heavy tailed distributions instead of normal distributions (Kruschke 2013), we used Bayesian one-sample t-tests to assess whether probabilities of avatar preference for each avatar pair were significantly different from chance using JASP v0.8.0.1. Here Bayes Factors (BF; default Cauchy prior width = 0.707) provide a numerical value that quantifies how well a hypothesis (H_1 ; preferred avatar significantly different from chance) predicts the data relative to a competing null hypothesis (H_0 ; avatar preference at chance), where a BF_{10} between 0 and 1, indicates support for the H_0 , and a BF_{10} greater than 1 indicates support for the H_1 . A two (motion: normal vs. decoupled) by two (avatar type: self vs. other) Bayesian repeated measures ANOVA was used to assess for main effects and interactions.

Results

All participants were able to understand and complete the task. Reported cybersickness was low (Average FMS: 1.625, SD = 1.41). As shown in Figure 5, when participants were confronted with two self-avatars, avatar preference was in the direction of the self-avatar with normal motion (mean: 54.5%, s.e. 5.1) but at chance (support for H_1 ; $BF_{10} = 0.446$). When confronted with two other-avatars, participants preferred the avatar with normal 1:1 motion (mean: 60%, s.e. 3.8; support for H_1 ; $BF_{10} = 2.643$). As expected participants preferred the self-avatar when participants were confronted with their self-avatar and the other-avatar, with the other-avatar having decoupled motion (mean: 76%, s.e. 7.8; support for H_1 ; $BF_{10} = 5.973$).

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Surprisingly, when participants were confronted with their self-avatar and the other-avatar, with the other-avatar having normal motion, participants no longer preferred their self-avatar by returning to chance preference (mean: 55.7%, s.e. 4; support for H_1 ; $BF_{10} = 0.687$). While there was no main effect of motion (support for H_1 ; $BF_{10} = 0.769$), there was a main effect of avatar type (support for H_1 ; $BF_{10} = 2.862$), as well as a significant interaction between motion and avatar type (support for H_1 ; $BF_{10} = 2.53$), driven by a significant difference between the two mixed avatar conditions (Bayesian paired sample t-test: support for H_1 ; $BF_{10} = 1.547$).

Figure 5: Experimental results. Probability of selecting the "self" avatar with 1:1 motion compared to the self avatar with decoupled motion was not different from

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chance (far left). The "other" avatar with 1:1 motion was significantly preferred over the other avatar with decoupled motion (middle left). The self avatar with 1:1 motion was strongly preferred to the other avatar with decoupled motion (middle right), however, this preference returned to chance probability when decoupled motion was applied to the self avatar and 1:1 motion to the other avatar indicating an interaction between self-motion and sex identification for the sense of self.

Discussion

When participants in our virtual reality experiment encountered two avatars that mirrored their actions, participants were more likely to select the avatar that they created to resemble themselves and that moved in close correspondence with their own self-motion. By decoupling visual self-motion feedback and by changing the avatar's apparent biological sex characteristics, however, our results from all conditions show that visual self-motion feedback and biological sex identification affect the sense of self in virtual reality through a significant interaction. This was most compelling where participants were equally likely to identify with either the same sex or opposite sex avatar when visual self-motion feedback was slightly decoupled for the same sex avatar. Together, these findings are consistent with previous research in healthy individuals showing that the sense of self and embodiment are relatively plastic and can lead to compelling perceptions of having ownership over additional limbs (Guterstam et al., 2011), body parts (Tsakiris et al., 2010), and whole bodies, even those of the opposite sex (Petkova and Ehrsson, 2008).

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Why is the sense of self so malleable? The central nervous system is challenged with constantly having to detect signals from the environment and from within the body to form a coherent representation of the self in its surroundings (Ernst and Bühlhoff, 2004). As these signals are detected from different sensory organs, our perceptual systems are continuously integrating and interpreting multisensory information to compute the spatial relationship between our body and the world around us (Ehrsson, 2010). This process could be quite computationally demanding and potentially create large delays in signal processing and action planning, which would be dangerous to the survival of any organism. However, the central nervous system can instead rely on internal models and prior knowledge about the body and the environment at the cost of misrepresenting the self. Such a framework can explain illusions that involve displacement (Botvinick and Cohen, 1998; Ehrsson, 2007), changes in size (Linkenauger et al., 2010), and experiences of being outside of one's body (Ehrsson, 2007; Lopez et al., 2008; Blanke, 2012), provided there are no gross violations concerning the basic structure of the human body (Tsakiris et al., 2010; Guterstam et al., 2011).

While the study presented here has bearing on both the philosophical and neuroscientific perspectives on the sense of self, there are some limitations that should be noted. First, this experiment was put together as part of a workshop for a visiting Korean group of students. While every effort was made to fully translate all instructions and ensure participants fully understood the nature of the experiment it is possible that the circumstances of this data collection could have some bearing on the results. While the sample size was also small due to the convenience sample

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of the visiting group, we used a robust Bayesian statistical framework that is capable of equally assessing both the null and alternative hypotheses. We do suggest that future research should replicate this experiment with a larger sample size under different recruitment circumstances. More importantly, we did not collect measures of presence nor did we collect gender preferences from our participants. This we also suggest should be addressed in future experimentation as our unique virtual reality paradigm would be ideally suited to assess to what degree to participants identify their self with their same or opposite sex. Moreover, the paradigm could also enable measurement of the sense of self for changes of other characteristics related to body size, satisfaction, and even adopting non-human avatars that could be embodied. Indeed parametric evaluation of the extend to which visual self-motion is decoupled from true motion in addition to changes in the trait characteristics of avatars would allow for the construction of predictive computational models for embodiment in virtual reality.

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