Human Tails: Ownership and Control of Extended Humanoid Avatars

William Steptoe, Anthony Steed, and Mel Slater

Abstract—This paper explores body ownership and control of an "extended" humanoid avatar that features a distinct and flexible tail-like appendage protruding from its coccyx. Thirty-two participants took part in a between-groups study to puppeteer the avatar in an immersive CAVE™-like system. Participants' body movement was tracked, and the avatar's humanoid body synchronously reflected this motion. However, sixteen participants experienced the avatar's tail moving around randomly and asynchronous to their own movement, while the other participants experienced a tail that they could, potentially, control accurately and synchronously through hip movement. Participants in the synchronous condition experienced a higher degree of body ownership and agency, suggesting that visuomotor synchrony enhanced the probability of ownership over the avatar body despite of its extra-human form. Participants experiencing body ownership were also more likely to be more anxious and attempt to avoid virtual threats to the tail and body. The higher task performance of participants in the synchronous condition indicates that people are able to quickly learn how to remap normal degrees of bodily freedom in order to control virtual bodies that differ from the humanoid form. We discuss the implications and applications of extended humanoid avatars as a method for exploring the plasticity of the brain's representation of the body and for gestural human-computer interfaces.

Index Terms—Avatars, virtual reality, body ownership, agency, body schema, plasticity, gestural interfaces

1 Introduction

Humans have a deep-seated cybernetic nature. When we play the violin, ride a bicycle, hammer a nail, or put on a Stetson hat, we extend our physical body structure through external objects and tools. Our instinctive ability to rapidly and dexterously incorporate such objects and learn how to use such tools provides a clue to the remarkable plasticity of how the human brain represents the body and encodes space. There is compelling observational evidence, coupled with supporting behavioral findings and other neurological studies, indicating that the brain's representation of the body, or body schema, can be extended or modified (see [13] for a review). The term 'body schema' of classical neurology [7] refers to such a neural system whereby space coding for action is centered on constantly updated, multisensory information about the body. It is a dynamic, distributed network of procedures aimed at guiding behavior [6] that includes proprioception, which refers to the inherent sense of our body's position and motion in space, together with capabilities arising from visuomotor sensory modalities [1].

Virtual reality (VR) technology is commonly used as a powerful tool to transform a user's sense of *place* by replacing a user's visual field with stereoscopic and perspective-correct imagery. However, VR can also present compelling transformations of an immersed user's *body*. Researchers have recently started to leverage such technology to explore the flexibility of the body schema, with a particular focus on the technological and sensory requirements necessary to support the experience of virtual body ownership. Current findings suggest that visuomotor and visuotactile correlations play important roles in determining whether a participant is likely to perceive a virtual body as their own [12, 5]. Research has demonstrated that it is possible to incorporate virtual arms and hands into the body schema [20, 16, 26] analogous to how a physical rubber hand may be incorporated in reality [1]. Ownership of whole virtual bodies has also been induced in immersive VR, and has been demonstrated to influence participants' perceptual body image, with measurable subjective and behavioral changes both during and after the VR experience [25, 4, 15].

This previous work investigating body ownership in virtual environments (VEs) has involved humanoid avatars. In the field of shared virtual and mixed reality environments, avatars are used to provide the necessary visual representations of connected users, and these avatars invariably exhibit a humanoid form, or approximations of it. This design choice, in both fields of study, is both intuitive (our real bodies are humanoid and we identify and interact with other humans daily) and functional (the humanoid form grants direct mapping between tracked body motion and avatar animation, leading to natural transmission and observation of even subtle nonverbal expression [22]). However, in VR, there are near-infinite opportunities for both extending and radically altering our virtual (and hence perceptually real) bodies. In doing so, we are granted further possibilities into body ownership research, as exotic morphologies, distortions, extensions and reductions can be realised. In addition, the question of how to control such extended- or non-humanoid bodies arises, and has implications for full-body gestural interfaces.

What we term 'extended humanoid' differs from what may be described as 'non-humanoid' in the sense that our avatar features a fundamentally human form, but includes an additional appendage. We decided to endow our experimental avatar with a movable tail as it is a vestigial structure as opposed to, for example, a supernumerary limb that potentially has medical associations [2] or a fantastical structure without evolutionary basis. Another reason we chose to use a tail is that, as the human coccyx is the remnant of a vestigial tail, the appendage is positioned at the centre of the body. This is likely to reduce the influence of participants' possible asymmetric motor dexterity between their left and right sides when they attempt to control the tail.

Examples of embodiment as non-humanoid avatars have been referred to by VE researchers, but have not previously been studied scientifically. Most prominently, Jaron Lanier has referred to early work at VPL Research, Inc. during which he made fascinating observations relating to a phenomenon he termed 'homuncular flexibility' [11]. Research has demonstrated that the body representation is not fixed but can be altered by simple manipulations resulting in illusory perceived changes to sensory, visual or proprioceptive information [1, 10, 3, 18]. This insight into the reversible and short-term plasticity of body representation, which leads to the experience of accepting a distorted body as your own, is part of Lanier's notion of homuncular flexibility when he describes embodiment as a non-humanoid avatar in immersive VR.

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The other component of homuncular flexibility in virtual embodiment relates to control of non-humanoid body parts. This refers to the brain's apparent ability to radically reorganise the body schema by learning how to remap normal degrees of freedom in order to control unusual body forms. In practice, this involves taking the tracked movements of various joints of a user's real body, and feeding that information into a composite signal which is used to control additional parts of a non-humanoid virtual body. Perhaps the most widely known example discussed by Lanier is a lobster, designed by Ann Lasko-Harvill [11]. This inherent sensorimotor intelligence, which appears able to learn motion patterns at a gestalt level, has also been explored by the visual artist Stelarc. His Third Arm project transformed muscle activity measured using electromyography (EMG), typically from his abdomen and thigh, in order to drive the movements of a mechanical human-like arm and hand attached to his right elbow [21]. Over a period of three months, Stelarc learned to control his third hand to a fine degree, including being able to write certain words (including "EVOLUTION") with three hands simultaneously.

1.1 Hypotheses

Our experiment was designed to test the hypothesis that visuomotor synchrony of the avatar's tail contributes positively to body ownership: both when considering the body holistically, and with respect to the tail specifically. Specifically, we expect participants who have experienced the ability to control the tail through synchronous movement of their own bodies to feel a greater degree of ownership over both the avatar as a whole and over the tail independently. This is because the control metaphor fosters visuomotor synchrony of the whole avatar including the tail, while the asynchronous condition does so only with regards to the avatar's humanoid majority, as the tail cannot be controlled, and moves around randomly. Thus, we expect the synchronous tail to reinforce body ownership. Upon the occurrence of a virtual threat to the tail, we expect those participants experiencing a higher degree of ownership to have a greater sense of threat and anxiety, and for this to be reflected both in movement data in response to the threat, and in subjective responses expressing anxiety or fear.

Before we present our second hypothesis, the notion of "synchronous" control of an appendage that is not part of the human body should be clarified. Naturally, humans do not have the morphology to move a virtual tail in the same way they do a virtual arm. The control concept we adopt in the synchronous tail condition is swinging the hips left and right to shift the avatar's tail posture accordingly (see Section 2.2 for full details).

This leads to our second hypothesis, that participants in the synchronous tail condition would be able to learn how to control their avatar's tail despite not having been taught how to do so before, and this would be reflected by improving performance over the course of the experiment. Thus, these participants would have a greater degree of agency, that is the sensation that they are controlling the movements of the avatar and its tail. Additionally, participants who are not able to control the tail (all those in the asynchronous condition and those in the synchronous condition who fail to work out the control metaphor) would simply perform more body movement as their attempts to control the tail would be relatively more chaotic and less purposeful than those who have mastered the tail control.

2 Materials and Methods

2.1 Technical Setup

The experiment was conducted in our four-walled Trimension ReaCTor CAVE™-like projection system. The front, left, and right walls are 2.98m×2.2m in size and back-projected, while the floor is 2.98m×2.98m and front-projected. The projectors are Christie Mirage DS+6K-M, operating at 1400×1050@100Hz. Each projector is driven by a PC running Windows 7 and equipped with a nVidia Quadro FX 5600 graphics card. The machines in the cluster are hardware synchronized to render active stereoscopic imagery (50Hz each eye) as viewed with CrystalEyes 3 shutter glasses. An Intersense IS-900 head tracking device attached on top of the shutter glasses grants perspective-correct rendering.

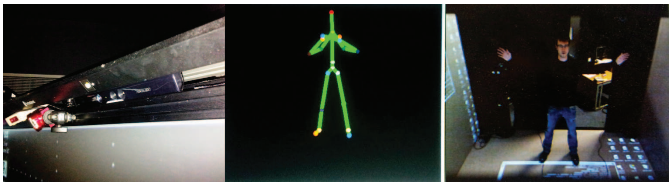


Fig. 1. Kinect tracking in our CAVE system. Left: mounted at a 23° decline in order to maximize the capture volume. Middle: Skeletal tracking. Right: The camera view.

We installed a Microsoft Kinect sensor just above the front wall of the CAVE to track participants' body movements. The Kinect features RGB and IR depth sensors running at 640×480@30Hz. The depth sensor has a horizontal field of view of 58°, and a vertical one of 43°. The maximal range of the depth sensor is approximately 3.5m, which makes it suitable for use in the majority of CAVE-like systems. To optimize the capture volume, the Kinect was tilted and fixed at a 23° decline, which provided coverage of the rear two-thirds of the volume. The Kinect setup in our CAVE is illustrated in Figure 1.

We developed our experimental application using the Unity game engine. The MiddleVR plugin was used to achieve stereoscopic perspective-correct rendering and allow 3D interaction in the CAVE cluster. Real-time capture of participants' motion was achieved using the Microsoft Kinect SDK skeletal tracking library [19], which we loaded as an OpenNI node. This allowed the high-quality skeletal tracking of Microsoft's solution to run within the framework provided by OpenNI, and for the whole setup to run through Unity using the OpenNI wrapper. We decided to use the Kinect as opposed to a professional motion capture system due to it being able to provide high-quality real time skeletal data without the need for participants to be fitted with a motion capture suit and calibrated in the system. While both latency and accuracy of Kinect tracking data is quantitatively inferior to that of a professional capture system, we considered it to be sufficiently good to run this perceptual experiment, and no participant noted it as a distraction or inadequate during post-experimental interview. Hence, the tracking technology was 'transparent', causing no encumbrance to the participants.

2.2 Avatar Design

We modified a male avatar and a female avatar taken from the Rocketbox Complete Characters HD set using Autodesk 3DS Max 2012. Texture and shading was modified to promote a fantastical appearance congruent with the avatar's exotic morphology. A long tail extending approximately 0.5m beyond the reach of each avatar's arm, and comprising of 35 interlocking cylinders, was modelled and attached at the avatars' coccyx. The avatar was then imported into Unity, and the translucency of the shading was increased so to allow participants to slightly see through their third-person perspective avatar to avoid occluding the environment beyond. (It may be noted that this semi-transparent visual technique is common in third-person perspective Kinect games for the XBOX 360.) The avatars are illustrated in Figure 2. Their visual appearance and body forms were carefully designed to be generally recognisable as humanoid with gender. As clarified in the following section, a critical design feature was that the avatars' tails have a greater reaching radius than their arms.

In Unity, the avatars were integrated with the Kinect SDK tracking via the OpenNI wrapper, and their relevant joints were attached to the tracking nodes for real-time animation of the humanoid skeletal structure. This included both position and orientation of the hips (the root of the hierarchy), and orientation of head, shoulder, elbow, wrist, leg, knee, and ankle joints. The tail behavior and animation was developed over a number of iterations and through consultancy with cognitive neuroscience and psychology researchers. The final tail control scheme is driven by lateral hip movement as measured from the mean horizontal center of body mass taken as the horizontal positions of the head and both feet. The horizontal offset of the hips relative to this center is used to reposition the tail between five key locations that form an arc

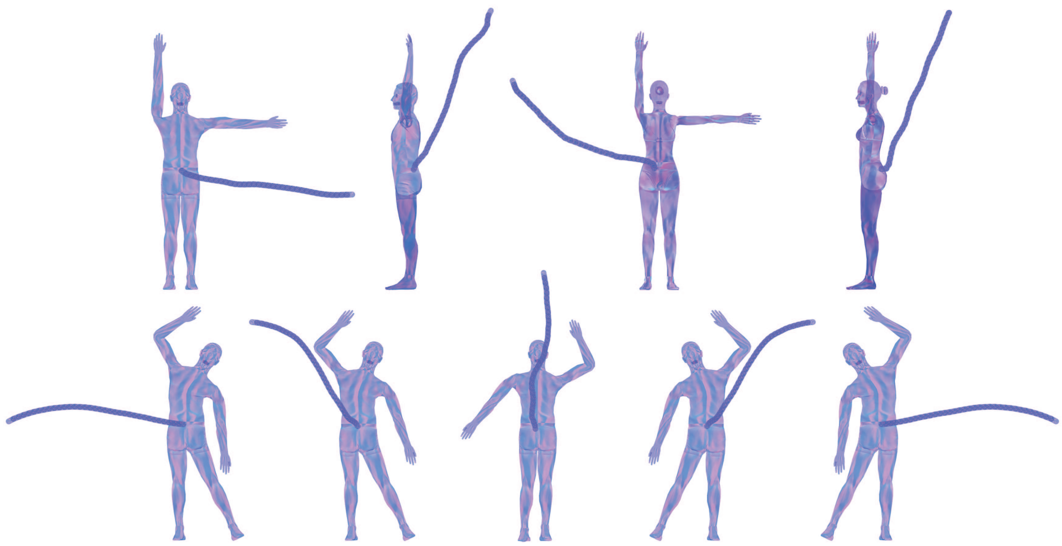


Fig. 2. Top row: Front and side views of the male and female avatars. The tail's reach radius is approximately 0.5m greater than that of the arms. Bottom row: Body poses to direct the tail. As the relative horizontal positions between the center of mass (mean of head and feet positions) and that of the hips changes, the tip of the tail is directed to one of five positions. These positions match those of the outer arc of emitters as shown in Figure 3. Note that hand positions are inconsequential to tail movement.

above the avatar in the VE. Thus, if a participant stood straight upright, or indeed crouched straight, the tip of the tail would remain centrally behind and above them at 90°. However, if a participant adjusted their hips to the left or right, the tail would follow accordingly. Finally, the magnitude of the participant's hip offset relative their center of mass defined the horizontal position of the tail: a small offset (typically around 0.15m to the left or right) would result in the tip of the tail positioning itself at 45°, while a greater offset (typically around 0.25m) directed the tip of the tail to a horizontal position of 0°. Each participant's height was used to scale these offset thresholds, so taller participants had to move their hips further, in terms of absolute distance, than shorter participants. The relationship between hip and tail positions are illustrated in Figure 2.

2.3 Game Design

The experimental scenario took the form of an involving and challenging game. The game provided both an explicit aim and consequent motivation to accurately control the avatar and its tail. The core gameplay mechanic involved the participant intercepting (via their avatar) green particle beams fired towards them from emitters positioned around 5m ahead of them. The participant's goal was to block as many beams as possible over a period of around ten minutes. During this period, emitters would fire beams in a predefined sequence. The emitters were positioned in such a formation that beams fired from each were sensibly and logically reachable using either the hands, feet, or tail. An orthographic view of the emitter formation, together with the avatar is illustrated in Figure 3.

As noted in Section 2.2, a crucial aspect of the game design was that the avatar's tail could reach further than its hands. Thus, beams fired from the outer ring of emitters could only be reached with the tail. This enforced a strategic advantage to using the tail, prompting participants to attempt to master control over it. In the synchronous condition, participants could potentially direct the tail so that its tip blocked the path of any one of the five emitter beams, while in the asynchronous condition, the tail moved randomly between the five intercept points. Thus, in the asynchronous condition, the tail was likely to be in the correct position, and hence would block, approximately 20% of the beams fired by the outer emitters.

More than one emitter could fire at one time, but only one emitter designed to be reached by a specific body part fired at once. Thus, the maximum number of emitters that could fire at once was five: covering the right hand, left hand, right foot, left foot and tail. The predefined pattern of emitter firing became more complex over the course of the experiment, so participants were increasingly required to coordinate their whole body (plus tail) to successfully block the beams. In this way, we aimed to engage participants in an enjoyable and challenging somatic experience that may be likened to dancing or playing a simple musical instrument.

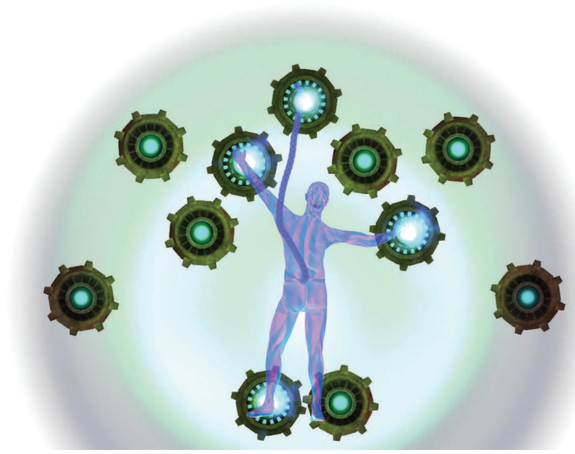


Fig. 3. Orthographic view showing emitter position and avatar. The participant must block the the green particle beams that are emitted. The emitters are laid out symmetrically and logically to be blocked by either the hands, feet, or tail. Critically, the outer ring of emitters is beyond the reach of the hands and feet, and can only be reached with the tail.

2.4 Threat Design

The purpose of the game stage described above was to acclimatise participants to the virtual body in an environment encouraging free movement and somatic experimentation. Immediately and seamlessly following the game stage, a threat occurred to the avatar's tail, and then to its whole body. The threat sought to elicit anxiety responses from participants, thereby providing insight into the extent of body ownership they were experiencing. In designing the threat, a recognisable signal of danger was required, and for this we chose fire. At the climax of the game stage, the emitters all slide into a central position, a high-pitched alarm sounds, and the lighting changes from bright green to bright red. The emitters then burst outwards, roaring flames towards the participant. The avatar's tail sets on fire and starts to burn down towards the body

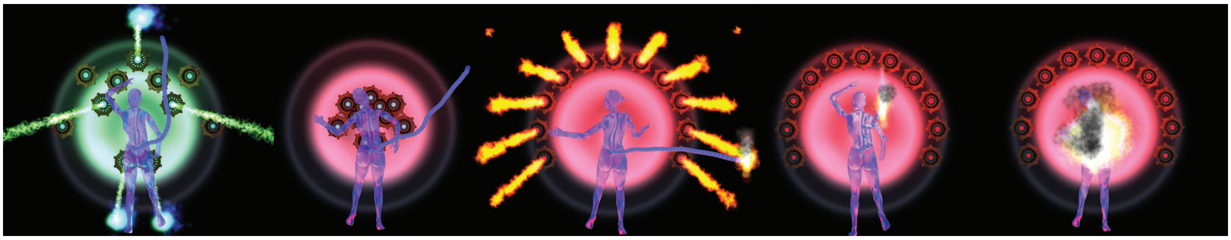


Fig. 4. Threat stage of the experiment. Left to right: the final moments of the game; the emitters fold to the center, an alarm sounds and the lighting changes to bright red; the emitters burst out to the perimeter shooting flames and the tail sets on fire; the tail burns down; the body sets on fire.

Table 1. Post-experimental questionnaire eliciting information relating to body ownership, agency, and response to threat. Variable names relating to the analysis section are also defined.

Topic	Variable Name	Question
Ownership	*mybody*	I felt as if the body I saw in the game might be my body
	tailpartofbody	I felt as if the tail was a part of the body I saw in the game
	realtail	At times during the game, I imagined that I had a real tail
	taillikearmslegs	I considered the tail to be as much of a part of the body as the arms and legs were
Agency	*mymovements*	Not considering the tail, the movements of the body I saw in the game seemed to be my movements
	tailcontrol	I could easily move the tail to where I wanted
	notailcontrol	The tail seemed to be moving from around on its own
	learnedtail	I learned how to control the tail more accurately as the game went on
	tailnatural	There were times in the game that moving the tail came naturally to me
Threat	*anxiousbody*	I felt anxious when the body was on fire
	extinguishbody	I tried to avoid or extinguish the flames in some way when the body was on fire
	harmedbody	I had the feeling that I might be harmed when the body was on fire
	anxioustail	I felt anxious when the tail was on fire
	extinguishtail	I tried to avoid or extinguish the flames in some way when the tail was on fire
	harmedtail	I had the feeling that I might be harmed when the tail was on fire

over a period of 30 seconds. When the fire reaches the body, the body itself bursts into flames and continues to burn for 30 seconds until the displays fade to black and the experiment is over. Images from this sequence are shown in Figure 4.

2.5 Procedure

Ethical approval from our university ethics committee was obtained. A total of 32 participants (10 females) with normal or corrected-to-normal vision were recruited from the student and staff population at our university. The experiment used a between-subjects design, so 16 participants experienced the avatar with the synchronous tail, and the remaining 16 experienced the avatar with the asynchronous tail. Participants were unaware of this independent variable, and were not given any information with regards to how to control the tail. Table 2 shows the mean and standard deviation of ages and video game experience for participants in each condition. Using the two-sample Wilcoxon rank-sum (Mann-Whitney) test, there is no significant difference in age (P=0.73), hours a week playing video games (P=1.0) or motion video games (P=0.15) (all significance levels two-sided).

At the laboratory, participants were given a handout providing a description of the game with its aim to block as many of the green beams as they could over the ten-minute period. The handout stated that the avatar would be located approximately 0.5m in front of their own body, and that it would move synchronously with their motion. The participant's ability to move freely and as desired within the CAVE, while their avatar moved synchronously, was clarified. The handout also stated that they might be able to learn how to direct the avatar's tail. No further information was provided in this regard. A final consent form requesting permission to record their tracked movement data, and warning of the possible side effects from experiencing VR, such as nausea and epileptic episodes was issued. Participants were given the option of withdrawing from the experiment, which none took.

Each participant was then taken into the CAVE system and fitted with the shutter glasses to resolve the stereo imagery. The application was started, and the gender-matched avatar with either synchronous or

Table 2. Mean and standard error of age, hours per week playing video games and motion-based games for participants in each condition.

Condition	*Age*	*Games*	*Motion games*
Synchronous	27.6 ± 0.77	3.5 ± 1.3	0.125 ± 0.09
Asynchronous	26.4 ± 0.77	4.6 ± 1.9	0 ± 0

asynchronous tail was automatically calibrated to the participant via the Kinect skeletal tracking. The experimenter then left the CAVE area. Before the game stage began, participants were given a three-minute period during which they could take the opportunity to experiment with their virtual body. Following this training period, the game stage seamlessly began. Finally, immediately and seamlessly following the game stage, the threat stage occurred. Participants were not made aware that a virtual threat would occur.

Following the virtual experience, participants were taken to a nearby computer, where in private they completed a questionnaire featuring questions relating to the experience. An informal post-experimental discussion then took place with the experimenter. The whole process took approximately 30 minutes for each participant.

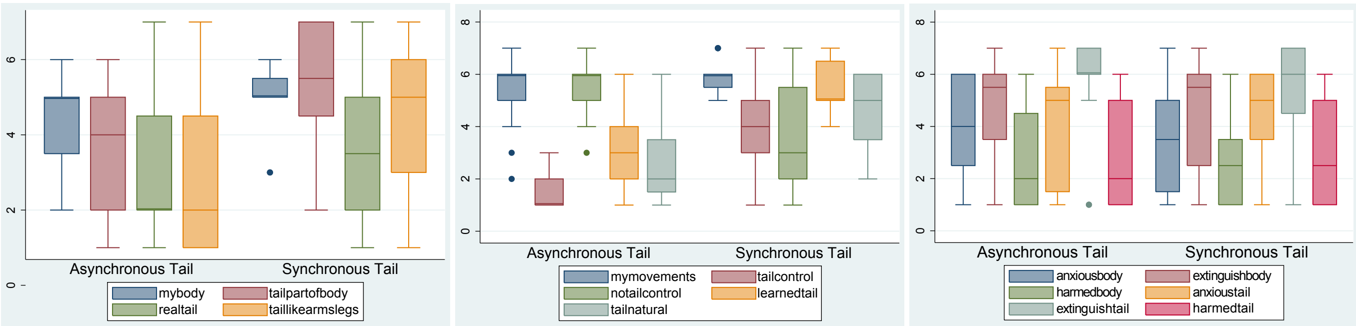
2.6 Data Collection

2.6.1 Questionnaire

A post-experimental questionnaire addressed a number of experiential issues relating to body ownership, agency, and sense of threat. Body ownership relates to the extent to which a participant perceived the virtual body to be themselves, agency describes the sense of control of the virtual body, and sense of threat is a participant's anxiety or feeling of the need to extinguish the virtual fire during the threat stage. These categories were further partitioned into statements about the body, and statements specifically about the tail. Participants responded to a set of statements each with an associated 1–7 Likert scale, where an answer of 1 indicated complete disagreement, and 7 indicated complete agreement. The questionnaire, together with variable names used in the following analysis section, is presented in Table 1.

Table 3. Questionnaire responses showing medians and interquartile ranges, and Wilcoxon rank-sum (Mann-Whitney) tests for each condition.

		Asynchronous Tail		Synchronous Tail		
		Median	IQR	**Median**	IQR	*P* value (two-tailed)
Ownership	*mybody*	**5**	1.5	**5**	0.5	0.08
	tailpartofbody	**4**	3	**5.5**	2.5	0.007
	realtail	**2**	2.5	**3.5**	3	0.34
	taillikearmslegs	**2**	3.5	**5**	3	0.028
Agency	*mymovements*	**6**	1	**6**	0.5	0.20
	tailcontrol	**1**	1	**4**	2	<0.001
	notailcontrol	**6**	1	**3**	3.5	0.004
	learnedtail	**3**	2	**5**	1.5	<0.001
	tailnatural	**2**	2	**5**	2.5	<0.001
Sense of Threat	*anxiousbody*	**4**	3.5	**3.5**	3.5	0.53
	extinguishbody	**5.5**	2.5	**5.5**	3.5	0.94
	harmedbody	**2**	3.5	**2.5**	2.5	0.86
	anxioustail	**5**	4	**5**	2.5	0.66
	extinguishtail	**6**	1	**6**	2.5	0.95
	harmedtail	**2**	4	**2.5**	4	0.92



(a) Body ownership variables (b) Agency variables (c) Sense of threat variables

Fig. 5. Box-plots for questionnaire variables associated with Table 3. Medians, interquartile ranges, and full ranges are shown.

2.6.2 Body Tracking and Performance

Each participant's body movement was recorded. Three-dimensional position (*x,y,z*) pertaining to each of their tracked joints was output to a human-readable log file at 60Hz. Recorded joints were the hips, torso, head, shoulders, elbows, hands, knees and feet. Additionally, the current position (1–5) of the tail was logged at each line. When combined, these values provide a thorough representation of the participant's skeletal motion and how they may have been attempting to control the tail. In the analysis section, we discuss the amount of movement that participants performed as a measure of both control aptitude during the game stage and response to the threat.

Alongside the tracking data, the same log file also recorded participants' performance in terms of their ability to successfully block the beams fired from the emitters during the game stage. This took the form of a binary value for each of the eleven emitters, indicating whether the participant was successfully blocking the beam at the time, and what body part (including tail) was being used to block it. If the emitter was not currently firing, then a null value was written to the file. This performance data is pertinent to participants' overall kinetic coordination, and in particular, how well the participants in the synchronous condition were able to learn how to control the tail over time as the experiment progressed.

3 Results

3.1 Questionnaire Responses

The questionnaire elicited subjective experience of body ownership, agency, and sense of threat. Table 3 shows medians and inter-quartile ranges of questionnaire responses recorded on the 1–7 Likert scale for each tail condition. Wilcoxon rank-sum (Mann-Whitney) tests for statistical significance between responses for the two conditions are also shown. The table divides the questions into those relating to body ownership, agency, and sense of threat.

3.1.1 Body Ownership

Figure 5(a) shows the box-plots associated with Table 3 for the questionnaire scores relating to body and tail ownership. Medians, interquartile ranges, and full ranges are shown. Participants in the synchronous group tended to give higher subjective ratings than those in the asynchronous group to overall body ownership (*mybody*), that the tail was part of the body (*tailpartofbody*), and that they considered the tail to be as much a part of the body as the arms and legs (*taillikearmslegs*). There was no difference with respect to the illusion that the tail was real. Regarding *mybody*, although the medians are the same for both conditions, it can be seen that the variance is much lower in the synchronous group. Also there are two points that are outliers (*score=3*). A value, x, is an outlier if $x <$ *lower quartile* - *1.5* $\times$ *interquartile range* or if $x >$ *upper quartile* + *1.5* $\times$ *interquartile range* [23]. When these two outliers are removed the significance level becomes P = 0.015.

3.1.2 Agency

Figure 5(b) shows the box-plots associated with Table 3 for the questionnaire scores relating to agency. Medians, interquartile ranges, and full ranges are shown. As would be expected given that all participants experienced the avatar's humanoid majority to represent synchronous movement mapped from their own motion, scores relating to the statement that movements of the body (that is the avatar apart from the tail) were based on their own movements (*mymovements*) were high in both conditions. The remainder of the questions concerning the tail were also as according to the design. Participants in the synchronous condition were more likely to report greater ease of control (*tailcontrol*), and less likely to report that the tail seemed to move around on its own (*notailcontrol*). Participants who experienced a synchronous tail reported higher scores relating to learning how to control the tail (*learnedtail*), and that moving the tail came naturally (*tailnatural*).

Table 4. Game performance for hands, feet, and tail, and combined total. Mean scores (%), standard error, and ANOVA tests are shown.

Body Part	*Asynchronous*	*Synchronous*	*P value*
Hands	0.721 ± 0.18	0.66 ± 0.128	0.276
Feet	0.936 ± 0.067	0.979 ± 0.024	0.089
Tail	0.234 ± 0.092	0.568 ± 0.107	<0.001
Total	0.539 ± 0.085	0.676 ± 0.079	<0.001

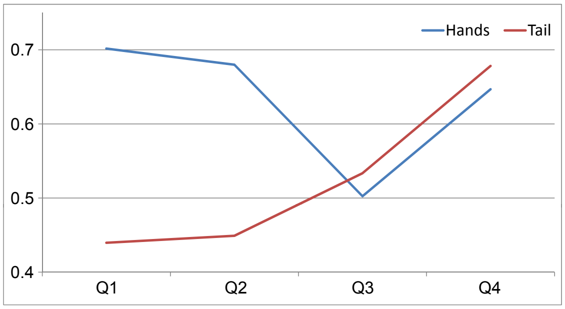


Fig. 6. Performance of synchronous tail participants in each quarter of the game stage. Hand and tail performance is shown.

3.1.3 Sense of Threat

Figure 5(c) shows the box-plots associated with Table 3 for the questionnaire scores in relation to anxiety or being harmed during the threat stage of the experiment. Medians, interquartile ranges, and full ranges are shown. There are no differences between the synchronous and asynchronous conditions considering both the tail and body fires. With respect to the body, the median level of anxiety (*anxiousbody*) was quite high (4 out of a possible maximum of 7) but also the interquartile range is quite high. The reported attempt to extinguish the fire (*extinguishbody*) was also high in both groups (5.5), but the feeling of being harmed (*harmedbody*) was low (2). A similar pattern emerges in relation to the feelings about the tail, with scores of 5, 6, and 2 for *anxioustail*, *extinguishtail*, and *harmedtail* respectively. It can be concluded that, irrespective of the synchronicity of the tail, the virtual threats to both the tail and to the body resulted in participants feeling anxious and led to attempts to extinguish the fires, but not to the illusion that they would come to actual harm.

3.2 Movement Analysis

3.2.1 Game Performance

Analyzing game performance provides insight into the ability of participants in the synchronous condition to learn how to control the tail as the experiment progressed. Table 4 shows the mean percentage scores for the hands, feet, and tail over the two conditions, that is, the proportion of beams that participants managed to block during the entire game stage, with each body part. Scores for hands and feet show no significant difference between conditions. Scores for the tail, however, indicate that participants in the synchronous condition learned how to direct it with intent and success, attaining a mean score of 57% over the length of the game stage. The tail score for the asynchronous participants was 23%, which is in accord with chance given the five randomized tail positions.

Focussing only on the synchronous tail condition, we now explore how those participants' ability to successfully direct the tail changed over the ten-minute game stage. Figure 6 divides the game period into quarters and plots tail performance alongside hand performance. Participants' ability to work out and learn how to remap hip movement in order to control the virtual appendage as time goes on is apparent. What is also telling is the dramatic decrease in hand performance during the second and third quarters of the game, which occurs in parallel with the rapidly increasing proficiency in tail control. This suggests that tail control was learned at the expense of hand performance. This is understandable considering the task of learning how to control the tail while simultaneously coordinating the rest of the body, together with the moderate limitations to normal degrees of freedom imposed by the tail control scheme. Hand performance recovers during the final quarter of the game, indicating that participants have both accommodated the tail control into their body schema and adapted their normal movements in order to successfully control the extended-humanoid form. While we cannot make quantitative judgments on difficulty, the game progressively became more challenging in terms of required movement coordination. This reinforces our observations with regards to learning.

Table 5. Mean amount of movement (m) and ANOVA tests during threat stage for each condition and combined total. Threat stage split into tail fire, body fire, and total periods.

Threat Stage	*Asynchronous*	*Synchronous*	*Total*	*P value*
Tail Fire	86.4 ± 11.7	56.9 ± 6.6	71.6 ± 7.1	0.055
Body Fire	53.9 ± 6.6	39.1 ± 4.8	46.5 ± 4.2	0.152
Total	129 ± 19.2	74.4 ± 10.3	102.2 ± 11.8	0.042

3.2.2 Movement in Response to the Threat

We now consider amount of movement in response to the threat. Table 5 shows the mean amount of movement performed during the tail fire, the body fire, and total period. These metrics are the sums of translational movement of the hands, feet, torso and head measured in meters. We present a combined value as opposed to considering each body part separately as the data for all body parts show the same pattern between conditions. As these measurements were recorded at the threat stage, participants in the synchronous condition will have potentially learned how to control the tail as discussed in Section 3.2.1. Participants in the asynchronous condition tend to move more than those in the synchronous condition. This indicates that people simply moved less when they had the tail under control, since their movements were purposeful, compared with the relatively haphazard and random movements of those that did not have the tail under control.

3.3 Overall Impact of the Tail

Above we have analyzed metrics describing individual contributions to the illusion of tail ownership. However, there are potentially complex interactions where the condition of tail synchronicity influences the degree of ownership and agency, which in turn influences the feeling of anxiety when the tail sets on fire, which in turn might influence the desire to extinguish the fire. Additionally, simply the ability (or inability) to control the tail might directly influence the feeling of anxiety and/or the desire to extinguish the burning tail. Here, instead of classical single equation models, we employ the standard technique of path analysis [9] to examine a set of simultaneous equations representing potential relationships between variables. These relationships and variables were chosen based on our initial hypotheses. In particular we are interested in the extent to which the condition of synchronicity influenced tail ownership and agency, and how these in turn affected anxiety, and how this in turn affected the desire to extinguish the fire. This exploratory analysis will also allow us to test the direct influence of condition on both anxiety and desire to extinguish the fire.

We chose a representative variable from the questionnaire and movement stages. We use *taillikearmslegs* to represent the degree of ownership of the tail, *tailcontrol* as the most clear expression of agency, *anxioustail* to represent the sensation of possible harm, *extinguishtail* to represent the desire to extinguish the flames and *tailfiremovement* to consider the amount of movement performed while the tail was on fire. The path analysis was carried out using Stata 12, and used the non-parametric asymptotic distribution-free method (since we have no reason to believe that the underlying data is multivariate normal). We ran the path analysis on standardized data so that all the different types of variables were on the same scale and so that normalized coefficients would be shown.

The path diagram is shown in Figure 7, and corresponding detailed data and P values in Table 6. The set of paths pointing towards a variable represent a linear equation with that variable on the left hand side, and the estimated coefficients as path labels. The overall fit of

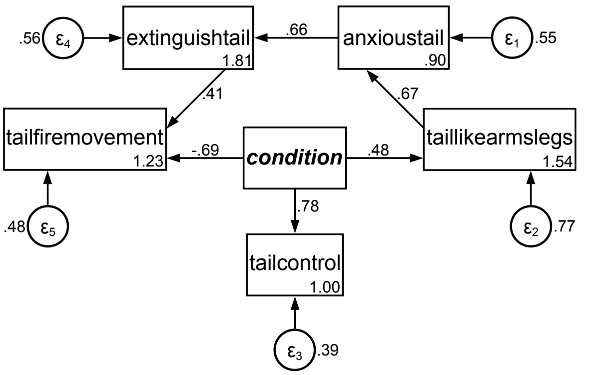


Fig. 7. Path diagram. Numbers between variables indicate that synchronous tail responses were *n* times greater than asynchronous responses. *condition* is 0 for asynchronous and 1 for synchronous.

Table 6. Path Analysis corresponding to Figure 7 showing standardized coefficients, standard errors and P values (asymptotic distribution free).

		Coefficient	Std. Err.	*P* value
tailcontrol	*condition*	0.78	0.05	0.000
	constant	1.00	0.14	0.000
taillikearmslegs	*condition*	0.48	0.14	0.001
	constant	1.54	0.26	0.000
anxioustail	*taillikearmslegs*	0.67	0.11	0.000
	constant	0.90	0.42	0.032
extinguishtail	*anxioustail*	0.66	0.08	0.000
	constant	1.81	0.72	0.012
tailfiremovement	*condition*	-0.69	0.09	0.000
	extinguishtail	0.41	0.11	0.000
	constant	1.23	0.48	0.011

the model is acceptable, using the Chi-Squared against the saturated model (Chi-Squared = 13.42, 9 d.f., P = 0.14). Here, the greater the P value the better the fit. In the following paragraphs we present an interpretation of the path diagram in terms of our original hypotheses. While the path diagram certainly does not prove 'causation' it does suggest connections between variables which could also be considered as hypotheses to be tested with additional data.

The path analysis suggests that condition (asynchronous / synchronous) is positively associated with the sense of tail control (arrow from *condition* to *tailcontrol*), but the sense of tail control does not influence any of the other variables (all paths from *tailcontrol* were not significant). A way to interpret the path diagram is that the synchronicity of the tail influences ownership with respect to the tail, specifically that the tail is experienced as being part of the body like the arms and legs to a greater extent (path from *condition* to *taillikearmslegs*). The higher the degree of such ownership, the greater the reported anxiety becomes (path from *taillikearmslegs* to *anxioustail*). The path from *anxioustail* to *extinguishtail* suggests that these two variables are also positively associated: the higher the anxiety the greater the desire to extinguish the fire, which in turn is associated with greater movement during the tail fire (path from *anxioustail* to *tailfiremovement*). Thus, the amount of movement is directly related to the expressed desire to extinguish the fire, confirming the veracity of the high questionnaire response for *extinguishtail*. This relationship was hidden in our previous analysis due to the reduced amount of movement performed by participants in the synchronous condition during the fire (path from *condition* to *tailfiremovement*) as described in Section 3.2.2.

4 Discussion

Our first hypothesis predicted the positive influence that visuomotor synchrony of the avatar's tail would have on body ownership: both when considering the body as a whole, and specifically regarding the tail. Questionnaire responses relating to body ownership support this prediction, with participants in the synchronous condition being more likely to both feel ownership of the extended-humanoid body, and to consider the tail extension as being a part of that body. Our first hypothesis also predicted that, on the occurrence of a virtual fire, participants experiencing a high degree of body ownership would feel a greater sense of threat, manifesting as anxiety or feeling the need to extinguish the flames. Individual analysis of questionnaire responses and movement data is unable to uncover potentially complex interactions between the degree of body ownership being experienced and the ensuing reaction to the threat. Our path analysis investigated these relationships, revealing a positive association between the sense of body ownership and anxiety in response to the virtual threat. Further, the increased anxiety was positively associated with a desire to extinguish the fire, which itself was positively associated with increased movement for the expressed desire to extinguish the flames. While this increased movement positively influenced these preceding variables, it is not directly influenced by the condition of tail synchronicity.

Our second hypothesis predicted that participants in the synchronous condition would be able to successfully learn how to control the tail over the course of the experiment, and that these participants would experience a greater degree of agency. The affirmative evidence from both questionnaire responses and performance data is validation both of participants' inherent somatic intelligence, and the affordances provided by the tail control interface. Of particular interest is how participants' tail control proficiency improved over the course of the experiment, and how hand performance was adversely affected until a reasonable level of tail control had been achieved. This perhaps suggests that participants allocated higher priority to the unfamiliar body part while learning, and more generally, that somatic learning may result in the impaired movement of body parts that are non-critical to the learning task as both brain and body are "busy". Once participants were able to control the tail with a degree of proficiently, hand performance was seen to improve and recover to levels observed in the first half of the game stage, which involved more simple tail coordination. This phenomenon appears comparable to the process of learning to perform simultaneous manual tasks such as patting your head and rubbing your stomach, or, less trivially, an activity such as dancing or playing a grand piano that requires both body and brain to operate in an environment requiring rich somatic coordination and cognition.

It is important to articulate what the experiment covered in this paper is exploring, and what it is not (or may not be). Our results suggest that people can experience ownership of an extended-humanoid avatar in immersive VR, and highlight the importance of visuomotor synchrony in engendering this sensation. However, no matter how convincing the illusion of having the extended body may be, and how fine a control over the extra body parts a participant might be able to command, the process of motor prediction [24], which is central to normal body movement, differs between the humanoid virtual body parts and those that do not have a counterpart in reality: in this case the tail. Normally, when you have the basic intention to move a part of your body in a particular way, an efferent signal is sent to the muscles, the movement is executed, and a copy of the signal is sent to the cerebellum, where the movement is emulated. You often see the body part move, which provides documentation of the movement. Simultaneously, afferent signals to the brain from proprioception also document the movement [14]. This feedback loop and documentation system is a critical process for our sensation of movement, and while it remains intact when puppeteering both the humanoid majority of the avatar and the tail, visual feedback is altered in the latter case. It is logical that, upon the intention to move the tail, the efferent signal is directed to the muscles involved in hip movement and the afferent signal is returned as usual, but the subsequent visual stimuli affirms both the hip movement and also the presence and movement of a tail. As discussed below, visual stimuli is dominant in forming our perception of reality, especially when reinforced by synchronous motor activity, and so, seeing may also mean believing.

In this regard, extending the human body in VR may share elements with phantom limb sensation and awareness. People who experience phantom limbs, often following amputation, have no visual feedback for their intended movements as due to the physical arm or leg being missing [17]. However, they can often sense their phantom limb and sometimes feel it move. In our VR case, a participant can see their virtual body's tail, but they cannot feel it: it is a phantom with respect to all senses except visual, and, for participants in the synchronous condition, seems to move synchronously with body movement. The dominance of visual feedback to the feeling of both ownership and agency may go some way to compensate for the absence of other sensory feedback. The crucial importance of visuomotor feedback has been demonstrated in phantom limb patients by Ramachandran et al. through the use of a mirror box [17]. The patient places their real arm into one half of the box, and two mirrors are positioned to visually collocate the reflection of that arm with the position where the phantom arm is sensed to be. When the patient is asked to move both arms symmetrically, they see their real arm and also its mirror image in the location of their phantom arm, and they feel both arms to move. Thus, visual feedback alone can provide vivid kinaesthetic sensation of ownership and agency.

The success of participants in the synchronous condition to both solve and learn a novel control metaphor in a short time hints at the preadaptive nature of the brain, and relates to our dexterity with tools. It is interesting to consider the extent to which participants treated the virtual tail as a part of their body as opposed to treating it as an external tool. Recent research suggests that external tools are modularly organized in the cerebellum [8], and that peripersonal space expands with tool use [13]. The experience of embodying an extended-humanoid avatar may engender similar adaptation, however, the difference between our avatar's tail and a tool seems to be the sense of ownership and agency that is likely to arise. Our analysis shows that a feeling of tail ownership arises more prominently in the synchronous condition, in which participants have agency over the tail, and this results in increased anxiety when the tail is threatened, which subsequently increases the desire to avoid and extinguish the threat. We suggest that this chain of events would be less likely to transpire if participants were considering the tail as a tool, but further investigation is required.

Our results indicate that our methodology may be fruitful for further explorations into how the brain represents the body, the extent of this plasticity, and investigation into both short- and long-term effects of the embodiment of altered bodies. Results may contribute towards a framework of virtual embodiment as most recently presented in [6]. Foreseeable application areas of altered body forms include clinical fields such as rehabilitation related to vestibular deficits and dismorphia, and in training and education, where participants would "become" the subject of their learning. Our results relating to agency raise opportunities for extending gesture-based interfaces by using an extended set of the body's degrees of freedom than the traditional hand-based metaphors to enable multi-channel somatic interaction.

5 Conclusions

We described an experiment exploring immersive embodiment of an extended-humanoid avatar featuring a tail. Participants experienced the avatar's humanoid majority to move synchronously with their own body, but the tail either moved randomly, or could be potentially controlled through logical hip movement. Measured by both quantitative and qualitative methods, results suggest the importance of visuomotor synchrony in forming convincing perceptions of body ownership and agency, and that this factor was significant in determining response to perceived threats to the virtual body. The higher task performance of participants in the synchronous condition indicates that people are able to quickly learn how to remap normal degrees of freedom in order control exotic virtual body forms. Due to the difficulties in presenting first-person embodiment in a CAVE-like system, participants in our study viewed the avatar from a third-person perspective. We plan to further investigate embodiment of extended-humanoid avatars using a head-mounted display system and also to study the effect of tactile feedback on the sensation of body ownership and agency. Specifically, we plan to investigate how altered body representations affect balance behavior. The success of our methodology and experimental findings invite further exploration into both the plasticity of the brain's representation of the body and somatic learning using VR. This may find both clinical and educational applications, and also suggests opportunities for whole-body metaphors in the field of gestural interaction.

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