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# Recognising your self in virtual avatars

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**Abstract:** We are interested in the way players identify with their virtual characters, and how this identification could be exploited to augment players' cognitive abilities. Our approach is based on the cognitive neuroscience theory of common coding and related experiments, that suggest that perception, imagination and execution of movement are linked by a common representation in the brain. We report three experiments that examine players' identification with the avatar and one effect of this identification on the player's cognitive abilities. The first experiment laid the foundation for the design and development of a full-body puppet interface for transferring a player's own movements to a virtual avatar. Subsequent experiments used the puppet to investigate: (1) whether players recognised their own movements in a virtual avatar and (2) whether this self-recognition improved the player's ability to perform mental rotations. Our results show that the puppet interface is effective in personalising an avatar, and it can augment players' cognitive abilities.

**Keywords:** tangible interface; digital puppetry; video games; virtual avatar; cognitive science; common coding theory; body memory.

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## 1 Introduction

This paper describes research that investigates the mapping of a player's own body movements onto a virtual character and the cognitive effects of this transfer. When players move through a virtual environment, they need a means to project their intentions and expressions into the virtual space, such as a control device or interface. Many video games allow players to execute actions that the physical body cannot perform. As a result, there is a significant – and often necessary – abstraction process, where the players' actions on the control device are mapped in a variety of ways to the movements of the virtual object that is being controlled. Most current game systems make use of a number of generic hand-based controllers for this purpose, such as keyboards, mice, joysticks and gamepads. These input devices are generally 2D positioning devices or arrays of buttons that are controlled by the hands and provide low-bandwidth single-channel streams of information. Complex characters, however, have many degrees of freedom to control, and this level of control is not easily supported by these hand-based input devices, which provide two degrees of freedom at most. More recent and innovative interface designs such as motion-tracking (Nintendo's Wii and Sony's Move) and advanced cameras (Microsoft's Kinect) provide a clearer mapping between the user's actions and the actions of the character.

Our work explores the mapping between real and virtual movements, using a combination of tangible interfaces, experimental results from cognitive science and 3D visualisations. Our goal is to develop a control interface that facilitates the player's recognition of her own movements in avatars. We treat such self-recognition as an indication that the interface allows the players to develop a close identification with the character. This assumption is based on the idea that there is a distinction between being able to control a system and recognising a representation of you controlling the system. The latter skill can occur only after a sufficient level of expertise and comfort with the former, and therefore such recognition of oneself in a representation can be treated as an indicator of a high level of expertise and comfort with the action and its control. This means recognising oneself in an avatar can be used as a metric for judging the quality of controllers that seek to provide an immersive experience in video game environments.

Further, once a controller allows self-recognition, it is possible that actions executed on screen could help to change the player's motor system. This possibility is based on the cognitive neuroscience model of 'common coding', which proposes that the planning/imagination, execution and perception of movements share a common representation in the brain, as these modalities are, and need to be, interconnected. One effect of this common coding, which has wide experimental support, is that actions in one modality (say perceived actions) will activate actions in another modality (say imagined actions). This model of actions is a very useful framework for thinking about interactions in video games and virtual environments, as it allows the designers to predict possible cognitive effects of their designs.

Our work has, thus far, consisted of three main steps: the first step involved extending previous cognitive psychology experiments to test whether users could recognise their own movements in the abstracted representation of a 2D virtual character (Section 3). This laid the foundation for the design and development of a full-body puppet interface for transferring a player's own movements to a 3D virtual character. In the second step, we tested whether users would be able to recognise their own movements in this virtual character when it is controlled by the puppet (Section 4). Once these initial steps were successfully completed, the third step (Section 5) examined the cognitive effects of such a projection of self into a virtual world, using a mental rotation task, where players had to imagine rotating a series of patterns, before playing a video game using the puppet interface and again after playing the game. We then compared the accuracy and speed of the imagined rotations before and after the game. Here, we summarise results from these three steps of our project. Section 2 outlines the theoretical background of this research project.

## 2 Background

Recent research focuses on using the human body and its movements to design interactions with digital media. A theoretical account of such embodied interaction was proposed by Dourish (2001), and many innovative sensing and interaction technologies have been developed. However, we still do not understand the human side of this interaction – the embodied cognition mechanisms that allow our bodies to interact with digital media. On the other hand, technologies such as virtual reality have been used in embodied cognition research to demonstrate how human experiences can be extended in new directions (e.g. the recent papers in *Science* outlining the generation of out-of-body experiences in the lab – Ehrsson, 2007; Lenggenhager et al., 2007). But, such innovative experimental results from the human sciences are rarely extended to develop novel interaction designs. Our research addresses both these gaps: we exploit innovative experimental results from embodied cognition to develop novel interaction designs; we then use the technology that was developed to investigate the cognitive principles that support our body-based interaction with digital media. This coupling of basic science and technology development creates a positive spiral of embodied cognition and interaction, bringing computing and the human sciences closer, and teaching us more about ourselves as well as our interaction with technology.

A central pillar of embodied cognition is the converging evidence from recent cognitive psychology and neuroscience experiments showing that planning, execution, perception and imagination of movements activate a common neural representation or a common code (Hommel et al., 2001; Prinz, 2005). One way to understand the relation between common coding and other embodied cognition approaches (Barsalou et al., 2003; Gibbs, 2006) is to consider embodied cognition as a high-level description and common coding as one of the neural mechanisms that support such cognition. A fundamental effect of the common code connecting movements is motor simulation; the covert activation of the motor system when planning, perceiving and imagining movement, which is also related to mimesis (Girard and Doran, 2008; see also Damasio, 1994; Ito, 1993). This covert activation has been shown clearly by a range of experiments (see Chandrasekharan et al., 2010 for a review) and this motor simulation mechanism is now considered to play a central role in a range of cognitive phenomena, ranging from imitation (Brass and Heyes, 2005), motor learning (Casile and Giese, 2006), action recognition (Bosbach et al., 2005), joint action (Knoblich and Sebanz, 2006), to empathy (Decety and Jackson, 2006), conceptual change (Chandrasekharan, 2009), scientific reasoning (Nersessian, 2008) and language processing (Wilson and Gibbs, 2007). Further, recent models propose that a range of symptoms associated with psychiatric disorders are caused by damage to the common coding system. These include lack of volition and delusions of control in schizophrenia (Frith, 2006), lack of social skills in autism (Oberman et al., 2005) and failure of action control in clinical depression (Schneider, 2006). As a corollary, these models of mental disorder also suggest that motor simulations are central to our sense of self, as well as our ability to function in society.

Motor simulation may, thus, be critical to being human, and understanding this process more deeply would contribute significantly to our understanding of the human mind and to the design of embodied technological interventions that augment our cognitive skills. A central experimental result supporting motor simulation is the self-recognition effect (Knoblich and Sebanz, 2006). As common codes develop through the execution of action plans and the resulting perceptual consequences of those plans, the motor simulation system should be better activated when watching one's own actions. Knoblich and Sebanz (2006) report experiments showing that people can recognise their own clapping from a set of recordings of clapping, and pianists can pick out their own rendition of a piece from a set of recordings of the same piece. Our experimental and interface development work builds on, as well as extends, these experiments to show that this self-recognition effect exists for video game characters if the character is controlled by a novel interface that translates a player's own movements to the character.

## 3 Self-recognition in abstract figure

The first stage of our project investigated the extent of the self-recognition players have between their own movements and a virtual character that encodes these movements. To test this connection, we conducted a range of initial experiments to assess whether a person can identify her own movement patterns and the movement patterns of a puppet she controls, even when the 3D movement is visually abstracted to 2D. These experiments replicated some of the earlier work in common coding and also helped us to develop a good experimental protocol based on studies in cognitive psychology.

### *3.1 Experiment design*

This initial phase of experiments was based on a series of cognitive psychological studies of biological movement (Beardsworth and Buckner, 1981; Cutting and Kozlowski, 1977; Knoblich and Flach, 2001; Knoblich and Prinz, 2001) that have shown that when a person sees a visually abstract representation of her movement, she can recognise the image's movements as her own. We wanted to extend these studies to test whether participants were able to identify their own movement in an 'other' body – namely that of a hand puppet under their control. Consequently, we developed two sets of experiments. The first type assessed participants' ability to recognise their body movement; the second type investigated participants' ability to recognise the way they moved a puppet. We broke each section down further into two studies each to test with a higher granularity. The four resulting studies are described below:

*Study one – body condition*: Can participants identify their own body movements when they are represented as a proportionately correct but visually abstracted movement?

*Study two – body proportion condition*: Can participants identify their own body movements when they are represented as proportionately standardised (not in their own natural proportions) and visually abstracted movement?

*Study three – puppet and puppeteer condition*: Can participants identify themselves moving a hand puppet when they can see visually abstracted representations of their movements and the movements of a puppet?

*Study four – puppet only condition*: Can participants identify their movements of a puppet when all they see is a visually abstracted representation of only the puppet's movements?

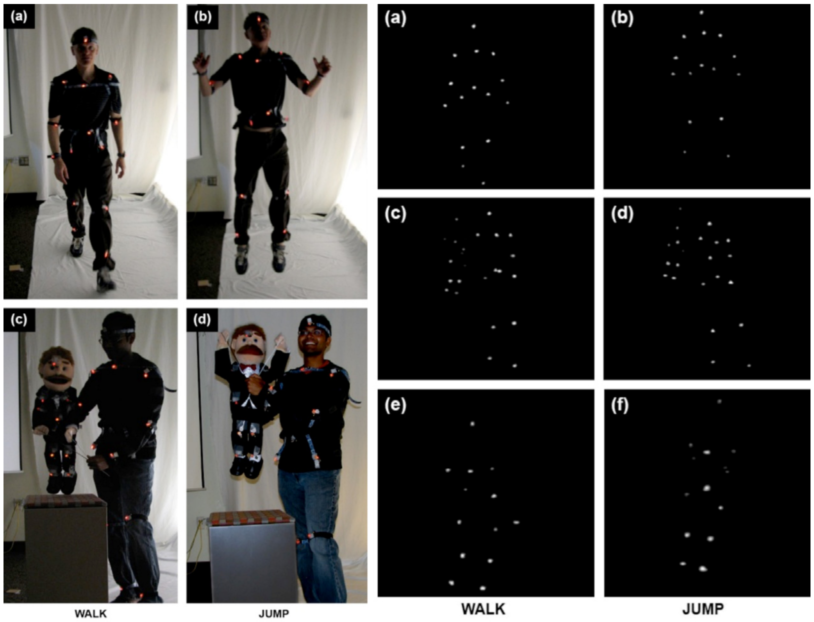
In each experiment, light-emitting diodes (LEDs) were attached to key points of articulation of the participant's and/or puppet's body: head, torso and limbs. The participant's movements were recorded by camera. In post-production, we generated abstract images of body movement where only the moving light points of the LEDs were visible (Figure 1).

There were a total of 20 participants in this study: 10 participants (5 male, 5 female) participated in the body movement experiments and 10 participants (5 male, 5 female) in the puppet movement experiments. None of them was an experienced puppeteer. For each participant, five walk and five jump (body or puppet) movements were captured during a recording session. Participants returned ten or more days later for a recognition session, during which they attempted to recognise their own (or their puppet's) walk and jump movements when presented alongside a clip of other participants performing the same movements. Participants did not know about this task during the recording session. The protocol for the recognition experiment is similar to the one described in Section 4.3, which presents a more complex version of the same experiment. These protocols were based on previous work (e.g. Knoblich and Prinz, 2001). See Mazalek et al. (2009) for more details on this study.

## 3.2 Results

For each participant, we computed the proportion of correct self-identifications. Since the guessing probability is 0.5, values significantly greater than 0.5 indicate that participants recognised their own movement.

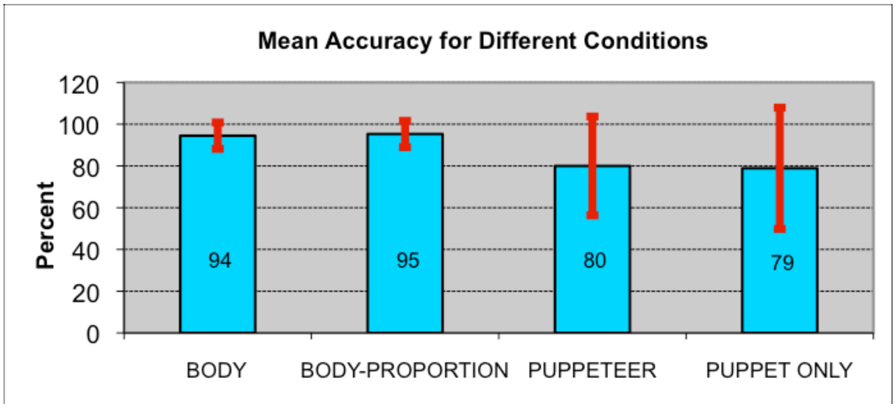
**Figure 1** (left) Walk and jump movement tracking with LED straps attached to: participant body (a and b) and both puppet and participant bodies (c and d); (right) Video stills of visually abstracted walk and jump movements for: participant body (a and b), participant body with puppet (c and d) and puppet only (e and f) (see online version for colours)



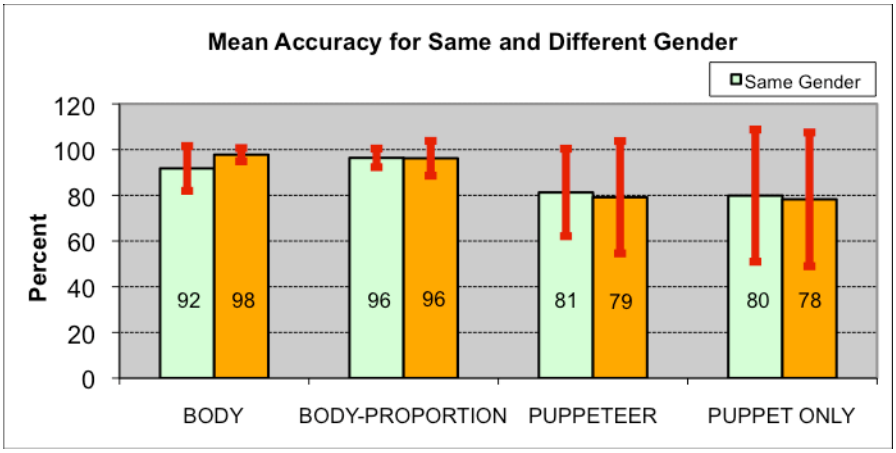
### *3.2.1 Accuracy*

Participants showed high levels of identification in all studies. All accuracy measures were significantly above chance level. The mean proportions of correct identifications are as follows: body condition: 95.71 (SD = 3.49, $\chi^2 = 296.51$, $p < 0.00001$); body proportion condition: 94.71 (SD = 5.42, $\chi^2 = 283.22$, $p < 0.00001$); puppet and puppeteer condition: 84.33 (SD = 18.36, $\chi^2 = 177.86$, $p < 0.00001$); puppet only condition: 82 (SD = 23.5, $\chi^2 = 182.73$, $p < 0.00001$) (see Figure 2). The high standard deviations in the last two conditions are due to one participant performing very poorly, averaging 40% and 31.6% correct scores, and another participant scoring 100%.

**Figure 2** (a) The average percentage of correct results for all tests across all four study trials; (b) the average percentage of correct results for same and different gender tests across all four study trials (see online version for colours)



(a)



(b)

### *3.2.2 Gender*

Previous experiments have shown that people can accurately recognise the gender of a point-walker (Cutting and Kozlowski, 1977). So it is possible that in trials where the two videos showed participants with different gender, people made the recognition decision by recognising the other person's gender and then eliminating that video. To check whether this occurred, we analysed the data based on the same/different gender in the video. The proportion of correct identifications for same gender trials and different gender trials were extracted for each condition and compared using *T*-tests ($p < 0.05$). No significant differences were found between the two cases. The lack of significant difference between the two gender combinations indicates that the self-identification was based on a simulation of the movements seen on video, rather than a logic-based elimination process.

### *3.3 Discussion*

These studies revealed that players can project and identify their own body movements in an abstracted character representation in a 2D video image. That is, participants were able to identify their own movements even if the self-representation is reduced to abstracted movements of points of light. Moreover, they were able to recognise their own performance even in the abstracted video images of a secondary puppet. This data suggests that if players control a secondary puppet (like a hand puppet, see Figure 1) and we track this puppet's movements, they are still capable of identifying their own movements from an abstracted video image of the puppet's movements. Given these supportive results, we designed a full-body puppet interface to transfer a player's own movements to a virtual 3D avatar and then examined the connection between the player and their avatar.

## 4 Self-recognition in 3D character

Building on the findings from the first experiment, a second set of experiments investigated the connection to a virtual 3D avatar acting in a game-like virtual environment. For these experiments, we designed a digital puppetry system to map a player's own body movements on to the avatar. Then, in the first phase of experiments, we recorded participants walking, tossing a ball, doing the twist and drinking using the tangible puppet interface, and tested whether they could identify their own movements in a later visit.

### *4.1 Puppet system*

To design an interface to translate body movement to a virtual character, we investigated tangible interfaces and puppet design to gain insight into existing approaches. Puppets provide a low-cost and portable approach for transferring player movements to 3D virtual characters. Puppeteering is already a dominant paradigm for current video game control mechanisms. In comparison to the level of abstraction in most commercial game controllers (gamepads, joysticks and keyboards), a puppet is tangible and can provide direct access to many degrees of freedom in the physical world, which can be mapped to a high level of granularity in the movements of the virtual characters. Another advantage of the puppeteering approach is that it can open up a space for expressive exaggeration, since puppets can be made to perform actions in the virtual world that would be unachievable with a direct mapping of the human body alone. Puppets can perform actions that are physically impossible to humans; their flexible forms and appearances open up control over non-human virtual characters; at times a puppeteer can even control multiple characters at the same time. The abstraction of a puppeteering device thus allows players to execute in virtual space actions that are impossible in real space, even as their body movements map directly onto the virtual performer. Commercially available control systems (like those used in game consoles) create a disconnect between the player's own body movement and the character movements. Even motion-controlled input devices such as the Wii controller or the Sony Move use heavily simplified mappings.

A number of past interaction research efforts have explored the use of physical interfaces for character control and animation. For example, the Monkey Input Device, an 18″ tall monkey skeleton equipped with sensors at its joints, allowed for head to toe real-time character manipulation (Esposito and Paley, 1995). Johnson's work on 'sympathetic interfaces' used a plush toy (a stuffed chicken) to manipulate and control an interactive story character in a 3D virtual world (Johnson et al., 1999). Similarly, equipped with a variety of sensors in its hands, feet and eye, the ActiMates Barney plush doll acted as a play partner for children, either in a freestanding mode or wirelessly linked to a PC or TV (Alexander and Strommen, 1998). Additionally, our own past and ongoing research has used paper hand puppets tracked by computer vision (Hunt et al., 2006) and tangible marionettes equipped with accelerometers (Mazalek and Nitsche, 2007) to control characters in the unreal game engine. However, unlike our work, none of these approaches have focused on creating a control device that can faithfully transfer a player's own body movements to a virtual avatar.

Although motion capture is dominant in recording real performances in high-end computer-generated imagery animation, some direct puppeteering controls have been implemented, too. Examples include the Waldo® telemetric input devices made by The Character Shop for controlling puppets and animatronics, and the Henson Company's real-time puppetry system which is used to perform virtual TV puppets. These systems are designed to fit a puppeteer or performer's body and the dependency on the human puppeteer's performance is seen as the reason for a puppet appearance that is 'organic and fun – it never drops into math' (Henson, 2009). According to Henson, puppets artistically maintain the 'organic' reference to the puppeteer's body, a claim we seek to examine scientifically in our experiments, which also allow examining the situations in which this connection breaks down.

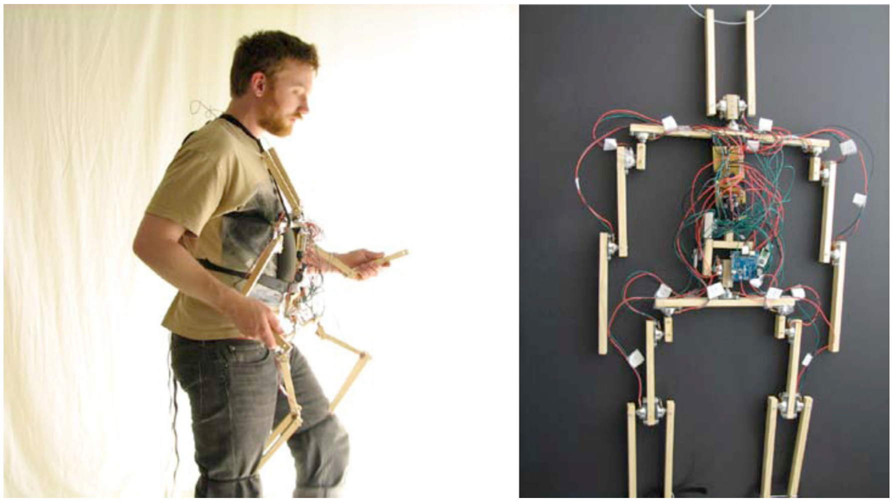
## *4.2 Implementation*

We began our puppet design process with a review of existing puppetry approaches and two main goals in mind for our own puppet. Firstly, we wanted to develop a puppet controller that would provide a high level of articulation and expressiveness in movement. Secondly, we wanted to develop a puppet that would be relatively easy to use so that it would not require the skill of a professional puppeteer to generate a range of expressions. We considered various types of the countless available techniques in puppet controls (based on Currell, 2004; Roth, 1975; Suib and Broadman, 1988), but our need to balance ease of use with level of expressivity led us to full-body puppets, which conform to the puppeteer's body configuration and allow expressions similar to body movements. We also found that hybrid puppets can help to compensate for the inverse relationship between direct contact and expression. For example, some rod-marionette puppets are attached to the body with strings. The puppeteer's hands move the rods to animate the puppet limbs, and their body moves back and forth to animate the whole puppet, giving a wider sense of control and expression. Inspired by this, we decided to create a hybrid puppet based on a full-body concept, but drawing on a combination of approaches. Such a hybrid approach provided the necessary combination of a faithful transfer of own body movements to the avatar, as well as the necessary abstraction between own movement and virtual puppet.

Our system consists of two main components, the physical interface and the 3D engine, which work together to provide an easy to use, flexible, low-cost solution for the real-time mapping of body motion on to a virtual 3D character.

The physical construction of our puppet attempts to provide a balance between comfort, flexibility and range of motion. It consists of ten joints at the knees, hips, waist, shoulders, elbows and neck to provide a wide range of expression and movement. Its feet attach to the player's knees, its head attaches to their neck and its mid-section attaches to their waist. The player's hands control the hands of the puppet (see Figure 3). In this way, the puppet can be easily controlled by both the hand and the full-body movements of the player. The puppet is built out of wooden 'bone' pieces connected with joints made of acrylic mounts and potentiometers, which act as sensors. There are 16 potentiometers across the 10 joints. Joints such as the shoulders, which rotate in two directions, contain two potentiometers oriented 90° from each other, so that the joint can rotate in each direction independently. The potentiometers are connected via a multiplexer to an Arduino Pro microcontroller attached to the chest of the puppet. The microcontroller sends the movement data to the host computer using a Bluetooth connection. A processing application on the host computer normalises the values and sends them to the rendering engine via the open sound control (OSC) protocol.

**Figure 3** (a) Player interacting with the puppet; (b) tangible interface puppet with ten joints for the knees, hips, waist, shoulders, elbows and neck (see online version for colours)



(a) (b)

The 3D renderer translates the data from the puppet into movement of an avatar in a 3D environment in real time. It is based on the Moviesandbox (MSB) application, which uses XML files to store the scenes and the settings for the characters and communicates with controllers using OSC. This allows for a very flexible usage of the renderer. MSB receives the OSC message from the processing application and maps the values onto the virtual avatar. Based on the settings for the joint rotations in the currently loaded XML character file, positions of the bones are set by MSB relative to one another using forward kinematics. In addition to character control, MSB currently supports camera placement, panning and tilting. MSB also includes advanced import functions and has basic animation recording options. Both are valuable for experimenting with different virtual puppets and comparing the animations which our puppeteers create with them.

The system provides us with a basic but highly flexible virtual puppetry engine that mimics the functionality of video game systems – in fact, its first iteration used the unreal game engine as renderer but to provide better flexibility, we moved on to an open graphics library approach.

## *4.3 Experiments*

We conducted two experiments to assess the hypothesis that a person can identify her own movement even when the movement is instantiated by an avatar. Unlike the highly abstracted video image in the previous experiments, the virtual representation here is a clear virtual body. Like most other virtual characters, this virtual body's size and shape remain uniform for all users and does not display any recognisable gender specifics (see Figure 4).

The first experiment with the new puppet design investigated participants' ability to recognise their body movement in different types of walking: normal walk, hip-walk and arm-out-walk. The second experiment analysed participants' ability to recognise their movements when they performed while standing in a fixed location. Movements here were: tossing an item, doing the twist and drinking an imaginary beverage. In both experiments, the participants used the puppetry system described above to translate their movements on to the avatar.

Each experiment involved a recording session and a recognition session. During the recording session participants performed each prototypical movement in the walking and standing sets five times. Their movements were translated into the 3D render program where they animated a virtual avatar. During this part of the experiment, participants were not able to see the animated avatar on screen. Instead, we recorded the animations for later use. There were a total of 24 participants in this study: 12 participants (6 male, 6 female) participated in the walking experiments and 12 participants (6 male, 6 female) in the standing movement experiments. None of them was an experienced puppeteer.

A week after the recording session, participants returned for recognition sessions during which they watched a series of trials, each with two video clips of a movement (see Figure 4). The recognition session closely followed the protocol used by previous studies in experimental psychology (Beardsworth and Buckner, 1981; Cutting and Kozlowski, 1977; Knoblich and Flach, 2001; Knoblich and Prinz, 2001). For the first experiment (walking), one clip showed the participant's own action (say, hip-walk) and the adjacent one showed the same action performed by another participant. The participant was asked to identify which video displayed her own action. There were 33 trials for each movement type (walk, hip-walk and arm-out-walk), making a total of

99 trials. The 99 trials were presented together, but in blocks of three walk first, followed by hip-walk and then arm-out-walk. This sequence of three trials was repeated in such a way that participants never saw the same movement in succession.

To avoid any patterning during the individual video trial, the program picked a random video clip of the participant from a list and another random video clip from a list of others making the same movement. The location on the screen where these two animations were presented (left, right) was also random. Participants were asked to press ‘P’ if they thought their video clip was on the right and ‘Q’ if they thought it was on the left. The videos looped until the participant made a choice. The video presentation program kept track of the randomisations of files and locations, the key press responses of participants and the time it took for a participant to respond.

The second experiment followed the same design, except that the participant viewed the standing movements. The recognition session followed the same pattern as the walk experiment. All the 99 trials were presented together. The order of presentation of the video trials were toss, twist and drink, with this pattern repeating 33 times.

## *4.4 Results*

For each participant, we computed the proportion of correct self-identifications (see Figure 5). Since the guessing probability is 0.5, values significantly greater than 0.5 indicate that participants recognised their own movement.

**Figure 4** Stills of the 3D avatar in the walking movements ((a) walk, (b) hip-walk and (c) arm-out-walk) and in the fixed position movements ((d) toss, (e) twist and (f) drink) (see online version for colours)

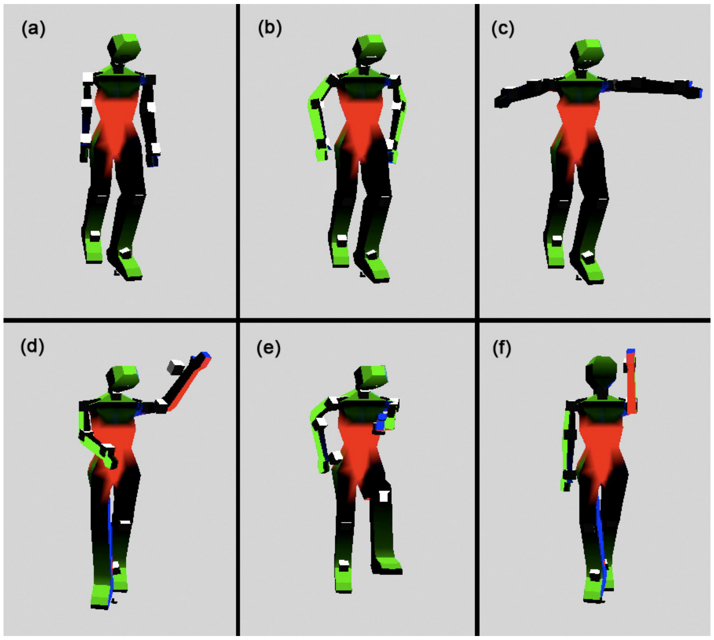
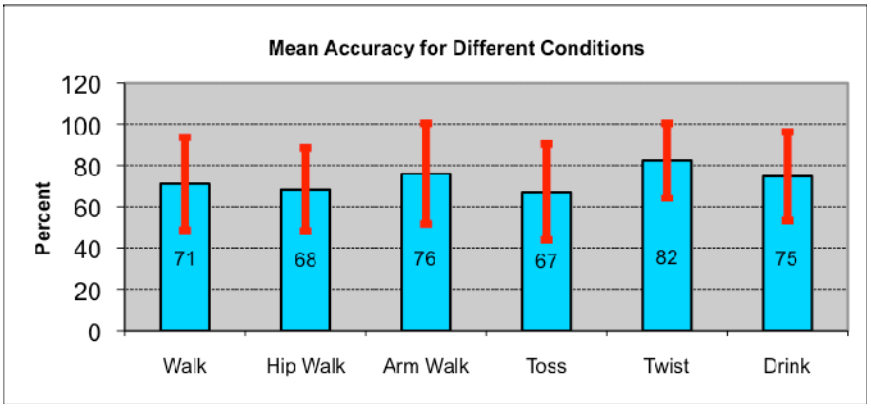


**Figure 5** The average percentage of correct results across all six study trials (see online version for colours)

| | Percent Correct | SD |
|---|---|---|
| **Walk** | 71.21 | 22.55 |
| **Hip Walk** | 68.43 | 20.20 |
| **Arm Walk** | 76.01 | 24.36 |
| **Toss** | 67.17 | 23.29 |
| **Twist** | 82.32 | 18.04 |
| **Drink** | 74.75 | 21.48 |



Participants showed high levels of identification in both experiments. All accuracy measures were significantly above chance level. The mean proportions of correct identifications for the walk experiment were as follows: walk: 71.21 (SD = 22.54, $\chi^2 = 72.54$, $p < 0.001$); hip-walk: 68.43 (SD = 20.20, $\chi^2 = 56.54$, $p < 0.001$); arm-out-walk: 76.01 (SD = 24.36, $\chi^2 = 96.66$, $p < 0.001$). The mean proportions of correct identifications for the no-walk experiment were as follows: toss: 67.17 (SD = 23.28, $\chi^2 = 62.72$, $p < 0.001$); twist: 82.32 (SD = 18.03, $\chi^2 = 106.36$, $p < 0.001$); drink: 74.74 (SD = 21.47, $\chi^2 = 82.00$, $p < 0.001$). The high standard deviations suggest significant individual differences and follow the pattern in our previous experiment and other studies in the literature.

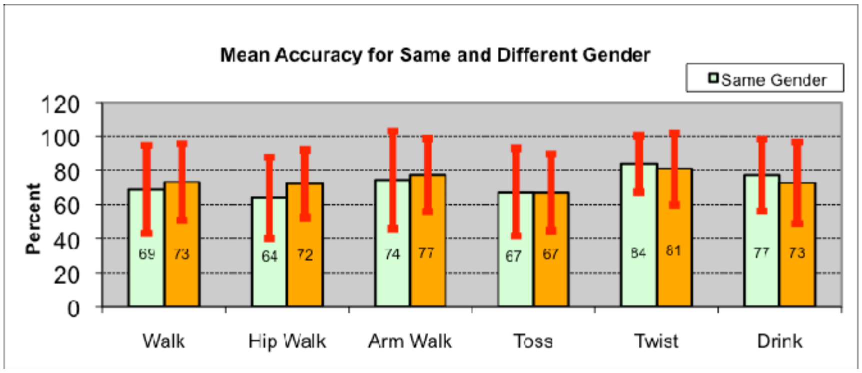
Since previous experiments have shown that people can accurately recognise the gender of a point-walker (Cutting and Kozlowski, 1977), it is possible that in trials where the two videos showed participants with different gender, people made the recognition decision by recognising the other person's gender and then eliminating that video. To check whether this occurred, we analysed the data based on the same/different gender in the video. The proportion of correct identifications for same gender trials and different gender trials were extracted for each condition (see Figure 6). Performance for different gender was higher only in the walk experiment; in the no-walk experiment, same gender scored higher. Even in the walk condition, the differences were not very large. For walk, we noticed less than a 5% difference and for arm-out-walk less than a 3% difference. For hip-walk, there was an 8.33% rise in performance. It is possible that this difference is based on the above proposed logical mode of recognition. However, the lack of a pattern across the two experiments and the absence of a performance advantage in the other two walk conditions suggest that the self-identification was based on a simulation of the movements seen on video, rather than a logic-based elimination process. Further supporting this view, our previous video-based study showed no effect of gender in recognition decisions.

## 4.5 Discussion

Overall, the results show that players/puppeteers can recognise their own movements if they are transferred to an avatar using a puppet interface. The recognition rate is not as high as the recognition of own body movements in a point-light-walker video (~95%), but is comparable to the self-recognition of a point-light-animation recorded from the movements of a hand puppet operated by a non-professional puppeteer (~80%) that we observed in our first experiment. The difference between the hand puppet movement recognition and the more complex hybrid marionette recognition presented in this Section could be explained by the unfamiliarity with the interface. Both the hybrid puppet and the avatar are currently at a prototype stage and still limited in their expressive range. In contrast, the hand puppet appeared to be more familiar to most participants. The avatar we used is androgynous and cannot really display walking in space. Point-light-walkers display walking in space and they also display smoother movements. We believe that the recognition levels could be raised further by improving the avatar's visual presentation and movement patterns and by optimising the physical interface to be more comfortable and easy to use.

**Figure 6** The average percentage of correct results for same and different gender tests across all six study trials. The recognition of walking movements is slightly higher when the genders are different (see online version for colours)

| | Same Gender | SD | Different Gender | SD |
|---|---|---|---|---|
| **Walk** | 68.89 | 25.95 | 73.15 | 22.58 |
| **Hip Walk** | 63.89 | 23.86 | 72.22 | 19.82 |
| **Arm Walk** | 74.44 | 28.69 | 77.31 | 21.38 |
| **Toss** | 67.22 | 25.66 | 67.13 | 22.41 |
| **Twist** | 83.89 | 16.44 | 81.02 | 21.12 |
| **Drink** | 77.22 | 20.98 | 72.69 | 23.86 |



These results indicate an effective translation of self to the avatar using the puppet interface, suggesting that we indeed project ourselves to the movements of 3D virtual characters whose movements derive in second order from our own body memory, probably through a common coding system. We believe these results could be exploited to develop new media, new interfaces and also new applications for video game and digital media, particularly in the medical field. To begin investigating the potential applications of our results, we designed and conducted a set of experiments to compare our interface to other standard video game control interfaces.

## 5 Evaluating the effect of self-recognition in virtual environments

Having found that the puppet interface is effective in personalising an avatar by transferring a player's own movements to the virtual character, we were interested in examining the performance of the puppet as a control interface, in comparison to standard video game control interfaces. Specifically, we looked at:

1. whether the puppet interface facilitates player performance by providing more accurate responses when controlling their virtual avatar
2. whether perceiving a 'personalised' video game character executing slow full-body rotation movements not executable by the player leads to improved cognitive performance in the player, specifically performance in a mental rotation task.

### *5.1 Experiment design*

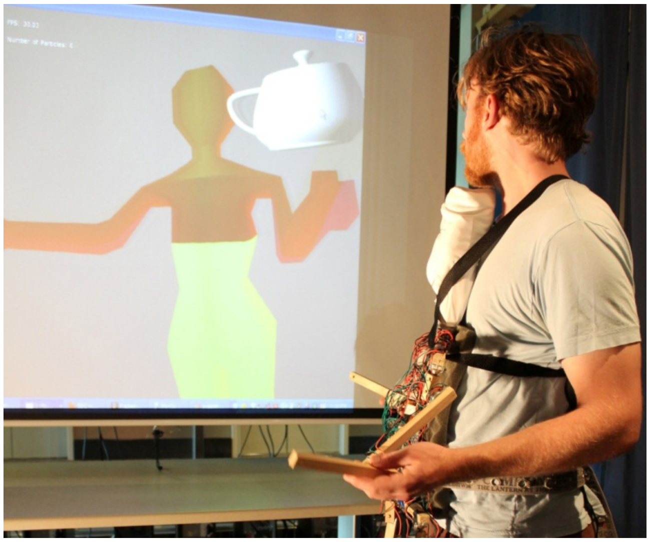
To examine the first question, we needed a 'neutral' task, different from standard tasks seen in games, because if game-related tasks are used, expert game players would perform at high levels and possibly skew the data towards standard interfaces. Further, the puppet interface affords novel forms of interactions within video games, and we therefore wanted to develop a task not commonly seen in standard video game interactions. To examine the second question, we needed a task where the user imagined movements not commonly executed in the real world, so that we could examine the effects this imagination had on cognition in isolation from any previous motor training.

Based on these goals and constraints, we developed a game where players see virtual objects (teapots) appear in proximity to their 3D avatar, and they have to make the avatar touch these objects using the appropriate interface (puppet, game controller or keyboard; see below for details). The teapots appear randomly at different points near the avatar, and players have to move their hands or feet to make the avatar touch the teapot. Table 1 shows the mappings between the keyboard and Xbox controllers and the movements of the virtual avatar. Figure 7 shows a person playing the virtual contact game using the puppet interface.

**Table 1** Mappings between the keyboard/Xbox controllers and the virtual character movements

| | *Arm/leg toggle* | *Shoulder/hip movement* | *Knee/elbow bending* |
|---|---|---|---|
| Keyboard | F (left) | W,A,S,D (left) | Q,E (left) |
| | H (right) | I,J,K,L (right) | U,O (right) |
| Xbox | Click joysticks (left/right) | Move joysticks (left/right) | Triggers (left/right) |

**Figure 7** Playing the virtual contact game with the full-body puppet controller (see online version for colours)



To make the game 'neutral' and also to investigate the self-projection and mental rotation abilities, we added a special camera behaviour to this game task. The camera slowly rotates around the avatar in an unpredictable manner, making the avatar float in space in different orientations. This apparent movement of the avatar forces the players to reconsider the position and orientation of the virtual avatar in relation to the interface strapped to their bodies and the virtual teapots they have to touch. Once touched, each teapot disappears and a new one appears in a different location. The player's goal is to touch as many teapots as possible in the time provided (13 min). The number of teapots touched and the time at which each teapot is touched are tracked by the system.

The study involved 30 participants playing the virtual contact game and completing mental rotation tests. The participants were pseudo-randomly assigned (our only constraint was having equal *n* across the conditions) to one of the three interfaces: puppet, Xbox controller and keyboard. There were thus 10 participants per interface, of which 50% were female (i.e. 5 per condition or 15 overall).

The two components of the study (teapot touching and mental rotation) were conducted within a single session. The participant was first asked to complete two sessions of a standard mental rotation test. After this, the participant was asked to play the virtual contact game using one of the three control interfaces. After they had played the game for 13 min, participants completed another two sessions of the mental rotation task.

The first research question (whether the puppet interface facilitates player performance) is answered by counting the number of teapots touched by each interface group. The second research question (whether 'personalised' virtual characters help to improve cognitive performance) is answered by looking at the pre-/post-performance by each group in the mental rotation task.

### *5.2 Mental rotation*

Recent research has shown that playing video games has cognitive effects, such as improvement in attention, spatial ability and mental rotation (Feng et al., 2007; Green and Bavelier, 2003). Similarly, Wexler and van Boxtel (2005) showed that manipulating virtual objects improves subsequent mental rotation and recognition of such objects. Based on these and our previous findings, we wanted to examine whether interacting with an avatar using an embodied interface led to any improved cognitive effects, primarily with respect to mental rotation ability, compared to interactions based on standard control interfaces. The benefits reported in the studies mentioned above developed while the players used traditional interfaces such as keyboards and controllers. We believe these cognitive benefits could be enhanced through embodied interfaces that more faithfully immerse the user in the virtual environment. To examine this prediction, we had players complete the mental rotation task described below before and after interacting with the avatar using one of the interfaces (puppet, Xbox and keyboard). We compared the accuracy and time taken for their responses in the mental rotation task across the three interface conditions.

#### *5.2.1 Stimuli*

Three small 2D patterns, within a white square (frame), prepared on a 3 × 3 matrix with only five cells being filled. One such pattern is illustrated in Figure 8(b). The visual angle was 1.5° × 1.5°. Each of these patterns were altered by rotating the original three patterns by 90°, 180° or 270°, creating three more patterns. In a particular trial, one of the possible four orientations of a particular stimulus pattern was randomly used as the stimulus.

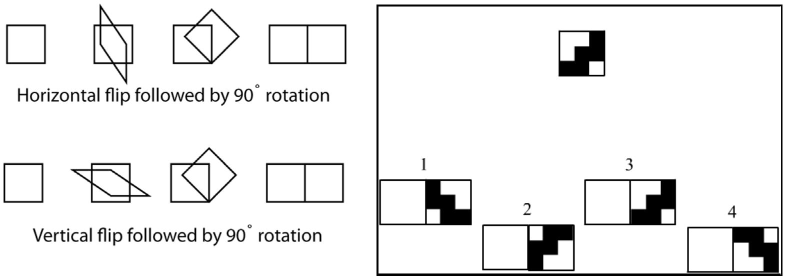
A second set of stimuli were the rotational operations (8 altogether, 4 × left/right directions; see Figure 8(a)). The rotation had two levels of complexity, low (rotations of 90°, right and left; and 180°, right and left) or high (vertical and horizontal flips followed by a rotation of 90°, left or right). The operations were demonstrated using video clips. Low complexity videos took 20 sec to display, while high complexity videos took 42 sec (each flip operation took 20 sec, each rotation operation took another 20 sec and there was a 2 sec gap between flip and rotation). The end position (frame) stayed for 5 sec after the rotational operation.

#### *5.2.2 Procedure*

Twenty-four trials (8 operations × 3 patterns) were presented randomly. For each trial, a rotation video clip was shown. Participants were asked to remember the rotation in the clip, apply the same operation on the pattern coming up in the next phase and then select the answer that best fitted their mental rotation of the pattern.

The next phase started after 2 sec (screen blank). A pattern to be mentally rotated was presented, along with four possible answers (as shown in Figure 8(b)). The answers remained on screen until participants produced a response, by typing 1, 2, 3 or 4. This initiated the next trial after 2 sec. Participants were presented 48 trials (two 24-trial blocks) before and after the virtual contact game.

**Figure 8** (a) Two of the rotation operations used in the mental rotation task; (b) example decision screen in which one of the bottom figures shows the top pattern rotated in the sequence displayed in a short video beforehand. The task is to pick the correct option



(a) (b)

### 5.3 Results

To determine if the puppet device has performance advantages over the more conventional devices, we analysed the mean number of successful teapot contacts using a one-way between-subjects ANOVA (alpha set at 0.05). *Post-hoc* analysis of the significant effect ($F(2, 27) = 5.87$; $p < 0.01$) using paired $t$-tests ($p < 0.05$) revealed significant advantages for the puppet and Xbox controllers over the keyboard in both contacts and time. Performance advantages of the puppet over the Xbox controller, although numerically large, only tended towards statistical reliability ($t(18) = 1.17$, $p < 0.24$; see Figure 9). Despite the absence of a statistically reliable difference, effect size calculations of the differences between puppet and Xbox controllers were in the medium range (Cohen's $d = 0.52$) suggesting important functional and practical differences in performance.

The influence of the different task conditions on the mental rotation task was assessed by submitting accuracy and response time on the mental rotation tasks to a 3 (group: puppet, Xbox and keyboard) by 2 (test: pre, post) mixed ANOVA. The main effect for test ($F(2, 27) = 11.27$, $p < 0.01$) revealed that, as a whole, participants improved in accuracy in the mental rotation task following the experience with the teapot game. Specific planned comparisons of the accuracy of the different groups in the pre- and post-tests using paired $t$-tests revealed that this increase in accuracy was driven by the performance of the puppet group. That is, of all the three groups, the puppet group demonstrated the largest improvement and was the only group to demonstrate a statistically reliable improvement in performance ($t(9) = 2.68$, $p < 0.05$). Improvements in the Xbox ($t(9) = 2.00$, $p > 0.07$) and keyboard ($t(9) = 1.37$, $p > 0.20$) were not significant. Further, effect size for the improvement following the puppet controller was in the medium range ($d = 0.61$) but were in the small range following the Xbox ($d = 0.28$) and keyboard ($d = 0.46$) interfaces (Table 2). The absence of similar between group differences in response time suggests that these improvements were not the results of a speed-accuracy trade-off in which the puppet group performed more accurately because they took more time to complete the task in the post-test. Thus, consistent with our hypothesis, it seems that the more consistent perceptual-motor mapping afforded by the puppet interface had facilitatory influence on the users' cognitive capabilities.

**Figure 9** The average number of teapots touched across the three conditions (puppet, Xbox and keyboard)

| | **Puppet** | **Xbox** | **Keyboard** |
|---|---|---|---|
| **Contacts** | 123.9 | 90.6 | 41.1 |
| **SD** | 74.1 | 50.74 | 28.33 |

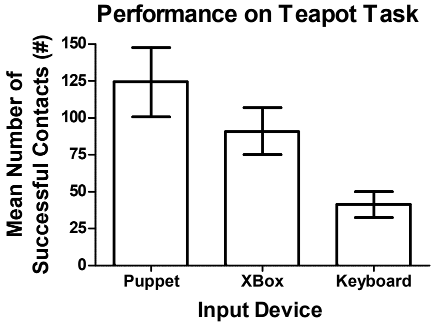


**Table 2** Mean accuracy and speed improvement in the mental rotation task across the three conditions (puppet, Xbox and keyboard)

| | *Puppet* | | *Xbox* | | *Keyboard* | |
|---|---|---|---|---|---|---|
| | *Pre* | *Post* | *Pre* | *Post* | *Pre* | *Post* |
| Accuracy | 15.1 | 19.0 | 15.5 | 17.4 | 16.5 | 18.8 |
| SD | 6.2 | 6.6 | 7.1 | 6.5 | 4.8 | 5.2 |
| Time | 11.9 | 7.2 | 9.43 | 7.1 | 14.38 | 10.5 |
| SD | 3.7 | 2.7 | 3.7 | 3.5 | 7.3 | 7.8 |

## *5.4 Discussion*

Overall, the experiment showed that the embodied puppet interface improved accuracy in the virtual contact game, compared to Xbox and keyboard interfaces. Participants performed the task better using the more embodied interface. This finding points to the value of embodied interfaces for the development of more personalised and less restricted interaction with virtual worlds (like video games). Almost all participants who used the puppet interface commented on its ease of use, and many found it to be a fun and novel way of interacting with the avatar. If interaction design deviates from the still dominating level of abstraction, then interfaces like ours offer the necessary opportunities for participation and involvement.

Consistent with previous research (Feng et al., 2007; Green and Bavelier, 2003), the embodied interaction in the virtual contact game improved accuracy in mental rotation as well. Further experiments are required to examine this effect more clearly, but the results demonstrate a positive effect of the puppet interface. One element that might influence the results here is the fact that the puppet interface, even though it was generally perceived as relatively unobtrusive and engaging, presents a completely new interface to the test participants. None of the test participants was a trained puppeteer. In comparison, it can be assumed that the Xbox controller and especially the keyboard are much more familiar. It could, thus, be projected that the puppet interface would perform even better once users get used to it.

It is worth noting here that our experiments provide further support for the common coding model, as they show that the self-recognition effect is robust and transfers well to movements executed by puppets controlled by oneself, and characters that encode the movements of the puppets. These results point at the role of the common code in the brain's ability to 'appropriate' an external artefact/tool, to create a smooth extension of the body. The improvement in mental rotation also supports the common coding model.

## 6 Conclusion and future work

The research presented here illustrates ongoing work at the interface between basic science and technology development in the application of common coding theory to virtual character control through tangible interfaces. It is part of our larger and ongoing project investigating the value of tangible user interfaces and virtual characters to augment a user's body memory gradually, by exploiting the common coding system and the self-recognition effects that derive from this common code. We have presented our implementation of a tangible puppet interface and 3D virtual environment tailored to optimise the mapping between player and virtual avatar, and a set of experiments that demonstrate that players can recognise their own movements in a virtual character. They could do this when their movements were presented alongside others' movements offline (i.e. in an experimental setting and not when they were playing the game using the puppet). Also, the players did not observe their movements being transferred to the avatar and the recognition occurred after a week of the transfer. The recognition effect is thus quite robust. We have, thus, clearly demonstrated that our puppet interface design supports players' self-recognition in a 3D virtual character. We also showed that playing a novel video game using the puppet interface improves mental rotation abilities, which is a crucial component of creative thinking in science and engineering (Nersessian, 2008). Based on these results, we are conducting an additional set of experiments to examine whether controlling the avatar using our puppet interface leads to better artistic performance (e.g. in the context of making sketches) of the player in comparison to other interfaces (such as game controllers and keyboards). Such an effect, consistent with the mental rotation effect, could lead to developing video game-based applications in education and scientific research, like the recent protein-folding game *Foldit*.

The work reported here presents the possibility that the connection between self and virtual avatar, enabled by the puppet interface, could be used as a channel to transfer novel movements executed by the character on screen back to the player. This is made possible by the common coding between perception of movements and imagination/execution of movements. This channel could also be used to create opportunities for players to shape their own identities in virtual worlds, as well as their notion of self in the real world. This possibility presents a range of potential applications, particularly in the development of social skills through role-playing and increased empathy. A related application is medical rehabilitation for patients with movement disorders and also possibly disorders of volition like schizophrenia, where the common coding system is considered to be damaged (Frith, 2006). In work supporting this view, it has been shown that an increased self-presence can positively affect the educational impact of digital environments (Annetta et al., 2010), improve exercise behaviour (Fox and Bailenson, 2009) and support neurocognitive rehabilitation (Panic, 2010). Our current experiments examine whether perceiving a 'personalised' video game character executing novel body movements can help a player's regain motor function lost due to stroke.

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## References

Alexander, K. and Strommen, E. (1998) 'Evolution of the talking dinosaur: the (not so) natural history of a new interface for children', in *CHI 98 Conference Summary on Human Factors in Computing Systems*. New York, NY: ACM, pp.7–8.

Annetta, L.A., Folta, E. and Klesath, M. (2010) *V-learning: Distance Education in the 21st Century Through 3D Virtual Learning Environments*. Dordrecht, Heidelberg, London, New York: Springer.

Barsalou, L., Simmons, W., Barbey, A. and Wilson, C. (2003) 'Grounding conceptual knowledge in modality-specific systems', *Trends in Cognitive Sciences*, Vol. 7, pp.84–91.

Beardsworth, T. and Buckner, T. (1981) 'The ability to recognize oneself from a video recording of one's movements without seeing one's body', *Bulletin of the Psychonomic Society*, Vol. 18, No. 1, pp.19–22.

Bosbach, S., Cole, J., Prinz, W. and Knoblich, G. (2005) 'Understanding another's expectation from action: the role of peripheral sensation', *Nature Neuroscience*, Vol. 8, pp.1295–1297.

Brass, M. and Heyes, C. (2005) 'Imitation: Is cognitive neuroscience solving the correspondence problem?', *Trends in Cognitive Sciences*, Vol. 9, No. 10, pp.489–495.

Casile, A. and Giese, M.A. (2006) 'Non-visual motor learning influences the recognition of biological motion', *Current Biology*, Vol. 16, No. 1, pp.69–74.

Chandrasekharan, S. (2009) 'Building to discover: a common coding model', *Cognitive Science*, Vol. 33, pp.1059–1086.

Chandrasekharan, S., Mazalek, A., Chen, Y., Nitsche, M. and Ranjan, A. (2010) 'Ideomotor design: using common coding theory to derive novel video game interactions', *Pragmatics & Cognition*, Vol. 18, No. 2, pp.313–339.

Currell, D. (2004) *Making and Manipulating Marionettes*. UK: Crowood Press.

Cutting, J.E. and Kozlowski, L.T. (1977) 'Recognizing friends by their walk: gait perception without familiarity cues', *Bulletin of the Psychonomic Society*, Vol. 9, pp.353–356.

Damasio, A.R. (1994) *Descartes' Error: Emotion, Reason, and the Human Brain*. New York: G.P. Putnam.

Decety, J. and Jackson, P.L. (2006) 'A social-neuroscience perspective on empathy', *Current Directions in Psychological Science*, Vol. 15, No. 2, pp.54–58.

Dourish, P. (2001) *Where The Action Is: The Foundations of Embodied Interaction*. Cambridge, MA: MIT Press.

Ehrsson, H.H. (2007) 'The experimental induction of out-of-body experiences', *Science*, Vol. 317, No. 5841, p.1048.

Esposito, C. and Paley, W.B. (1995) 'Of mice and monkeys: a specialized input device for virtual body animation', in *Proceedings of the 1995 Symposium on Interactive 3D Graphics*, ACM, New York, NY, pp.109–114.

Feng, J., Spence, I. and Pratt, J. (2007) 'Playing an action video game reduces gender differences in spatial cognition', *Psychological Science*, Vol. 18, pp.850–855.

Fox, J. and Bailenson, J.N. (2009) 'Virtual self-modeling: the effects of vicarious reinforcement and identification on exercise behaviors', *Media Psychology*, Vol. 12, No. 1, pp.1–25.

Frith, C. (2006) 'Interpersonal factors in the disorders of volition associated with schizophrenia', in N. Sebanz and W. Prinz (Eds.), *Disorders of Volition*. Cambridge, MA: MIT Press, pp.233–248.

Gibbs, R.W. (2006) *Embodiment and Cognitive Science*. New York: Cambridge University Press.

Girard, R. and Doran, R. (2008) *Mimesis and Theory: Essays on Literature and Criticism, 1953–2005*. Stanford, CA: Stanford University Press.

Green, S. and Bavelier, D. (2003) 'Action video game modifies visual selective attention', *Nature*, Vol. 423, pp.534–537.

Henson, B. (2009) 'Keeping it real', *American Theatre*, pp.56–60.

Hommel, B., Müsseler, J., Aschersleben, G. and Prinz, W. (2001) 'The theory of event coding (tec): a framework for perception and action planning', *Behavioral and Brain Sciences*, Vol. 24, pp.849–878.

Hunt, D., Moore, J., West, A. and Nitsche, M. (2006) 'Puppet show: intuitive puppet interfaces for expressive character control', in *Medi@terra 2006, Gaming Realities: A Challenge for Digital Culture*, Athens, 4–8 October 2006, pp.159–167.

Ito, M. (1993) 'Movement and thought: identical control mechanisms by the cerebellum', *Trends in Neurosciences*, Vol. 16, No. 11, pp.448–450.

Johnson, M.P., Wilson, A., Blumberg, B., Kline, C. and Bobick, A. (1999) 'Sympathetic interfaces: using a plush toy to direct synthetic characters', in *Proceedings of Human Factors in Computing Systems*. New York, NY: ACM, pp.152–158.

Knoblich, G. and Flach, R. (2001) 'Predicting the effects of actions: interactions of perception and action', *Psychological Science*, Vol. 12, No. 6, pp.467–472.

Knoblich, G. and Prinz, W. (2001) 'Recognition of self-generated actions from kinematic displays of drawing', *Journal of Experimental Psychology: Human Perception and Performance*, Vol. 27, No. 2, pp.456–465.

Knoblich, G. and Sebanz, N. (2006) 'The social nature of perception and action', *Current Directions in Psychological Science*, Vol. 15, pp.99–104.

Lenggenhager, B., Tadi, T., Metzinger, T. and Blanke, O. (2007) 'Video ergo sum: manipulating bodily self-consciousness', *Science*, Vol. 317, No. 5841, pp.1096–1099.

Mazalek, A., Chandrasekharan, S., Nitsche, M., Welsh, T., Thomas, G., Sanka, T. and Clifton, P. (2009) 'Giving your self to the game: transferring a player's own movements to avatars using tangible interfaces', in *Sandbox 2009: ACM SIGGRAPH Videogame Symposium*. New York, NY: ACM, pp.161–168.

Mazalek, A. and Nitsche, M. (2007) 'Tangible interfaces for real-time 3D virtual environments', in *Proceedings of the International Conference on Advances in Computer Entertainment Technology*. New York, NY: ACM, Vol. 203, pp.155–162.

Nersessian, N.J. (2008) *Creating Scientific Concepts*. Cambridge, MA: MIT Press.

Oberman, L.M., Hubbard, E.M., McCleery, J.P., Altschuler, E.L., Ramachandran, V.S. and Pineda, J.A. (2005) 'EEG evidence for mirror neuron dysfunction in autism spectrum disorders', *Cognitive Brain Research*, Vol. 24, pp.190–198.

Panic, A.S. (2010) 'Addressing patient motivation in virtual reality based neurcognititve rehabilitation', BA Thesis, Electrical Engineering, Hogere Technische School Arnheim, Arnheim.

Prinz, W. (2005) 'An ideomotor approach to imitation', in S. Hurley and N. Chater (Eds.), *Perspectives on Imitation: From Neuroscience to Social Science*. Cambridge, MA: MIT Press, Vol. 1, pp.141–156.

Roth, D. (1975) *The Art of Making Puppets and Marionettes*. Radnor, PA: Chilton Book Company.

Schneider, W.X. (2006) 'Action control and its failure in clinical depression: a neuro-cognitive theory', in N. Sebanz and W. Prinz (Eds.), *Disorders of Volition*. Cambridge, MA: MIT Press.

Suib, L. and Broadman, M. (1988) *Marionettes: How to Make and Perform with Them*. New York: Dover Publications.

Wexler, M. and van Boxtel, J.J.A. (2005) 'Depth perception by the active observer', *Trends in Cognitive Sciences*, Vol. 9, pp.431–438.

Wilson, N.L. and Gibbs, R.W. (2007) 'Real and imagined body movement primes metaphor comprehension', *Cognitive Science*, Vol. 31, pp.721–731.