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Robotic Embodiment Developing a System for and Applications with Full Body Ownership of a Humanoid Robot

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PhD thesis presented by
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Robotic Embodiment - Developing a System for and Applications with Full Body Ownership of a Humanoid Robot

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Abstract

It has been shown that with appropriate multisensory stimulation an illusion of owning an artificial object as part of their own body can be induced in people. Such body ownership illusions have been shown to occur with artificial limbs, such as rubber hands, and even entire artificial or virtual bodies. Although extensive research has been carried out regarding full body ownership illusions with mannequins and virtual bodies, few studies exist that apply this concept to humanoid robots. On the other hand, extensive research has been carried out with robots in terms of telepresence and remote manipulation of the robot, known as teleoperation. Combining these concepts would give rise to a highly immersive, embodied experience in a humanoid robot located at a remote physical location, which holds great potential in terms of real-world applications.

In this thesis, we aim to apply this phenomenon of full body ownership illusions in the context of humanoid robots, and to develop real-world applications where this technology could be beneficial. More specifically, by relying on knowledge gained from previous studies regarding body ownership illusions, we investigated whether it is possible to elicit this illusion with a humanoid robot. In addition, we developed a system in the context of telepresence robots, where the participant is embodied in a humanoid robot that is present in a different physical location, and can use this robotic body to interact with the remote environment. To test the functionality of the system and to gain an understanding of body ownership illusions with robots, we carried out two experimental studies and one case-study of a demonstration of the system as a real-world application.

In the **Brain-Computer Interface versus Eye Tracker study**, we used our system to investigate whether it was possible to induce a full body ownership illusion over a humanoid robot with a highly ‘robotic’ appearance. In addition, we compared two different abstract methods of control, a Steady-State Visually Evoked Potential (SSVEP) based Brain-Computer Interface and eye-tracking, in an immersive environment to drive the robot. This was done mainly as a motivation for developing a prototype of a system that could be used by disabled patients. Our results showed that a feeling of body ownership illusion and agency can be induced, even though the postures between participants and the embodied robot were incongruent (the participant was sitting, while the robot was

standing). Additionally, both BCI and eye tracking were reported to be suitable methods of control, although the degree of body ownership illusion was influenced by the control method, with higher scores of ownership reported for the BCI condition.

In the **Tele-Immersive Journalism** case study, we used the same system as above, but with the added capability of letting the participant control the robot body by moving their own body. Since in this case we provided synchronous visuomotor correlations with the robotic body we expected this to result in an even higher level of body ownership illusion. By making the robot body the source of their associated sensations we simulate a type of virtual teleportation. We applied this system successfully to the context of journalism, where a journalist could be embodied in a humanoid robot located in a remote destination and carry out interviews through their robotic body. We provide a case-study where the system was used by several journalists to report news about the system itself as well as for reporting other stories.

In the **Multi-Destination Beaming** study, we extended the functionality of the system to include three destinations. The aim of the study was to investigate whether participants could cope with being in three places at same time, and embodied in three different surrogate bodies. We had two physical destinations with one robot in each, and a third virtual destination where the participant would be embodied in a virtual body. The results indicate that the system was physically and psychologically comfortable, and was rated highly by participants in terms of usability in real world. Additionally, high feelings of body ownership illusion and agency were reported, which were not influenced by the robot type. This provides us with clues regarding body ownership illusion with humanoid robots of different dimensions, along with insight about self-localisation and multilocation.

Overall, our results show that it is possible to elicit a full body ownership illusion over humanoid robotic bodies. The studies presented here advance the current theoretical framework of body representation, agency and self-perception by providing information about various factors that may affect the illusion of body ownership, such as a highly robotic appearance of the artificial body, having indirect methods of control, or even being simultaneously embodied in three different bodies. Additionally, the setup described can also be used to great effect for highly immersive remote robotic embodiment applications, such as one demonstrated here in the field of journalism.

Resumen

Se ha demostrado que con la estimulación multisensorial adecuada es posible inducir la ilusión de apropiación de un objeto artificial como parte del propio cuerpo. Tales ilusiones de apropiación corporal han demostrado ser posibles sobre extremidades artificiales, como por ejemplo manos de goma, e incluso cuerpos enteros tanto artificiales como virtuales. Aunque se ha llevado a cabo una amplia investigación acerca de las ilusiones de apropiación corporal con maniquís y cuerpos virtuales, existen pocos estudios que apliquen este concepto a robots humanoides. Por otro lado, se ha llevado a cabo investigación extensa con robots por lo que respecta a la telepresencia y la manipulación remota del robot, también conocida como teleoperación. Combinar estos conceptos da lugar a una experiencia inmersiva de encarnación en un robot humanoide localizado en una posición física remota, cosa que acarrea un gran potencial por lo que respecta a las aplicaciones del mundo real.

En esta tesis, pretendemos aplicar el fenómeno de las ilusiones de apropiación corporal al contexto de los robots humanoides, y desarrollar aplicaciones en el mundo real donde esta tecnología pueda ser beneficiosa. Más concretamente, mediante el conocimiento adquirido en los estudios previos relacionados con las ilusiones de apropiación corporal, investigamos si es posible inducir esta ilusión sobre un robot humanoide. Además, desarrollamos un sistema dentro del contexto de robots de telepresencia, donde el participante encarna un robot humanoide que está presente en una localización física diferente a la del participante, y puede usar el cuerpo robótico para interactuar con el entorno remoto. Con el objetivo de probar la funcionalidad del sistema y avanzar en el conocimiento de las ilusiones de encarnación corporal con robots, hemos llevado a cabo dos estudios experimentales y un caso práctico de una demostración del sistema como aplicación en el mundo real.

En el estudio **Interfaz Cerebro-Ordenador contra Rastreador Ocular**, usamos nuestro sistema para investigar si era posible inducir una ilusión de apropiación corporal sobre un robot humanoide con una apariencia altamente 'robótica'. Además, comparamos dos métodos abstractos de control diferentes, una interfaz cerebro-computadora (Brain-Computer Interface, BCI) basada en potenciales evocados visuales de estado estable (Steady-State Visually Evoked Potential, SSVEP) y un rastreador ocular, en un entorno inmersivo para dirigir un robot. Este estudio se realizó como motivación para

desarrollar un prototipo de un sistema que pudiera ser usado por pacientes discapacitados. Nuestros resultados mostraron que es posible inducir una ilusión de apropiación y agencia corporal, aunque la postura del participante y la del robot sean incongruentes (el participante estaba sentado y el robot de pie). Además, tanto el método BCI como el rastreador ocular se mostraron como métodos válidos de control, aunque el grado de ilusión de apropiación corporal estuviera influenciado por el método de control, siendo la condición con BCI donde se obtuvo un mayor nivel de apropiación corporal.

En el caso práctico **Periodismo Tele-Inmersivo**, usamos el mismo sistema que el descrito anteriormente, pero con la capacidad adicional de permitir al participante controlar el cuerpo del robot mediante el movimiento de su propio cuerpo. Teniendo en cuenta que en este caso añadíamos la correlación síncrona visuomotora con el cuerpo robótico, esperamos que esto conllevara un mayor nivel de ilusión de apropiación corporal. Haciendo que el cuerpo del robot sea el origen de las sensaciones asociadas pudimos simular un tipo de teleportación virtual. Aplicamos este sistema exitosamente al contexto del periodismo, en el cual un periodista podía encarnar un robot humanoide en una destinación remota y llevar a cabo entrevistas a través de su cuerpo robótico. Aportamos un caso práctico donde el sistema fue usado por varios periodistas para informar del mismo sistema entre otras historias.

En el estudio **Multi-Destino Beaming**, ampliamos la funcionalidad del sistema incluyendo tres destinos posibles. El objetivo del estudio era investigar si los participantes podían enfrentarse al hecho de estar en tres lugares simultáneamente, y encarnar tres cuerpos sustitutos. Disponíamos de dos destinos físicos con un robot en cada uno, y un tercer destino virtual donde el participante encarnaba el cuerpo virtual. Los resultados indican que el sistema era cómodo tanto física como psicológicamente, y los participantes lo evaluaron altamente en términos de usabilidad en el mundo real. Asimismo, obtuvimos un nivel alto de ilusión de apropiación corporal y de agencia, sin ninguna influencia del tipo de robot. Esto nos provee información acerca de la ilusión de apropiación corporal con robots humanoides de dimensiones diversas, además de conocimiento sobre la propia localización y la multilocalización.

En resumen, nuestros resultados demuestran que es posible inducir una ilusión de apropiación corporal sobre cuerpos robóticos humanoides. Los estudios presentados aquí dan un paso más en el marco teórico actual de la representación corporal, la agencia y la percepción de uno mismo mediante la información adquirida sobre diversos factores que pueden afectar la ilusión de apropiación corporal, tales como la apariencia altamente robótica del cuerpo artificial, métodos indirectos de control, o incluso estar encarnado simultáneamente en tres cuerpos distintos. Además, el equipo descrito también puede ser usado en aplicaciones altamente inmersivas de encarnación robótica remota, tales como la mostrada aquí en el campo del periodismo.

Acknowledgements

My first introduction to the 'virtual' happened seven years ago, when I walked into this slightly dark room that had projectors instead of walls, not knowing what to expect. When the machines whirred and the screens turned on, I was instantly transported. Suddenly, I was in a bar with another Arsenal fan having a chat about last week's game! I didn't even realise it then, but that moment changed my life. Since that day I've been captivated by this thrilling world of virtual reality, and the one person that has been *'present'* throughout all my learning, and is responsible for where I am today is **Prof. Mel Slater**. Learning from him, first as a Masters student at UCL and later as a PhD student at the EventLab has been one of the most refreshing and intellectually invigorating experiences for me. His knowledge, insight, and passion for science have been an inspiration! I would like to thank him for all his support and trust throughout these years, and for giving me the opportunity to work by his side.

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Contents

List of Figures

List of Tables

List of Publications

Kishore, S., Gonzalez-Franco, M., Hintermuller, C., Kapeller, C., Guger, C., Slater, M., & Blom, K. J. (2014). Comparison of SSVEP BCI and Eye Tracking for controlling a humanoid robot in a social environment. *Presence: Teleoperators and Virtual Environments,* 23(3).

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Kishore, S., Navarro, X., Bourdin, P., Berkers, K., Friedman, D., & Slater, M. Multi-Destination Beaming: Being in Three Places at Once Through Robotic and Virtual Embodiment. *(Submitted)*

Other Publications

Spanlang, B., Navarro, X., Normand, J.-M., Kishore, S., Pizarro, R., & Slater, M. (2013). Real time whole body motion mapping for avatars and robots. *In Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology - VRST '13* (p. 175). New York, New York, USA: ACM Press.

Glossary

1PP First-Person Perspective.

3PP Third-Person Perspective.

BCI Brain-Computer Interface.

BEAMING Being in Augmented Multimodal Naturally Networked Gatherings.

BOI Body Ownership Illusion.

DoF Degrees of Freedom.

FBOI Full Body Ownership Illusion.

HMD Head Mounted Display.

HUMAN HALCA Unity3D Mapping Avatars through Networks.

IVR Immersive Virtual Reality.

MSI Multisensory Integration.

PI Place Illusion.

Psi Plausibility Illusion.

RHI Rubber Hand Illusion.

SSVEP Steady State Visually Evoked Potential.

"In a properly automated and educated world, then, machines may prove to be the true humanizing influence. It may be that machines will do the work that makes life possible and that human beings will do all the other things that make life pleasant and worthwhile."

Isaac Asimov
Robot Visions, 1991

1

Introduction

Almost a century ago, in the year 1920, Czech writer Karel Capek described his vision of utopia in his theatre play, R.U.R. (Rossum's Universal Robots) (Capek et al., 1920).

> *"Within the next ten years Rossum's Universal Robots will produce so much wheat, so much cloth, so much everything that things will no longer have any value. Everyone will be able to take as much as he needs. There will be no more poverty. Yes, people will be out of work, but by then there will be no work left to be done. Everything will be done by living machines. People will do only what they enjoy. They will live only to perfect themselves."*

Few people at the time would have imagined that this incredible vision could ever be considered within the realm of possibility. Capek, however, introduced the word 'robot' to the English language and at the same time laid the foundations for what was to become one of the most fascinating subjects of the science fiction genre. Admittedly, the concept of anthropomorphic mechanical machines known as *automatons* is not new, having existed for many centuries, including one that was designed by Leonardo da Vinci as early as 1495. However, the vision introduced by Capek of a world with intelligent, autonomous humanoid robots co-existing with mankind became the plot of almost every popular science fiction story. In literature and film, humanoid robots have been portrayed in a vast variety of roles in futuristic societies. Ranging from positive scenarios, with domestic and industrial robots working together with mankind and co-existing peacefully, to the more popular dystopian storylines, including the original theatre play R.U.R. and the famous Terminator series where self-aware humanoid robots take over the world. Regardless of that, however, the imagination of science fiction writers over the years has inevitably helped in creating an entire industry devoted to research and development of robots.

Over the last few decades as technology catches up with these fantastic scenarios, many of these concepts are being transformed into a reality. Robotic manipulators are already being used in large scale industrial environments for a myriad variety of automated tasks. Particularly in the last 20 years this field has seen exponential growth, with robotics making inroads in several other fields of research. Robots are now already present and working in collaboration with humans in industries such as space exploration (Goza et al., 2004; Bell, 2012) , medicine (Green et al., 1995; Guthart & Salisbury, 2000; Marescaux et al., 2001), healthcare (Michaud et al., 2007; Shen et al., 2016), education (Fels et al., 2001; Herring, 2013), tourism (Thrun et al., 1999; Faber et al., 2009) and in hazardous environments as well (Hasunuma et al., 2002). While certain applications have the robot working completely autonomously, in many situations the robot is controlled and driven by a human operator, and sometimes, a combination of the two paradigms (Beer et al., 2014). *Teleoperation*, where a human operator drives a robot to perform tasks, provides several advantages ranging from the highly specific, such as the ‘Robonaut’ developed by NASA for assisting astronauts in space (Bluethmann et al., 2003) to general purpose telepresence robots that provide the operator with the ability to interact with people in remote locations (Guizzo, 2010).

Being in control of a robot that may be in a different location than the operator may give rise to the illusion of *telepresence*, which is defined as the feeling of being present in the same remote location as the robot, even though they may be physically located in two distinct locations (Sheridan, 1992). Telepresence has been studied comprehensively in the physical medium as well as in immersive virtual reality (IVR), where it is referred to as virtual presence, or simply *presence*. Presence is understood to be a very powerful concept and participants that have felt the illusion have been shown to react realistically to situations occurring in the remote location, as if they were really present there. This concept of presence can be further extended by not only giving participants the feeling of 'being there', but also providing them with a surrogate representation of their body, which they feel as if it were their own and are in control of its movements, a phenomenon known as *embodiment*. There has been significant research regarding embodiment, and its various constituents such as the *body ownership illusion* (BOI) and *sense of agency*, especially in the areas of cognitive science and psychology. Studies have shown that it is fairly straightforward to generate a strong illusion in people that their bodies have physically changed. As an example, in the famous rubber hand illusion (RHI) researchers were able to temporarily give participants the feeling of ownership over a rubber hand which they felt to be the source of sensation and *proprioception*, i.e. the sense of relative position, instead of their real arm (Botvinick & Cohen, 1998). Furthermore, they would even react realistically when this rubber hand was threatened (Armel & Ramachandran, 2003; Ehrsson et al., 2007). Even when the entire body of a person is 'replaced' by a mannequin, people have reported ownership over the mannequin and have shown realistic responses to threat to their artificial bodies (Petkova & Ehrsson, 2008; Petkova et al., 2011).

Thus, being embodied in a remotely located robotic body gives rise to the situation where a participant not only feels present in a remote location, but also has the illusion of ownership and agency over the robotic body. By combining the concepts of telepresence, teleoperation and embodiment, we achieve a system where someone is embodied in, and physically represented by a surrogate humanoid robot at another remote physical location. In this thesis, we will give a detailed technical explanation regarding development of such a system, discuss real-world applications where this system has been used and simultaneously try to enhance our understanding of the theoretical framework of self-perception and body representation in the brain.

1.1 Research Problem

The phenomena of virtual presence, and telepresence in conjunction with teleoperation and telerobotics have been studied extensively. Similarly, there also exists a large body of knowledge regarding body ownership illusions and the concept of embodiment. However, little experimental evidence exists that combines these topics together to induce BOIs with humanoid robots. Although there are several experiments that explore specific conditions that are necessary for inducing the illusion, experimentation with humanoid robots has been very limited. The literature that exists in the field of full body ownership illusions with humanoid robots typically suffers from two limitations. Firstly, the robot that has been used for most studies is an android robot built as a replica of a particular person (shown in Figure 2.8a). With a very humanlike appearance it can be considered to be closer to a mannequin than a typical humanoid robot. This can be seen as an issue when developing a universal application involving a robot since manufacture of these robots is highly specialised, and thus is not easily available. On the other hand, commercially available humanoid robots that are manufactured on a much larger scale are typically built with a very ‘robotic’ appearance.

Secondly, these studies employ a system that is limiting in terms of practical application of this technology, and has been built specifically only for investigating concepts such as BOI and agency. Although their setup is optimal for that purpose, converting it into a fully immersive solution for a usable application in a real-world scenario has not been attempted yet. We believe that in terms of applying this technology, there is immense potential. As an example, areas where this technology could be applied is with telepresence robots. Most of the telepresence robots available today that are used for remote interaction are desktop-based with operator control limited via a screen, and a keyboard or joystick. Although telepresence robots have been shown to give the illusion of presence, inducing a full body ownership illusion has not been feasible, given the physical constraints of the robots.

In order to develop such immersive systems, it is crucial to first build an understanding of body ownership illusions with humanoid robots. Consequently, real-world applications can be developed where this phenomenon can be leveraged to enhance the experience of the participants. Thus, during the research for this Thesis a system was designed and developed that allows an operator to be embodied in a remotely located humanoid robot. By viewing the environment through the perspective of the robot in stereoscopic 3D, and being in control of the limbs of the robot in a natural way, necessary conditions for inducing BOI over a humanoid robot are provided. Using prior knowledge, methods and systems generally used in immersive virtual reality, we built such a system, and tested it in several real-world applications.

1.2 Research Questions

Prior to developing applications or studying the effects of embodiment over a humanoid robot, the first step was to develop a system that gives us the possibility of inducing a full body ownership illusion over a remotely located humanoid robot. Development of this system is explained in Chapter 3. Subsequently, this system was used for testing the following hypotheses:

Hypothesis 1: *It is possible to induce the full body ownership illusion over a remote robotic body with a highly robotic appearance. Moreover, it is possible to induce feelings of agency over the robotic body, even with non-manual control.* The hypothesis was tested by providing participants with a first person perspective (1PP) view from the robot, with complete control over the robot's head via head-tracking, in real-time. Two different control methods, a Steady-State Visually Evoked Potential (SSVEP) based Brain-Computer Interface (BCI), and eye tracking were used for controlling the robot. Additionally, the two methods were also compared with each other in terms of performance when used inside a Head Mounted Display (HMD).

Hypothesis 2: *By embodying someone in a remote robotic body, they can be physically represented in that remote location by using the robot as a surrogate.* Embodiment was achieved by streaming full body motion capture data of a person and mapping it in real time, onto the limbs of a humanoid robot present at a remote location. A pair of cameras in the robot's 'eyes' would stream stereoscopic video back to the HMD worn by the visitor, and a two-way audio connection allowed the visitor to talk to people in the remote destination. Thus, by instantaneously transporting the physical 'consciousness' of the visitor, a type of virtual 'teleportation' was implemented. In addition, a case-study of this application was carried out in the context of journalism, where a journalist physically present in Los Angeles, USA, used the system to conduct interviews and moderate a debate via a humanoid robot located in Barcelona, Spain. This case-study was also the first application of the system that was developed for robotic embodiment.

Hypothesis 3: *Extending the setup in the previous hypothesis, it is possible for someone to be in three distinct locations simultaneously and perform tasks in each location, by embodying a physical (or virtual) surrogate body.* The setup described in the previous application was extended by adding more remote destinations, each with a remote (robotic or virtual) body that could be inhabited and be fully controlled by the participant, thereby giving them the illusion of ownership over each of them. Due to the modular nature of this system, a proxy was developed that would take over control of the surrogate bodies not being controlled by the participant. To observe the effectiveness, a study was carried where the system was used in a social interaction task. Participants could be in three distinct remote locations (two physical and one virtual environment) simultaneously, where they were in full control of a different humanoid robot at each physical location and a virtual avatar in the virtual location. They could see, hear and interact with the people present in all three remote locations and had to perform predefined tasks. The main questions that we were interested in were related to the possibility of feeling ownership over three surrogate bodies at the same time, as well as the feasibility of the system in terms of the participants' ability to cope with doing three tasks simultaneously.

1.3 Overview of the Thesis

The rest of the thesis is organised into the following chapters.

Chapter 2 presents a detailed review of the background literature pertaining to the relevant fields dealt with in this thesis. Starting with a brief introduction on the concept of telepresence and virtual presence, we move on to a discussion about various studies done with embodiment and the full body ownership illusion, both in physical reality and in IVR. Subsequently, an overview of the field of telerobotics is presented, specifically telepresence robots that are being used for the purpose of remote interaction. Finally, we review literature that is specifically relevant for eliciting full body ownership illusions (FBOI) with humanoid robots, and study the potential factors that could influence this illusion. The few studies that investigate FBOIs and agency with teleoperated robots are also discussed. Throughout this Chapter, relevant shortcomings and unexplored issues are raised, which are tackled in the remaining chapters.

Chapter 3 contains a detailed technical description of all the hardware and software systems used to develop a system that allows us to elicit the FBOI over a humanoid robot, with relevant explanations about the purpose of each component and their constraints. The terminology that is used for the remainder of the thesis is also discussed here, to ensure consistency when referring to various elements that comprise the system. Finally, the workflow and procedures used while running the various studies are also mentioned.

Chapter 4 deals with the first hypothesis. The BCI vs Eye-Tracker Study *(BCI-ET Study)* is presented, where a full body ownership illusion is induced with a humanoid robot with a highly robotic appearance, using one of two indirect control methods over the robot body: SSVEP based BCI or an eye-tracker. A brief overview of the literature regarding the two control methods is provided first, followed by a description of the study. Finally, the results are presented, which include a comparison of both methods in terms of task performance, and their effect on the ownership illusion and agency over the robot body. Additionally, there is a discussion about how this setup can be used as an application for providing locked-in patients or people with paralysis to feel ownership and full control over a robotic body.

Chapter 5 discusses the system mentioned in Hypothesis 2, which was developed and used for the purposes of *Tele-Immersive Journalism*. A specific technical overview of the system that was used for the case-study is given, putting focus on the general description of the system that was provided in Chapter 3. It is followed by a detailed account of the case-study, where this system was used by a journalist to interview a neuroscientist and a chef 900 miles distant, about food for the brain, resulting in an article published in the popular press. Finally, although we do not present empirical results regarding FBOI over the robot, we use anecdotal and observational data to discuss its implications. However, we do present some data related to the experience of the people interacting with the robot, and use it as a means to understand the importance of embodiment in that context.

Chapter 6 continues the discussion of the system mentioned in Chapter 5, specifically focusing on extending its functionality by increasing the number of remote destinations from one to three, thereby enabling *Multi-Destination Beaming*. A description of the implementation of the extra destinations is provided, along with an explanation of the proxy system that was developed specifically for this study. Finally, the study that was performed with 42 participants to test the effectiveness of the system is described, along with an analysis and discussion of the results that were obtained from both, the participants that were controlling the remote representations (robots and virtual avatar) as well as the participants that were interacting with the robot in the remote locations. Furthermore, we discuss the results in the context of FBOIs and agency with respect to the individual surrogate bodies, as well as in terms of task performance.

Lastly, Chapter 7 presents the overall significance of the research presented in this thesis and its relevance in the fields of robotics and research in full body ownership illusions. A potential experiment is discussed as part of the future work, which is based on the changes in attitudes and behaviour that may occur as a result of being embodied in a humanoid robot, in order to study negative biases against robots and their acceptance in society.

1.4 Scope of the Thesis

The main objective of the thesis is to explore the possibility of inducing a full body ownership illusion over a humanoid robot, and subsequently studying and developing real-world applications that exploit this concept. Rather than developing a detailed theoretical framework for measuring various factors that may influence the degree of this illusion, the focus lies on applying existing knowledge regarding FBOIs in order to elicit the illusion, and using that to develop real-world applications of being embodied in a humanoid robot.

In Chapter 4, since the objective of the study was to test whether FBOI with a humanoid robot could be induced using indirect controls, the experiment employed use of existing technological setups and control methods, namely SSVEP BCI and eye-tracking. The focus was mainly on the effectiveness and impact of these technologies on the illusion and experience, instead of attempting to advance the technologies themselves. Thus, a comparison of the results of the two control methods is presented, however technical discussion related to improving the experience of using these technologies is not included.

As the case-study mentioned in Chapter 5 attempts to demonstrate a real-world application of embodiment in a remotely located humanoid robot, the highest level of technology available to us was used for the setup. Understanding the individual influence of the various components of the system, and how they affect the degree of the FBOI was out of scope of this case-study. Pre-existing knowledge of inducing FBOIs were used to develop the system, with the belief that it would provide the journalist with the highest possible degree of the FBOI. Moreover, no attempt was made to compare the experience with a non-embodied form of remote interaction (such as video-conferencing) as that was not the aim of this study.

Similarly, the work presented in Chapter 6 also makes use of the highest level of technology available to induce the illusion of body ownership over three distinct bodies (two robots and one virtual avatar), as the objective was to test the effectiveness of the system, rather than the constraints of the illusion itself.

Finally, developing hardware solutions for improvement in construction of robots, for general use or use in FBOI studies and applications, was out of scope of this research. All the experiments and case-studies carried out during the course of this research were done using commercially available humanoid robots and state-of-the-art display and tracking systems. As a consequence, each study had certain limitations dependent on the physical capabilities of the systems and humanoid robots being used, which are mentioned in the appropriate chapters, if relevant. More details of the specific hardware systems and humanoid robots used with their physical properties are mentioned in Chapter 3.

1.5 Contribution

During the course of this research, we have developed a modular and robust system that can be used to embody someone in a humanoid robot present at a remote location, and to successfully elicit the full body ownership illusion over a surrogate robotic body. The system allows us to study the FBOI over a humanoid robot and to develop applications that have high potential of being extremely beneficial in the future. The thesis attempts to combine three distinct fields of body ownership illusions and body representation in the brain, immersive virtual reality, and robotics to develop immersive real-world applications in a novel way that has not been attempted earlier.

I. Specifically, in Chapter 3 we provide a technical description of the system that we have used for *Robotic embodiment* in this thesis. The system draws inspiration from existing hardware solutions in IVR to implement a completely immersive telepresence solution that includes real-time full-body motion tracking and retargeting, in conjunction with a stereoscopic 3D video streamer to an HMD and two-way audio streaming.

II. In Chapter 4 we show that it is possible for someone to feel ownership over a robotic body, even without direct agency over the limbs of the robot. We test and compare the effectiveness of two state-of-the-art interaction methods for controlling the robot while wearing an (HMD), which has not been done before. Along with providing an insight into the mechanisms of embodiment in a humanoid robot, this study also has the potential to be used as an application for locked-in patients that have lost control of their limbs to use a surrogate robotic body for interaction and performing tasks. The study is also novel in the sense that it uses a robot that has a highly ‘robotic’ appearance, rather than the Geminoid HI-1 used in the study by (Ogawa et al., 2012). This is an important feature since by using a commercially available humanoid robot we provide a much more universal solution as compared to the highly specialised Geminoid. Furthermore, there is debate regarding the Geminoid and the problem of the ’Uncanny Valley’, where its almost lifelike appearance may cause feelings of revulsion amongst people that interact with the robot. Regardless, however, the study provides us with the theoretical framework that allows us to observe differences in the FBOIs based on the appearance of the robot body.

III. Chapter 5 provides a fully working demonstration of the novel immersive telepresence system described earlier, where a participant is able to 'teleport' themselves to another physical location instantaneously. A potential application of this technology is also demonstrated where a journalist was able to conduct an interview and moderate a debate in Barcelona, Spain while she was physically located in Los Angeles, USA. A complete case-study of this demonstration is provided, including several design and technological decisions that provide essential clues to researchers attempting to replicate this system for other applications in the future.

IV. Chapter 6 extends the setup in Chapter 5 and describes a novel multi-destination system, where one participant can be embodied in several surrogate remote representations simultaneously, and has the option to switch to other remote locations instantly. This type of highly immersive embodied telepresence experience over multiple remote locations has never been attempted before. In addition to providing a complete technical description regarding development of this system, this study also gives an account of task performance of the participants, and discusses the possibility of feeling ownership over several robots at the same time and the influence of several other factors on the FBOI, such as the robot's appearance and its physical dimensions.

The combined contribution these studies make can be seen as twofold. On the one hand, this thesis provides theoretical knowledge and further understanding about the phenomenon of embodiment and eliciting the full body ownership illusion, specifically with humanoid robots. Several situations have been tested that provide information about the influence of various factors on the illusion. Secondly, there are detailed descriptions of the various applications that have been developed, which leverage this concept of FBOI over a remote surrogate robotic body which may have immense potential in terms of remote interaction and virtual 'teleportation' in the future.

* * *

"There is not a discovery in science, however revolutionary, however sparkling with insight, that does not arise out of what went before."

Isaac Asimov

Adding a Dimension, 1964

2

Background

In this Chapter, we present a review of the literature that is relevant to the work presented in this thesis. Since the research carried out spans across several disciplines, this Chapter has been organised accordingly, with each section describing the body of knowledge and current state pertaining to a specific concept or topic. The review presented in this Chapter is divided into three sections.

We begin with an overview of the concepts of telepresence, teleoperation and and virtual presence in immersive virtual reality. Here we provide working definitions of the various components of presence, and lay a foundation on which the work presented in the following chapters is based. Next, we introduce the concept of self-perception, and its relationship to the phenomenon of body ownership illusions (BOI). We give a detailed account of the significance of BOIs, and the various factors that tend to influence it. We then extend this concept to full body ownership illusions (FBOI), in physical space using mannequins, as well as in immersive virtual reality (IVR) using virtual avatars. Various studies related to embodiment in IVR are discussed, which give us a good indication of the various multisensory modalities that may affect BOIs. Following this, we move on to a brief overview of the field of telerobotics, focusing specifically on telepresence robots. We present the current state of the technology, and point out lacking issues that we attempt to overcome in this thesis. The review does not go into too much detail about robotics in general, since that is out of scope.

Finally, we combine our existing knowledge of FBOIs and try to apply it to humanoid robots. We discuss potential issues that we may encounter when trying to elicit this illusion with robots. In other words, we draw attention to two factors, namely, *appearance* and mechanism of robot control, i.e. *visuomotor feedback*, and their influence on FBOIs. Since there are few studies that have tried to elicit FBOIs with humanoid robots, we heavily rely on studies carried out with rubber hands, mannequins and with avatars in IVR in order to gain a proper understanding of the effect of varying these factors. However, wherever possible, we give special attention to those studies that have carried out some form of BOIs with robots. Throughout this Chapter, and specifically this section, we will draw attention to the various topics that are as yet unexplored, or certain shortcomings in the existing literature, and refer back to them in the following chapters as we attempt to provide a solution for those.

2.1 Telepresence

The concept of telepresence has been comprehensively studied for over five decades, and is considered to be a cornerstone of virtual reality research. The term itself can be thought of as an umbrella term that encompasses several other concepts that carry a more specific meaning. As defined by (Sheridan, 1992) telepresence is described as a *"sense of being physically present with virtual objects at the remote teleoperator site"*. The definition of telepresence here applies to an operator *teleoperating* a machine, i.e. driving a machine remotely from a different physical location, and refers to the illusion felt by the operator of sharing the same space as the machine, even though they are physically in two distinct places. Although telepresence was coined by cognitive scientist Marvin Minsky (Minsky, 1980), paradigms related to advancement of these teleoperation technologies were being considered much earlier. Philosophies such as having a teleoperating machine with controls that allowed an operator to 'project his presence' into the remote location, and even discussion regarding anthropomorphism and spatial correlation between machine and operator for better performance were already being contemplated in the late 60s (Corliss & Johnsen, 1968; Johnsen & Corliss, 1971) (See (Draper et al., 1998) for a review). According to (Sheridan, 1995), a teleoperator was defined as *"a machine enabling a human operator to move about, sense and mechanically manipulate objects at a distance"*, and a *telerobot* was defined as a teleoperator, where the machine could be a semi-autonomous robot, but not necessarily anthropomorphic, such as a drone.

With rapid advancement of computer technologies, the term telepresence was adapted to *virtual presence* or simply *presence* to signify the feeling of being physically present in a virtual simulated environment created through computer-controlled systems with visual, auditory and haptic displays (Sheridan, 1992; Slater & Wilbur, 1997; Lombard & Ditton, 1997), with telepresence being reserved only for the specialised scenarios involving teleoperation (Steuer, 1992). Although the studies described in this thesis are based on the traditional definition of telepresence since they involve remote ownership of a teleoperated robot, we can still apply the concepts of presence to have a better understanding of its underlying mechanisms.

Two terms have been defined to distinguish the various aspects of presence - *Place Illusion (PI)* and *Plausibility Illusion (Psi)* (Slater, 2009). While PI refers to the illusion of being in the place as shown in the virtual environment, Psi is used to describe the extent to which the events taking place are perceived as plausible, i.e. actually happening. It can be said that inducing PI relies on reliable head-tracking since this allows for head-based sensorimotor contingencies, so that a participant can explore a virtual environment using their natural head movements to look around. However, the concept of

Psi applies only to virtual environments since a telepresence scenario typically pertains to remotely controlling a teleoperator and viewing an actual physical location, usually via video.

Thus, in cases of being immersed in a virtual environment, even though cognitively the participant is aware that what they are experiencing is not really happening they will tend to behave as if it were real, if they have a high degree of PI and Psi. This has shown to be true by various studies, such as the study by (Meehan et al., 2002), where significant changes in physiological responses were observed when participants were asked to navigate a virtual room with a pit in the middle (Figure 2.1). Several studies leverage this quality of IVR for various applications. Experiments have been designed for providing therapy for certain phobias (Hodges et al., 1995; Pertaub et al., 2002), and for studying various social psychological phenomena, such as the virtual Stanley Milgram obedience experiment (Slater et al., 2006) and more recently, the *Bystander effect*. The Bystander effect is a social psychological phenomenon that describes people's reactions while witnessing a violent incident (Darley & Latane, 1968). The study, as described in (Rovira et al., 2009) depicts a scenario of a virtual bar where a participant witnesses a heated argument between two football fans (Figure 2.2). Factors such as in-group/out-group identification, or eye contact with the victim were tested to see if they made a difference in participant reactions, and it was found that identifying the victim as part of their ingroup led to a higher number of interventions (Slater et al., 2013). Thus, we see that having a high degree of presence leads to participants truly believing that they were present in another location and behaving realistically to the events unfolding in that location. The research presented in this Thesis relies heavily on eliciting this illusion, specifically PI, in order to ensure that the participants truly feel as if they are in the remote locations that are displayed.

In addition to the studies that aim to leverage the concept of presence for various applications, numerous studies have also attempted to discern the factors that may affect the feeling of presence itself, especially related to the technological aspects of simulating the virtual environment. Display fidelity (Ijsselsteijn et al., 2001; Hendrix & Barfield,

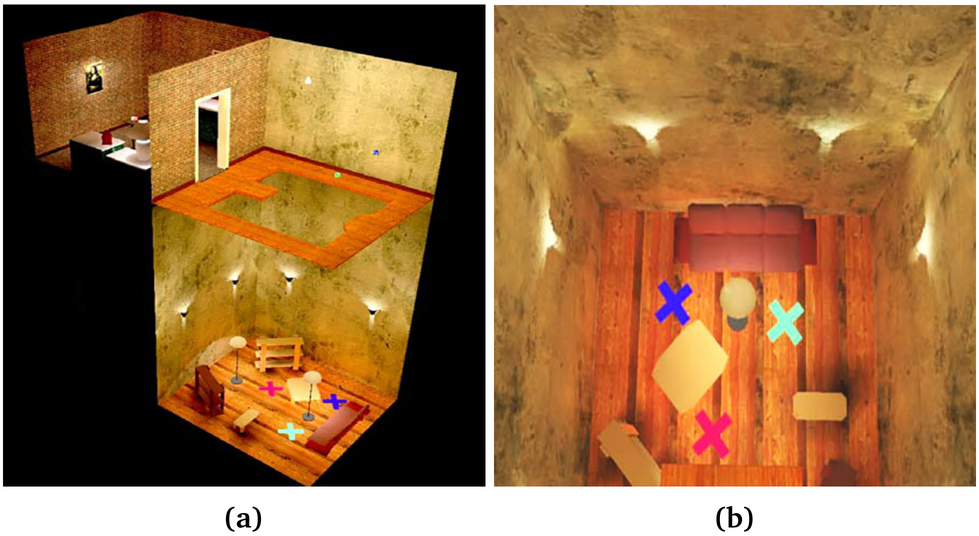


Figure 2.1: Images of the 'Pit Room' Experiment. (a) shows the cross-section view of the virtual environment, with the training room (upper-left), the pit room (upper-right) and the room below (lower-right). Figure (b) shows the view of the pit from the edge of the upper room. Images taken from (Meehan et al., 2002).

Figure 2.2: Virtual scenario of the experiment carried out by (Slater et al., 2013). The perpetrator (in white) causes an altercation with the victim (in red). Image taken from (Slater et al., 2013)

1996a), visual realism (Slater et al., 2009a), auditory (Hendrix & Barfield, 1996b), and tactile feedback (Basdogan et al., 2000), are some of the components that have been known to influence the feeling of presence. A key factor that is highly relevant for the studies presented here, mentioned in (Sanchez-Vives & Slater, 2005), discusses the impact of having a virtual body has on presence (Slater & Usoh, 1993). Along with the increase in presence a virtual body provides, the idea of embodiment (Biocca, 1997) gives an important conceptual foundation related to owning a body in IVR (here referred to as self-representation) on which a multitude of studies have been carried out. However, before we delve into a discussion of full body ownership illusions and the concept of embodiment, it is essential to have an understanding of the perceptual and psychological mechanisms underlying the concept of body ownership.

2.2 Body Ownership Illusions

Before we describe body ownership illusions (or bodily illusions in general) it is necessary to understand what it means to own a body. This question about the 'self' and its relationship with the body has been the subject of discussion for many years (James, 1890; Jeannerod, 2003; Metzinger, 2004). According to one definition, a person perceives their 'self' as the owner of their body and all its associated actions (Gallagher, 2000). Thus, perceiving the self and body can be understood as being based on the experience of being the owner of one's actions and perceiving external events from the surroundings. These external events are perceived by the body via means of various sensory modalities, such as sight, sound, taste or touch. The information that is received from these individual channels is combined in the brain to provide a holistic understanding regarding the events, this phenomenon known as *Multisensory Integration* (MSI). A crucial benefit of combining information from the various modalities is that it allows the brain to perceive an event faster and more reliably, than by relying only on individual information (Stein & Stanford, 2008). Importantly, body perception is also an instance of combination and integration of the various multisensory modalities to provide a multidimensional experience of body ownership. Furthermore, MSI also assists in creating a more robust perception of the surroundings in cases of unclear stimuli. Where input from one sensory modality could be ambiguous, information is taken from another modality and combined with the first to improve understanding and resolving ambiguities (Alais et al., 2010).

Consequently, these ambiguities in multisensory information can also lead to various bodily illusions. Several cases of altered body perception have been reported in patients suffering from various physical or neurological disorders, such as ownership of 'phantom limbs' in amputees (Ramachandran et al., 1995). However, apart from patients, bodily illusions can also be temporarily evoked in healthy participants by providing conflicting information to the multisensory channels. In order to comprehend this information, the brain tries to accept these conflicting signals and integrates them in order to create an understanding of the experience. For example, several experiments have shown how simple techniques can create a feeling of body deformation in healthy participants, such as the feeling of having a long nose (Lackner, 1988; Ramachandran & Hirstein, 1998) or a skinny waist (Ehrsson et al., 2005).

In the same vein as body deformation illusions, illusions of ownership over non-corporeal objects can also be elicited, evoking a feeling that the object in question is part of one's own body. Fundamentally, while body ownership can be defined as the feeling of owning a body, and accepting it to be the source of associated sensations (Gallagher, 2000; Tsakiris et al., 2006), a body ownership illusion refers to acceptance of a non-corporeal object (for example, a rubber hand) as part of their body representation and a source of associated sensations. In what is now a classic experiment that demonstrates a body ownership illusion, healthy participants perceived a rubber hand to be their real hand, the phenomenon now known as the Rubber Hand Illusion (RHI) (Botvinick & Cohen, 1998). In the experiment, participants were asked to sit with their arms outstretched on a table, with their left hand hidden out of sight. In an anatomically congruent position a rubber hand was placed on the table, on which the participants were asked to focus their attention. The experimenters then proceeded to stroke both, the hidden left hand and the rubber hand, either synchronously or asynchronously (see Figure 2.3). In case of synchronous tapping, the congruent visuotactile information caused the participants to feel as if the rubber hand was their own, as evidenced by the post-experiment questionnaires. In addition, another measure was used to judge the degree of the illusion where participants were asked to point to the position of their left hand from under the table. For the synchronous tapping condition, participants tended to estimate the position of their hand much closer to the rubber hand instead of their real hand, the distance termed as the *proprioceptive drift*. However, in case of asynchronous tapping, both the questionnaire scores and proprioceptive drift were significantly reduced.

The RHI has spawned research in several fields such as neuroscience and cognitive psychology. A multitude of experiments have been designed that attempt to test various factors that tend to influence this illusion, such as visuomotor or visuoproprioceptive feedback instead of the classic visuotactile method (Dummer et al., 2009; Kalckert & Ehrsson, 2012), understanding the effect of the texture or shape of the fake hand with regard to the participant's real hand (Haans et al., 2008; Tsakiris et al., 2010), or testing to see if the illusion can be induced with an object that does not have the morphology of a hand at all (such as a tabletop or wooden stick) (Armel & Ramachandran, 2003; Tsakiris & Haggard, 2005). Additionally, researchers have also attempted to understand the underlying brain mechanisms that lead to the illusion (Ehrsson et al., 2004; Guterstam et al., 2013), along with observing brain activation using fMRI and physiological activation using skin conductance response, in the event of a threat to the rubber hand (Armel & Ramachandran, 2003; Ehrsson et al., 2007).

All the results from these studies provide a thorough understanding of the factors that influence BOIs. This knowledge has been invaluable not just for eliciting ownership illusions over artificial limbs, but has also provided clues to extend this illusion to the entire body. The next sections provide an overview of the body of work that shows that it is possible to induce full body ownership illusions, along with several studies related to

Figure 2.3: Experimental Setup of the Rubber Hand Illusion, as described by (Botvinick & Cohen, 1998). The participant views the rubber hand (left), while their right hand (right) is hidden from sight. Image taken from the video demonstration of the Rubber Hand Illusion by EventLab. Link

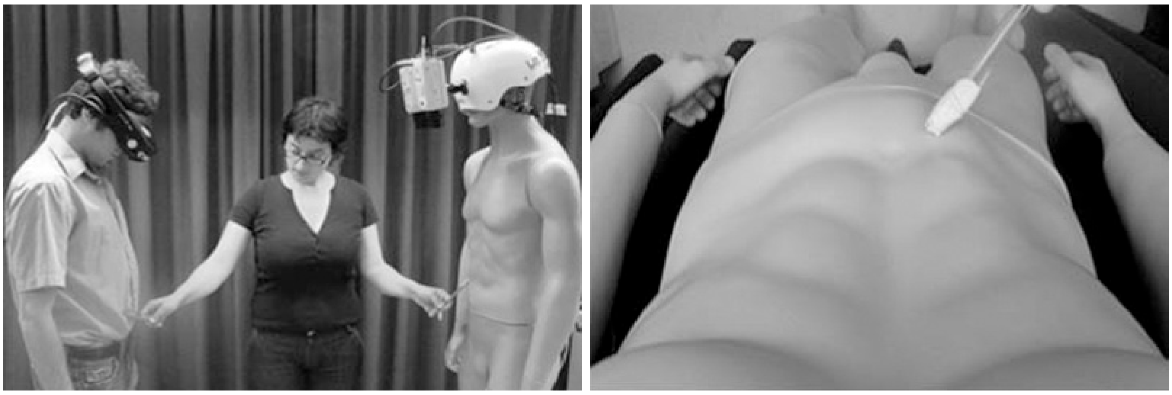
the factors that may affect it, and the physiological, psychological and cognitive changes that may occur as a result.

2.2.1 Full Body Ownership Illusions

By extending the concepts of BOI over an artificial limb and applying them to an entire body, ownership illusions over an artificial body have also been elicited successfully. In a method similar to the RHI, (Petkova & Ehrsson, 2008) evoked full body ownership illusions over a plastic mannequin body by providing synchronous visuotactile stimulus to the participants. The experimental setup involved giving participants a first person perspective view of a plastic mannequin body, collocated with their real body. This was done by fitting the participants with an HMD that displayed a live stereoscopic stream from two cameras attached to the mannequin's head, oriented downwards towards the plastic body. The participants were asked to adopt a similar pose so as to provide them with congruent visuoproprioceptive feedback, i.e. making the participants see the mannequin body from a first person perspective (1PP) in a congruent posture, where they would expect to see their own body (Figure 2.4). Subsequently, participants were given synchronous visuotactile stimulation in the form of repetitive strokes with a short rod on their abdomen, with the mannequin being stroked in the exact same position and at the same time. With just two minutes of synchronous stimulation, participants reported to have felt ownership over the mannequin body. This was further confirmed in the same experiment by using physiological responses to a threat to the mannequin body as a measure of ownership, and a significant increase in skin conductance response was found when the artificial body was threatened with a knife, as compared to a spoon.

Following this, another study was carried out by (Petkova et al., 2011) to analyse the effect of visual perspective on the full body ownership illusion. A similar setup was followed as described above, but with an extra condition where the participant would view the mannequin body from a third person perspective (3PP). They found significant differences in the ownership illusion with participants reporting much higher levels of the illusion when provided with 1PP of the mannequin body as compared to the 3PP condition. Similar to the earlier study, the results were also confirmed using the objective physiological measures in response to threat, which corroborated the findings. However, an experiment carried out by (Lenggenhager et al., 2007) demonstrated that FBOI could be elicited using 3PP, however, given the setup they used, it could be argued that this is a case of an *out of body experience*, rather than FBOI (Maselli & Slater, 2014) (see (Kilteni et al., 2015) for a review of FBOIs).

As in the case of the RHI, researchers have attempted to understand the various factors such as appearance of the artificial body, or its dimensions and the effect it may have on FBOIs. However the issue that arises with studying these factors for the whole body is that implementation is not as straightforward as it is for studies involving the RHI. Thus, immersive virtual reality (IVR) has been used to study these factors to great effect. Although it can be argued that the studies presented in this thesis are more closely related to the aforementioned studies with mannequins since our work does not employ



(a) (b)

Figure 2.4: Experimental Setup of the Full Body Ownership Illusion study, as described by (Petkova & Ehrsson, 2008). In (a) the participant views the mannequin body from 1PP via the HMD when he looks down to see his own body, due to the cameras attached to the mannequin's head. (b) The participant is given synchronous visuotactile stimulation by the experimenter to induce the full body ownership illusion over the mannequin. Images taken from (Petkova & Ehrsson, 2008).

the use of IVR for the purpose of embodiment, it is still crucial to recognise and understand the existing literature related to studying FBOIs regardless of medium, as they have revealed several new insights based on which all the studies have been designed.

2.2.2 Full Body Ownership Illusions in IVR

We discussed in Section 2.1 how immersive virtual reality provides a highly powerful and flexible tool that can be used in order to elicit realistic responses to real world stimuli from participants. This allows researchers to use IVR for studying not just concepts and applications of presence, but also highly complex ideas such as the self and body representation. As evidence of the veracity of using IVR for such research, the RHI was successfully induced in IVR by providing synchronous visuotactile feedback to a virtual arm that participants viewed as if projecting out from their shoulder (Slater et al., 2008). They also found similar results in terms of proprioceptive drift in the synchronous visuotactile condition. In addition, the virtual hand illusion was induced in participants in absence of visuotactile stimulation, but with visuomotor stimulation instead (Slater et al., 2009b; Sanchez-Vives et al., 2010; Yuan & Steed, 2010), thereby replicating the results of the studies carried out using traditional methods.

The phenomenon of full body ownership illusion has been elicited successfully in IVR, as described in (Slater et al., 2010). According to the experimental setup, they used an HMD to display an immersive virtual environment with an avatar body collocated with the real body of the participants. Three factors were studied, namely, visual perspective, visuotactile stimulation and visuomotor stimulation, and it was found that perspective was the most important factor related to eliciting the illusion, and was also correlated to the physiological stress level response (heart rate deceleration) by the participants to a threat to the virtual body. Additionally, they also used a virtual mirror to provide participants with a full view of their virtual body, which has been shown to increase the FBOI (González-Franco et al., 2010). By producing results in IVR similar to previous studies carried out with mannequins, these studies confirm that IVR can be used as a tool to study FBOIs. A great advantage of using IVR over other methods is that it lets participants view highly detailed virtual environments from 1PP of a virtual avatar via an HMD, which combined with head tracking provides powerful head-based sensorimotor contingencies. Simultaneously, full body tracking systems can also be used to track position and orientation of the participant's entire body, which when retargeted to the virtual avatar's body provides complete visuomotor synchrony (Spanlang et al., 2013) (See Section 3.3 for a discussion of motion retargeting in the context of humanoid robots).

Thus, participants not only feel a sense of body ownership over the virtual body, but also have a sense of agency, i.e. *"the sense of having global motor control, including the subjective experience of action, control, intention, motor selection and the conscious experience of will"* (Blanke & Metzinger, 2009). In other words, agency refers to the sensation of being the agent of one's own actions (Tsakiris et al., 2006). These strong multisensory correlations have been shown in several studies to be a significant factor for eliciting

FBOIs in IVR. Both, synchronous visuotactile and visuomotor stimulation individually have been shown to elicit the illusion successfully in IVR. Although in a study that examined the interaction and relative importance of the sensory modalities showed that the illusion is stronger and more positively influenced by synchronous visuomotor correlations rather than visuotactile (Kokkinara & Slater, 2014). This is a positive result, since the studies described in this thesis rely solely on synchronous visuomotor correlations to elicit FBOIs, with no visuotactile information provided. Thus, a combination of the feeling of agency caused by synchronous visuomotor correlation, and a feeling of body ownership can be referred to as the sense of *embodiment* (Kilteni et al., 2012a), while at the same time it is typically also understood as the process of *embodying* someone in a virtual (or robotic) body (Slater & Sanchez-Vives, 2014). This is an important definition since the term 'embodiment' is used frequently throughout the remainder of the thesis while describing the studies.

A key factor where embodiment in IVR is valuable is that it allows for great freedom in terms of developing complex scenarios for studying the factors that may influence the illusion, as well as understanding the cognitive or behavioural changes that may occur depending on the characteristics of the artificial body. Recent studies have utilised IVR for studying body representation with distorted morphologies, similar to the body deformation illusions mentioned earlier. For example, (Normand et al., 2011) showed that if provided with synchronous visuomotor and visuotactile feedback, participants felt ownership of a body with a much larger belly, while (Kilteni et al., 2012b) tested the extent of acceptance of a deformed limb by embodying participants in a virtual body with a long arm. Participants reported the illusion of ownership over the virtual arm up to three times its length. In addition to eliciting FBOIs in bodies with modified limbs, studies have shown that it is possible to evoke the illusion in bodies significantly different from one's own, such as in (Banakou et al., 2013), where participants reported ownership over a child body, and (Peck et al., 2013) were able to successfully elicit the illusion with a purple-skinned alien avatar. However, studies have shown that a human morphology is a necessary factor to induce the illusion (Petkova & Ehrsson, 2008;

Maselli & Slater, 2013). A more detailed discussion of the influence of appearance and body representation on FBOIs is presented in Section 2.4.1.

Interestingly, studies have also shown that the type of body may have an effect in the implicit attitude and behaviour of the embodied participant (Maister et al., 2015). For example, (Peck et al., 2013) showed that being embodied in a black avatar reduced the implicit racial bias of participants (which was also shown by (Maister et al., 2013), but with the RHI), while the aforementioned study of (Banakou et al., 2013) showed that feeling ownership of a child body led the participants to identify themselves with a child-like attitude. In a study by (Kilteni et al., 2013), participants played the African drum, the *Djembe* with much more freedom when embodied in a casually dressed dark-skinned avatar, as compared to a formally dressed light-skinned avatar. More remarkably, in the study by (Osimo et al., 2015), participants were able to provide better counselling to their own problems when embodied in a virtual body of Dr. Sigmund Freud than when embodied in an avatar that looked like themselves (See Figure 2.5). A potential study related to using embodiment to observe changes in implicit bias against robots is described in Chapter 7.

While these results provide us with great insight into the overall understanding of FBOIs, it is critical to delve deeper into the areas directly related with the issues that we may face while trying to embody a participant in a humanoid robot. However, before we are in a position to begin that discussion, it is essential to gain an understanding of the field of telerobotics, and more specifically telepresence robots, so we have a clear idea of the limitations, and valid reasoning for *why* we propose to study this topic. The next section provides a brief introduction to the field of telerobotics and telepresence robots, and then describes the various issues that need to be taken into consideration when discussing *robotic embodiment*.

(a)

(b)

(c)

Figure 2.5: Embodiment studies in IVR. (a) Participants felt ownership over an avatar with a larger belly when provided with synchronous visuotactile stimulation. Image taken from (Normand et al., 2011). (b) An experiment that observed movement of participants while playing the drum, embodied in a dark-skinned or light-skinned avatar (top-right). Image taken from (Kilteni et al., 2013). (c) A participant attempted to give counselling to their problems while embodied as a self-avatar, or an avatar of Dr. Sigmund Freud. Image taken from (Osimo et al., 2015).

2.3 Telerobotics

Telerobotics, as defined by (Sheridan, 1989), refers to a subclass of teleoperation, signifying *supervisory* control of semiautomatic systems. However, these systems did not necessarily have to be anthropomorphic to be considered as a 'telerobot', rather any teleoperator which has some degree of autonomy, but requires human monitoring is considered one (Sheridan, 1992). Being a subcategory of teleoperation systems, telerobotic applications were also built for remote telemanipulation, especially for use in hazardous environments. As an example, a telerobotic system was demonstrated by the German space agency, DLR (Hirzinger et al., 1993), which was a robotic arm used for remote telemanipulation in space, while a few years earlier, an electrohydraulic master-slave system with an isomorphic design and force-feedback was developed for use by the Naval Ocean Systems Center (Jacobsen et al., 1989).

In the same vein as the applications mentioned above, for most part of the history of telerobotics, specialised applications have been built to solve a highly specific problem. Applications such as telesurgery have shown great potential (Guthart & Salisbury, 2000; Marescaux et al., 2001) in this regard. Additionally, space exploration has been a major area where telerobotics has provided a fantastic opportunity. Rovers sent to Mars over the last decades are one of the finest examples of the potential of this technology (Bell, 2012). Furthermore, a semi-autonomous humanoid robot named Robonaut (Figure 2.6) was developed by NASA to work together with astronauts (Bluethmann et al., 2003). The robot has two arms, a three DoF (Degrees of Freedom) waist and a two DoF neck fitted with stereo cameras. This robot was also shown to have been controlled by a remote teleoperator fitted with an HMD and body tracking (Goza et al., 2004). The idea presented in this paper is similar to the studies presented in this thesis. However, the technology used for implementation, as well as the intention of their paper are extremely specialised, whereas we use the idea to present a more universal solution, and focus on using the technology to gain a deeper understanding of embodiment with

Figure 2.6: The Robonaut manufactured by NASA. Image taken from NASA. Link

robots. Nonetheless, we discuss the implications of this paper in slightly more detail in Section 2.4.

Contrary to the highly specialised applications mentioned above, development of a distinct subcategory of robots has also gained immense popularity, built not for a specific purpose but for general social interaction. These robots, known as *telepresence robots*, typically allow people to view a distant location via remotely manipulating a robot, and use the built-in communication devices in order to interact with the people present in the remote location. The next section provides a brief introduction to this specific subcategory of robots, since they can be thought of as most relevant to the applications that we discuss in the remainder of this thesis. We also point out the shortcomings of these telepresence robots as a motivation for our research.

2.3.1 Telepresence Robots

In the past few years, telepresence robots have become increasingly popular, mainly due to the growing ease of access to the technology that is needed for their development. One of the earliest telepresence robots developed, as described by (Paulos & Canny, 1998b), referred to their system as a PRoP (Personal Roving Presence) device that aimed to *"provide a physical mobile proxy, controllable over the Internet to provide tele-embodiment"*. The device was built on a simple mobile robot base with a 1.5 metres tall plastic pole that supported the speaker, microphone, a 30cm screen and a video camera with 16x zoom controllable by the operator. Furthermore, the robot also had a two DoF pointer for simple gesturing (Paulos & Canny, 2001). However, they define the term *tele-embodiment* to refer to just having a physical representation of the operator in the remote space, describing it as *"telepresence with a personified perceptible body"* (Paulos & Canny, 1997; Paulos & Canny, 1998a), with no mention of body ownership or agency.

Nowadays, several commercial telepresence robots are available (Figure 2.7), ranging from basic table-top products only capable of simple rotation and panning of a camera and screen (Kosugi et al., 2016), all the way to full-sized robots (Guizzo, 2010), with advanced capabilities such as semi-autonomous navigation and multiple cameras (see (Tsui et al., 2011) for a review). Although considerable research exists in terms of studying specific designs needed for special cases, such as robots for geriatric care (Michaud et al., 2007), security applications (Schultz et al., 1991), remote learning for sick children (Fels et al., 2001) or people with disabilities (Herring, 2013; Tsui et al., 2014), the overall setup of most telepresence robots still remains similar to the legacy setup described above. Moreover, most of the commercially available telepresence robots also

Figure 2.7: An image of the iRobot Ava 500, an autonomous roaming telepresence robot. Image taken from Wikimedia.org

follow the same design, albeit with improved hardware, which has been described as *"advanced video conferencing on wheels"* (Tsui et al., 2011).

Although there have been improvements in the capabilities of telepresence robots in terms of operator experience, such as inclusion of non-verbal gestures and camera control using face tracking (Adalgeirsson & Breazeal, 2010), there has been no research, to our knowledge, in terms of creating a truly embodied experience with a telepresence robot. The majority of telepresence robots are still driven via a keyboard/mouse (Schulz et al., 2000; Hu et al., 2001) or joystick (Sian et al., 2002), and the remote destination is displayed to them via desktop screen or tablet (Shen et al., 2016), albeit with advanced visualisation features (Nielsen et al., 2007) (see (Chen et al., 2007) for a review). Even when the telepresence robots have a humanoid morphology, control has still been limited to joysticks (Neo et al., 2007). Admittedly though, some attempts have been made to provide a more natural method of control, such as the system developed by (Becker-Asano et al., 2014) where they describe a telepresence robot that allowed operators to view the remote location in stereoscopic video via HMD. However, due to the telepresence robot's design not having a humanoid morphology, more specifically the lack of limbs restricted the system from having any form of body tracking or retargeting. In another study, four different methods of robot control were tested, ranging from a traditional joystick setup to a full-body tracked, gesture-based control method, and compared in terms of task performance and embodiment (Almeida et al., 2014). They found that the gesture and body tracking based method improved task performance. Although their setup had several key limitations, such as only a single camera video stream to the HMD instead of 3D, and the full body tracking method was more of a pose/gesture recognition system, since similar to the earlier study the robot they used was a typical telepresence robot without an anthropomorphic design. Finally, several studies have demonstrated a system where telepresence robots have been driven using abstract methods of control such as BCI (Millán et al., 2003; Gergondet et al., 2011; Tonin et al., 2011; Cohen et al., 2012). This is also of particular interest to us, since in Chapter 4 we describe a similar system, but in addition we also discuss the implications in the context of body ownership and agency.

Ultimately what is lacking with most of the telepresence setups mentioned above is a system where the operator not only feels telepresence, but also has a sense of body ownership and agency over their remote surrogate robotic body. This idea, however, raises its own set of challenges, mainly related to embodiment with humanoid robots, discussed in the subsequent section.

2.4 Embodiment with Humanoid Robots

As mentioned earlier, there is little research about the concept of embodiment and FBOI in humanoid robots, mainly due to limitations in terms of technology. But in recent years, as the field of robotics has continued to innovate, and commercial telepresence and humanoid robots have become available for research and consumer use, this topic has gained momentum. In order to develop an understanding of the issues, it is essential to review not just the research carried out with humanoid robots, but also to develop guidelines from the conclusions drawn from studies carried out using artificial bodies or virtual avatars. Following is a discussion of two possible issues, *appearance* and *control method*, with potential solutions based on the literature. Special attention is given to studies that have used embodiment of some form with humanoid robots.

2.4.1 Effect of Appearance on Embodiment

One of the fundamental differences between embodiment in a virtual avatar or mannequin, and a humanoid robot, is the appearance of the artificial body. Thanks to the advanced rendering software environments coupled with powerful graphic processing units and high resolution display systems, it is possible to render avatars to appear realistic and similar to a real human body. However, this is not the case with humanoid robots. Moreover, no standardised guidelines exist for manufacturing humanoid robots, which further increases the variability between robots developed by different companies. In addition to this issue, although humanoid robots are understandably built with a humanoid morphology, they are vastly diverse in their appearance, differing in dimensions as well as shape and texture. The main contributing factor for this variability is that humanoid robots are typically manufactured for solving a specific task, and thus major design decisions such as materials, dimensions and appearance are decided based on that.

In order to understand the effect of appearance on body ownership, we need to first understand how the body is represented in the brain. The general idea of BOIs are that they are a combination of top-down and bottom-up information processes (Tsakiris & Haggard, 2005). Bottom-up processes, such as detection and integration of multisensory information in the brain, combined with top-down processes such as existing knowledge and expectation about one's 'body image' (Tsakiris et al., 2007; Longo et al., 2009) influence the final degree of illusion. The artificial limb (or body) is always compared with this internal body model, and is only accepted as part of the body if it is congruent with that representation (Tsakiris & Fotopoulou, 2008; Carruthers, 2008; Tsakiris, 2010).

There is strong evidence that suggests the BOI to be highly influenced by the shape of the non-corporeal object. Several studies that used a modified version of the RHI paradigm with different objects instead of a rubber hand, such as a checkerboard (Zopf et al., 2010), a wooden stick (Tsakiris & Haggard, 2005), a white cardboard (Hohwy & Paton, 2010) or even a sheet with a texture similar to skin (Haans et al., 2008), reported no feelings of ownership. Admittedly, these studies used objects that are extremely different from a human hand, but in a study by (Tsakiris et al., 2010), where they tested the illusion with a wooden block at three intermediate stages of its transformation into a wooden hand and compared it with a realistic rubber hand, the participants only reported to feel ownership over the realistic rubber hand, with no reported ownership for the wooden objects, including the one that looked like a hand and had fingers. For the case of FBOIs, similar results were found. There were no reported feelings of ownership when a similarly sized chair or a table were used instead of a mannequin (Petkova & Ehrsson, 2008).

On the other hand, studies have also shown that the artificial limb (or body) does not have to be exactly congruent with the participant's body representation for BOIs to be induced. As we have seen with some of the studies mentioned earlier, researchers were able to successfully elicit the illusion with plastic mannequins (Petkova & Ehrsson, 2008; Petkova et al., 2011), virtual plastic mannequins in IVR (Maselli & Slater, 2013), and purple-skinned avatars as well (Peck et al., 2013). Furthermore, it has been shown that the size of the artificial limb also does not appear to influence the illusion, as BOIs were reported with small and large rubber hands without significant differences across the two conditions (Bruno & Bertamini, 2010; Heed et al., 2011). FBOIs were also reported with bodies of extremely varied heights (0.3 metres - 4 metres) (van der Hoort et al., 2011), and in IVR with a 4-year old child avatar (Banakou et al., 2013). The idea that

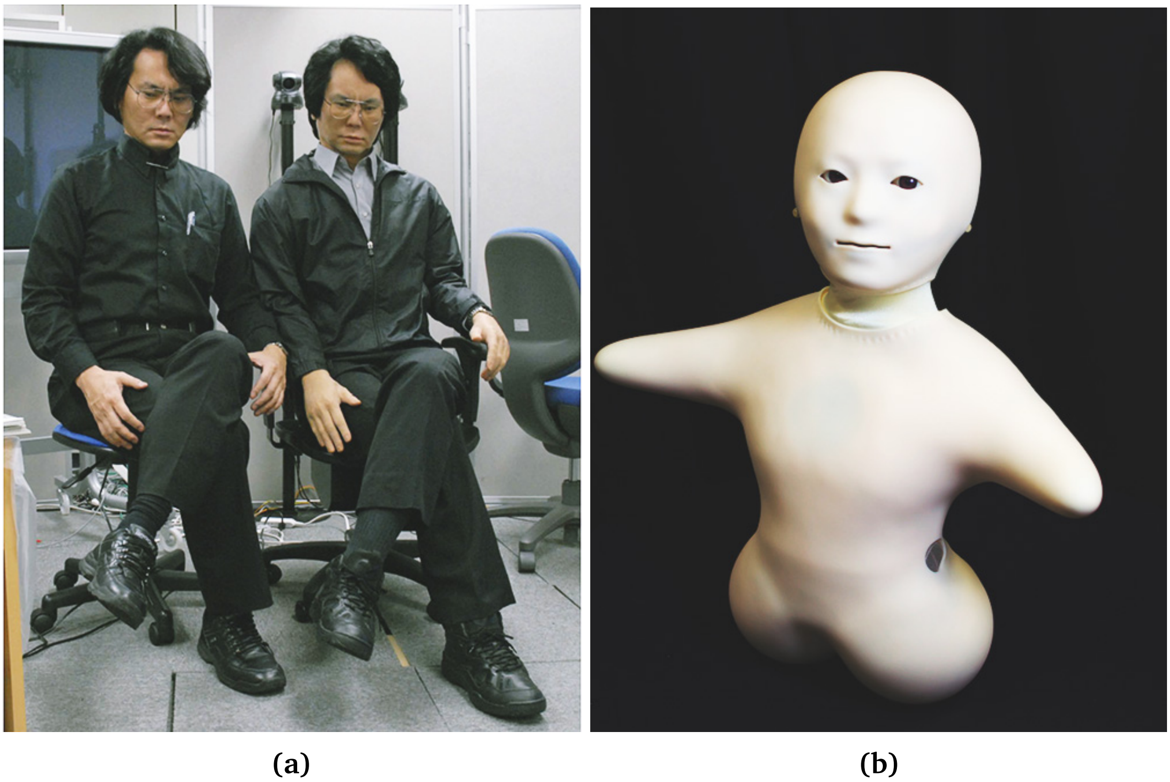


Figure 2.8: Examples of android robots developed specifically for research with remote teleoperation and telepresence. (a) The Geminoid HI-1 (right), modelled after Prof. Hiroshi Ishiguro (left), has been used for various studies regarding FBOIs and agency (Nishio et al., 2012; Ogawa et al., 2012). (b) The Telenoid robot, built with a minimal human appearance, designed to have no visual features or characteristics of its own, so as to allow participants to convey their own personality (Sumioka et al., 2012). Images taken from Geminoid.jp © ATR Hiroshi Ishiguro Laboratory.

the dimensions of the body are not critical for eliciting FBOIs is promising since one of the robots used in the study described in Chapter 6, the Nao, has a height of 60cm (see Section 3.2.2 for complete specifications of the robot).

Finally, there is a study that reports participants feeling ownership over a Geminoid HI-1 (Figure 2.8a), a teleoperated android robot (Nishio et al., 2007), when synchronous visuomotor stimulation was provided (Nishio et al., 2012). However, there is debate regarding the issue of the *'Uncanny Valley'* given the highly lifelike appearance of the

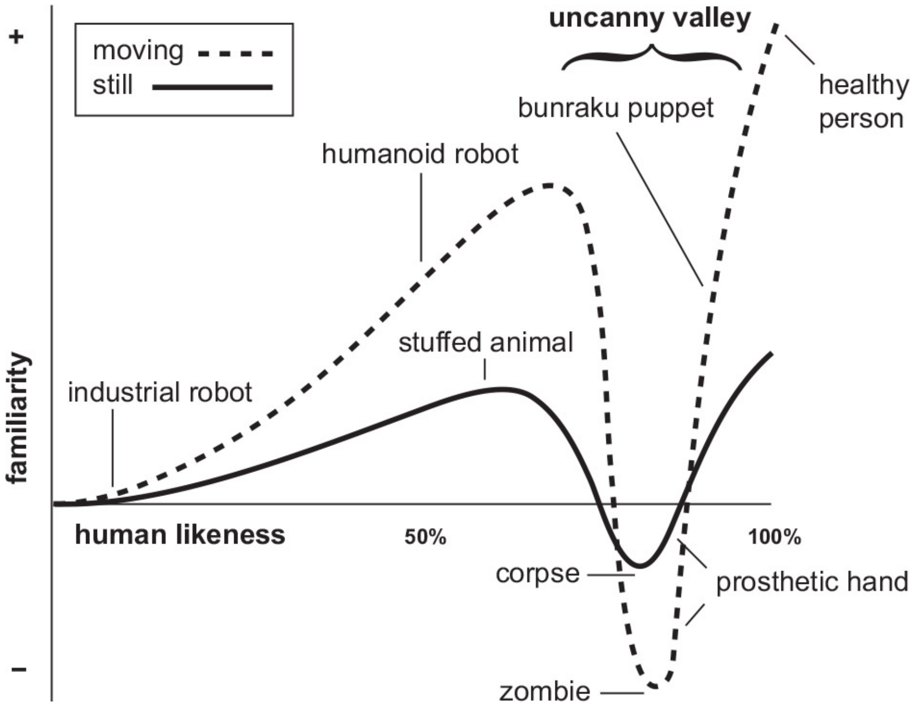


Figure 2.9: The Uncanny Valley hypothesis graph. Increasing human-likeness is plotted on the X-axis and the corresponding emotional response is plotted on the Y-axis. The dip in the graph depicts the feelings of revulsion towards entities that seem 'almost' human, which increases if the entity in question is moving (Mori, 1970; Mori et al., 2012). Graph taken from (MacDorman, 2005).

Geminoid. Uncanny Valley is a hypothesis that refers to a feeling of revulsion experienced by people while observing something (such as an avatar, robot, or a doll) that has features almost, but not exactly, like human beings (Mori, 1970; Mori et al., 2012). The 'valley' signifies the dip in the graph where increasing human-likeness is plotted on the X-axis and comfort level on the Y-axis (See Figure 2.9). In a study carried out by (Becker-Asano et al., 2010), 37.5% of the participants reported an uncanny feeling while interacting with the Geminoid robot, while 29% reported to have enjoyed it. In another study, no significant effects were found in the ratings of likability when comparing participant interaction with a human being (Prof. Ishiguro) or his Geminoid replica (Figure 2.8a) (Bartneck et al., 2009). The interpretations given for this result were that either there may not be a difference in likability between android robots and humans, or that there may exist different standards of evaluation, and each type (human or android) may have their own standard of likability. On the other hand, (Mathur & Reichling, 2016) recently showed that the likability of a robot fell drastically as they started looking more human-like in appearance. Furthermore, (Ho & MacDorman, 2010) argue that *likability* or *warmth* miss the concept of the uncanny valley, which can be understood to be closer to *eeriness*. While we can presume that this potential drawback of its appearance may not have a big effect on FBOI, since the only time a participant would be able to view their robotic body is by looking at a mirror, the issue of the Uncanny Valley was not commented on in the subsequent studies carried out with the Geminoid investigating FBOIs. Regardless of that, however, this provides us with good motivation to carry out studies with humanoid robots that look robotic instead of highly lifelike androids, as the humanoid robots may be 'human' enough to provide participants with a sense of familiarity, but still look 'robotic' enough in appearance and avoid the potential valley. Furthermore, avoiding elicitation of a negative emotional response in the observer becomes even more relevant for the work presented here since all our studies involve a telepresence setting with someone in the remote destination interacting directly with a robot.

Finally, (Sumioka et al., 2012) describe the telerobot 'Telenoid' (Figure 2.8b), which has been built specifically to have minimal human appearance, i.e. enough for providing telepresence, but no specific features appearance-wise so as to allow the operator to convey their personality via the robot. However, no studies using the Telenoid related to FBOI or remote telepresence were found, though one study found that when interviewed about their impressions, almost half the participants reported having negative feelings towards the Telenoid, but changed their opinions from negative to positive after giving it a hug (Ogawa et al., 2011).

It is clear that the appearance of the fake body are fundamental in affecting FBOIs. Even though there are several studies that show little tolerance in terms of acceptance of artificial limbs in terms of shape or texture, we also have successful demonstrations of FBOIs with bodies that are greatly abnormal. Thus, we understand that as long as the fake body (or humanoid robot) being used for embodiment satisfies certain semantic rules, such as a humanoid morphology, it should be possible to induce the illusion. The exact boundaries of the violations that can still be tolerated are not understood completely (Kilteni et al., 2015), and all the studies in this thesis attempt to unravel more information about this topic, by using humanoid robots with a highly robotic appearance.

2.4.2 Effect of Control Method on Embodiment

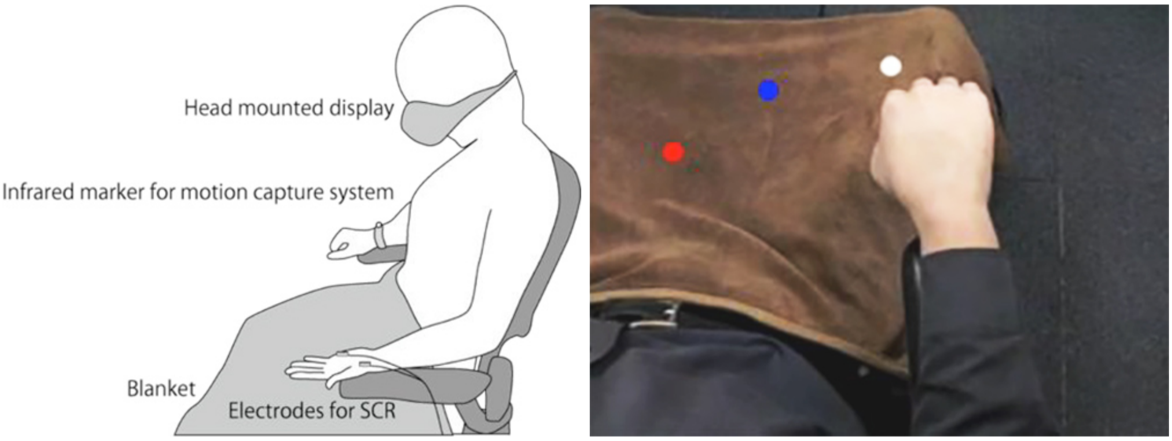
Since one of the objectives of this thesis involves development of a system that provides a high degree of full body ownership over a remote robot in a telepresence setup, it is essential to discuss the various possibilities in terms of driving the robot. The most obvious way of achieving a high level of agency would be to allow the participant to move the robot's body by simply moving their own corresponding body part, as has been demonstrated in several studies in IVR. The ability to recognise movement as one's own has been shown to be a fundamental contributor to body ownership (Jeannerod, 2003). In terms of eliciting BOIs, there are multitudes of experiments that use visuomotor stimulation, where emphasis is given to the synchrony of *felt* movement of the participant and the *seen* movement of the artificial limb or body. The importance of reviewing this topic becomes even more crucial, since providing synchronous visuomotor feedback by driving a robot in real-time can be a challenging task. There are several issues to overcome, depending on the build of the robot, the latency of the tracking system (to ensure the movement is carried out without lag) and the display system (to ensure the movement is seen without lag), among others. Thus, we discuss the various studies in BOIs that specifically manipulate visuomotor feedback in order to understand how it influences embodiment, and the factors that need to be taken into account when developing the robotic embodiment system.

Traditional experiments that leverage the RHI paradigm with visuomotor feedback have typically used various devices that linked movements of the participants' hand with the fake hand (Dummer et al., 2009; Longo & Haggard, 2009; Kalckert & Ehrsson, 2012), while studies in IVR rely on full body tracking systems to provide synchronous or manipulated visuomotor feedback (Kilteni et al., 2013; Banakou & Slater, 2014; Kokkinara & Slater, 2014) using motion retargeting techniques (Spanlang et al., 2013). One of the earliest studies was carried out by (Dummer et al., 2009), where they were able to induce ownership over the rubber hand with synchronous *active* (movement performed by participant) and *passive* (movement performed by the experimenter) movement of the fake and real hands. This effect was demonstrated successfully in IVR as well (Sanchez-Vives et al., 2010; Yuan & Steed, 2010). Subsequently, FBOIs were also elicited in IVR using synchronous visuomotor feedback, while delayed or asynchronous feedback were reported to inhibit the illusion (Banakou et al., 2013; Osimo et al., 2015). It was found that temporal delays (500 ms or more) between the seen movement and the felt movement cause a significant decrease in the illusion (Longo & Haggard, 2009; Kalckert & Ehrsson, 2012; Kalckert & Ehrsson, 2014a). According to (Franck et al., 2001), the maximum acceptable temporal delay for participants to attribute a movement as their own was 150 ms, while (Shimada et al., 2010) found it to be about 200 ms. However, a study on delayed visuomotor stimulation with the Geminoid robot (as seen in Figure 2.8a) showed no significant difference in illusion in the synchronous and delayed feedback (1 second) condition, which implies that the underlying mechanism of the ownership illusion with a teleoperated robot may have some discrepancies as compared to the RHI (Nishio et al., 2012). Regardless, by using state-of-the-art tracking systems, we avoid most of the latency issues related to head and body tracking. As an example, the head tracker used in our studies has a reported latency of 4 ms (see Chapter 3 for full specifications of the materials).

Providing an operator with the ability to control a humanoid robot by simply moving their own body has been demonstrated several times in the last few years. The central issue that needs solving while developing a system like this is the fact that motion capture data always needs to be adapted for the specific robot that is being used. In all cases there is a mismatch, which is dealt with by developing a custom solution that works for that robot, typically using mathematical techniques such as inverse kinematics (Pollard et al., 2002; Yamane et al., 2003; Riley et al., 2003) (See Section 3.3 for an explanation of the methods used in this thesis). Using similar techniques, (Koenemann & Bennewitz, 2012) demonstrated real-time full body motion retargeting by using an Xsens MVN inertial tracking system for controlling an Aldebaran Nao robot. Additionally, they also developed methods to ensure the robot would maintain its balance, including during movement of its feet.

Though the aforementioned studies provide solutions for retargeting motion of the operator to a humanoid robot, they did not include any type of visual feedback to the operator from the perspective of the robot. The first time this was developed in the context of an immersive embodied application was by (Goza et al., 2004) with the Robonaut humanoid robot (Figure 2.6), using motion retargeting techniques described in (Miller et al., 2004). Since their focus was on developing the application and not on studying the psychological and perceptual factors of the illusion itself, only anecdotal evidence regarding the operator's experience was reported. They observed that the operator would *"jerk their feet back in response to falling objects nearby the robot"*, thus hinting that the operator may have felt some form of body ownership over the robotic body, as realistic responses to threatening events have been considered as an indicator towards body ownership (Armel & Ramachandran, 2003; Ehrsson et al., 2007).

More recently, several studies related to remote body ownership and agency with the Geminoid robot (as seen in Figure 2.8a) have been carried out. In the experiment by (Nishio et al., 2012) mentioned above, participants were given a 1PP view of the Geminoid's right arm through an HMD, which moved either synchronously with the participant, with a delay of 1 second, or did not move at all. In each of the conditions, the participants were asked to move their arms sideways for one minute after which the arm was threatened with an injection. The synchronous condition showed a significant increase in skin conductance response suggesting some degree of illusion. A subsequent study that used the same materials to test change in perspective and visuomotor correlation found that participants felt ownership even in the 3PP condition and the 1PP condition with a mirror (Ogawa et al., 2012). The setup that they used in their study



(a) **(b)**

Figure 2.10: Experimental setup of the FBOI experiment with the Geminoid HI-1 (Ogawa et al., 2012). (a) describes the experimental setup of the participant. (b) shows the view that the participants would see when looking through the HMD. Images taken from (Ogawa et al., 2012). © 2012 IEEE.

can be seen in Figure 2.10. Furthermore, (Alimardani et al., 2013; Alimardani et al., 2015) showed that even without direct control over the limbs of the Geminoid, FBOI and agency can be induced via indirect controls such as BCI. Similar results were seen by using fMRI as a control scheme as well (Cohen et al., 2012). This relationship of non-direct method of control with body ownership is discussed in Chapter 4 as it forms part of the hypothesis. These studies with the Geminoid provide a rare insight into understanding these perceptual illusions with a teleoperated robot, although these studies can be thought of to resemble the traditional mannequin studies more than the what we have described in the thesis for two main reasons. Firstly, the the highly customised, life-like appearance of the robot appears more like a mannequin rather than humanoid robot that is more 'robotic' in its appearance. Secondly, similar to the mannequin studies, their setup does not provide correlated head movement, and asks participants to focus only on the arms, without moving their head as it would not drive the head of the robot. However, in our setup we aim to provide the participant with complete control over all the limbs of the robot.

Finally, the last aspect of discussion related to visuomotor correlations is that of spatial accuracy of the movement. While we have discussed potential issues related to temporal delays and latency, spatial accuracy of the movement can also influence the perception of the participants. As mentioned above, retargeting motion capture data of a participant to a humanoid robot is a complex issue and requires advanced mathematical algorithms to solve. In addition, depending on the dimensions and actuator-type of the robot, some compromises may have to be made in terms of precision of movement in 3D space. Hence, it is essential to learn the extent to which discrepancies can be tolerated. Since most of the RHI studies that mentioned above involved placing an artificial (or virtual) limb that was not exactly collocated with the real hand, it is evident that small spatial incongruencies can be overcome, if the visuomotor correlations are synchronous. More specifically, no significant differences in body ownership were found when the artificial and real hand were separated horizontally by a distance of 10 cm, but still had synchronous movement (Yuan & Steed, 2010). Similarly, synchronous visuomotor correlation induced the BOI even with a vertical distance of 12 cm between the real and artificial hand, although larger distances (27.5 or 43 cm) significantly reduced the illusion but not agency, which was reported to be felt at all distances (Kalckert & Ehrsson, 2014b).

2.5 Summary

In this Chapter we have given an overall description of the various concepts of the literature that are referenced throughout this thesis. We provided an overview of various perceptual concepts relevant to the work presented here, such as self-perception, telepresence, virtual presence and its further subclasses. We also gave a detailed explanation of BOIs with emphasis on the various factors that influence the illusion, and extended the discussion to include FBOIs, using a mix of traditional studies with mannequins, studies in IVR with avatars, and a few studies with robots.

We have raised several issues throughout the various sections, regarding lack of information in certain areas, or shortcomings with some methodologies, that we have tried to solve with our work. Specifically, we have laid out two main issues in this Chapter that we would like to provide a solution for. Firstly, we throw light on the lack of a highly immersive telepresence system that can be used to provide a participant with a truly immersive and embodied experience with a remote humanoid robot. We present a novel solution for this issue in this thesis by proposing to use commercially available technologies like humanoid robots, tracking systems and HMDs for the purposes of tele-immersive communication. Secondly, we draw attention to the fact that very little knowledge exists regarding the perceptual and cognitive mechanisms of FBOIs and agency with humanoid robots. We try to apply the concepts learned from the FBOI studies mentioned in this Chapter, to develop a robust system capable of eliciting the feeling of ownership over a surrogate robotic body, and in the process try to improve our understanding of these topics. In Chapters 4, 5 and 6 we describe our solutions through experimental studies and a case-study of an immersive tele-journalism application.

Before that, however, in the next Chapter we will present the system that we have developed in order to successfully elicit full body ownership illusions with a humanoid robot. Also presented are some common methodologies and definitions of certain terms that are used for the remainder of this thesis.

* * *

> *"Science, my boy, is made up of mistakes, but they are mistakes which it is useful to make, because they lead little by little to the truth."*
>
> **Jules Verne**
>
> **Journey to the Center of the Earth, 1864**

3

Materials and Methodology

This Chapter presents the materials used and the basic methodology followed for all the studies that are part of this thesis. Since the work presented here relies on the concept of inducing full body ownership illusions, we first provide an explanation of how it is implemented. This includes a description of the various hardware systems required to successfully elicit a strong FBOI, along with a brief overview of the humanoid robots that we have used for the studies, focusing specifically on their specifications and constraints. Following this, we describe the motion remapping library that was developed specifically for the purpose of being able to control a humanoid robot by tracking natural body movement of the participant and retargeting it on to the limbs of the robot in real-time over a network connection. We then present an outline of the European FP7 Integrated Project BEAMING, under which the studies described in Chapters 5 and 6 were carried out, since many of the terms that are used to describe the various components of the studies have been defined under this project. Finally, the process of recruiting participants and potential ethical concerns are also addressed in the last section.

3.1 Embodiment

As discussed in Section 2.2.1, certain key factors are essential for eliciting BOIs. In this section, we describe the hardware and software systems that have been used in the studies mentioned in subsequent chapters. The setup described below has been developed in accordance with the framework described in (Spanlang et al., 2014), which, although has been described mainly in terms of eliciting FBOIs in IVR with virtual avatars, should be suitable with humanoid robots as well.

3.1.1 Head Mounted Display

The Head Mounted Display (HMD) is the device through which the participants view the remote environment. The HMD forms an extremely important part of the setup as this is what mainly separates the current system from traditional telepresence/telerobotic systems where the remote display is presented via a desktop screen. Utilising a high quality HMD that displays the remote environment from a 1PP of the remote body plays a crucial factor in inducing a high BOI over that body (Slater et al., 2010). As described in Section 2.2.2, this means that when the participants look down to see their body, it is replaced by the remote body instead (Figure 3.1). Additionally, instead of viewing the environment via a single camera, an HMD gives the participant the ability to view the remote environment in stereoscopic 3D, by streaming real-time stereo video to its left-eye and right-eye displays.

The specific HMD used for our studies is the NVIS nVisor SX111[1], as seen in Figure 3.2. The HMD is fitted with dual SXGA displays with 76°H x 64°V Field of View (FOV) per eye in a 13° outward rotated setup. The total horizontal FOV is 111°. Each display is driven at a resolution of 1280 x 1024 per eye and displayed at 60 Hz. A calibration step was implemented as well, since it is important to ensure optimal placement of the

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[1] http://www.nvisinc.com/product.php?id=48

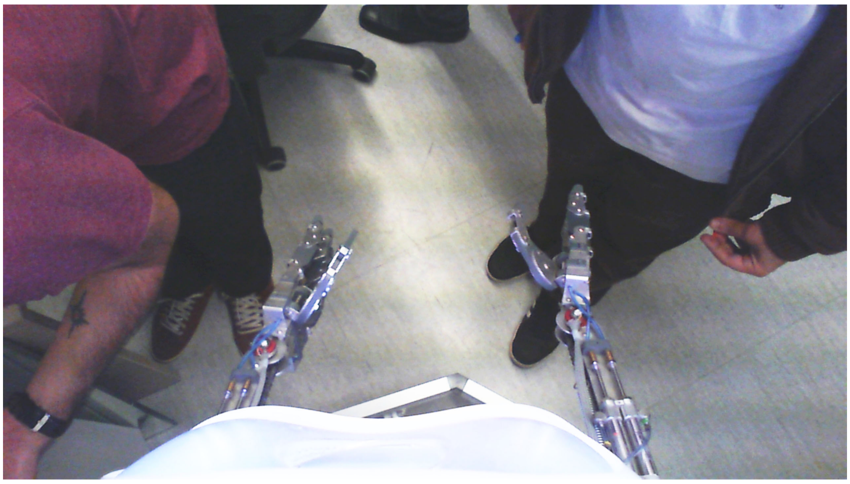

Figure 3.1: First-Person Perspective view of the Robothespian body. Participants can look around in the remote environment by moving their head naturally. Furthermore, when they look down they can see the robot body instead of their own. This visual sensorimotor correlation is a key factor in eliciting BOIs. (Slater & Sanchez-Vives, 2014)

left and right screens for each participant (Grechkin et al., 2010). The weight of this HMD is 1.3 kilograms, mainly due to its large screens. This factor was always taken into account while designing the studies since it has been shown that wearing a heavy HMD for a continuous period of time can lead to fatigue (Knight & Baber, 2007).

3.1.2 Head Tracking

In addition to being able to view a remote environment in stereoscopic 3D, the images displayed in the HMD need to be constantly updated, based on the head movement of the participants. Allowing participants to view the remote location in a natural way, i.e. by simply moving their head towards the direction they would like to view, leads to high visual sensorimotor contingencies (Slater, 2009), which is an essential requirement for presence (specifically place illusion) as well as eliciting FBOIs. This is implemented by tracking the orientation and position of the participant's head and mapping these movements on to the remote body, such that the remote view always stays updated. As

Figure 3.2: The NVIS nVisor SX111 HMD

described later in Section 3.2, both the robots used for our studies were fitted with a set of two webcams separated at the standard interocular distance on their head. Thus, direct mapping of the participant's head movement to the robot's head led to the view of the cameras being updated synchronously in real-time as well. The implementation of tracking and mapping these movements is discussed below in Section 3.3.

The head-tracker used in our studies is an Intersense 900[2] device. The device employs a hybrid acoustic/inertial technology to track head movement in 6 degrees of freedom (DoF). It provides a precision of 0.75mm and 0.05° with an update rate of 180Hz, and a latency of 4ms. Owing to the low latency and sharp accuracy, there is virtually no delay in capturing and streaming the head movements of the participants. The bottleneck may occur on the other end where this data is mapped on to a humanoid robot, based on the construction and movement mechanism of the specific robot that is used. However, both the robots used in this study have DC motors with high refresh rate for the neck actuators, thus providing precise control over the head orientations at all times. Furthermore,

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[2] http://www.intersense.com/pages/20/14/

since the tracking systems have a much higher refresh rate than the actuators of both robots, the values received by the robots at any given moment are always the latest, which ensure movement synchrony between the participant and robot throughout the experiment. Although, this might lead to the robots ignoring intermediate data frames sent by the tracking systems while they are performing their own built-in interpolation methods to move from one value to the next. This, however, was not noticeable in any of the studies and the movements appeared to be smooth.

3.1.3 Body Tracking

Similar to head tracking, the full body of the participants are also tracked. These body movements of the participants are captured, streamed and remapped to the remote body in real-time, thereby providing a high degree of visuomotor correlation. As discussed in Section 2.4.2, visuomotor feedback has been shown to be a powerful tool for eliciting the BOI. Furthermore, as was mentioned earlier, out of the two forms of stimulation, visuomotor edges out visuotactile correlations for eliciting a stronger FBOI (Kokkinara & Slater, 2014). Thus, participants were embodied in the humanoid robot with full control over the robotic body for the relevant studies. Multiple solutions exist for implementing full-body motion-capture, classified according to the technology that they are built upon, such as: *Optical, Inertial, Magnetic and Mechanical*. For the studies mentioned in Chapters 5 and 6, two different hardware systems were used.

3.1.3.1 Inertial Tracking Systems

The system described in Chapter 5 utilised the MVN system manufactured by Xsens[3]. It is a type of inertial full-body tracking system, which works with a specialised suit (Figure 3.3a) that contains gyroscopes and accelerometers to track the orientations and positions of each of the limbs of the participants. This system was specifically chosen for

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[3] http://www.xsens.com/

this case-study as it is extremely portable and provides high accuracy of motion-capture data. Portability played a huge role while choosing a system for this case-study since the journalist utilising the system would not be in a specialised laboratory environment. As compared to the marker-based optical system described in the following section, the Xsens does not need multiple cameras or any other specialised equipment other than the suit itself and the accompanying software running on a computer in close proximity. Furthermore, this suit has already been used for tracking and retargeting human motion to the Nao robot in real-time by (Koenemann & Bennewitz, 2012). A minor disadvantage of this suit, however, is that it is susceptible to positional/rotational drift over time, especially around metallic objects in the environment, but it can be fixed with a recalibration step whenever required.

3.1.3.2 Marker-Based Optical Systems

Marker-based optical systems, such as the Optitrack Arena System from NaturalPoint[4] (Figure 3.3b), require participants to wear a suit with reflective markers in a special room that is fitted with multiple infrared cameras. Two calibration steps are required in order to use this system - The first is calibrating the 12 cameras in the room so that they are set up correctly, without any points of occlusion in the tracking area. This needs to be done only once, and subsequently only in case the cameras might have moved. The second calibration is performed each time the suit is used, to map the morphology of the participant with the underlying skeletal structure of the system. Although this system is not portable, it provides high accuracy and is straightforward to set up. Portability was not a concern for the study in Chapter 6 since it was carried out inside the laboratory. Moreover, in a scenario where multiple participants would be participating in the study in rapid succession, it was essential to accommodate tracking suits of different sizes that could be set up fairly quickly. This can be easily done in the Optitrack system as the process involves simply replacing the reflective markers on to another suit via velcro.

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[4] https://www.naturalpoint.com/optitrack/

(a) Xsens MVN Suit **(b) NaturalPoint Optitrack Suit**

Figure 3.3: Two full-body tracking systems that were used. The suit shown in (a) was used for the system described in Chapter 5 due to its portability and high accuracy, while (b) was used in the study described in Chapter 6, owing to its versatility when being worn by multiple participants.

On the other hand, the MVN system described in the previous section can require up to 2 hours or more for wiring a suit of a different size.

3.2 Robots

Since the focus of the studies is on developing a general solution for robotic embodiment, and to demonstrate various real-world applications related to BOIs with robots, a reasonable approach was to purchase commercially available humanoid robots. Two different humanoid robots were used for the studies, chosen based on their physical specifications, ease-of-use and availability. Following is a short description of the robots, including motivation for selecting them for the purposes of this system. Additionally, limitations and restrictions in terms of dimensions or actuator design are also laid out.

3.2.1 Robothespian

The humanoid robot used for all three of the studies was the Robothespian, manufactured by Engineered Arts, UK[5]. The robot is a 1.8 metres tall humanoid robot, with two legs, a torso, two arms, and a head. The joints of the robot's upper limbs are pneumatic, driven by an air pressure pump, while the torso and head, each with three degrees of freedom, move with a DC motor. The shoulders have three degrees of freedom, the elbows have one degree of freedom, and the forearm has the ability to rotate along its own axis as well. The wrist, which has one degree of freedom, is left at its default value, as the tracking systems that we use do not provide information of hand rotation. The fingers, which can be programmed to be either *open (1)* or *closed (0)* are also left in the open state due to lack of information from the tracking system. However, devices such as the Leap Motion[6] or Perception Neuron[7] by Noitom can be potentially used to track and control the wrist and fingers as well. The robot also has a built-in speaker and an omnidirectional microphone that are used by a built-in Skype API for two-way audio communication by the participant to talk to people at the remote location, via the robot's body. Furthermore, the Skype API also detects incoming audio, which is used for simple lip-syncing by moving the robot's lower jaw based on the amplitude of the incoming sound.

The Robothespian was a fairly straightforward choice as a robot for studying FBOIs with humanoid robots. Already marketed as a telepresence robot designed for human interaction in public spaces, it has several features that can be used to great potential.

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[5] https://www.engineeredarts.co.uk/robothespian/

[6] https://www.leapmotion.com/

[7] https://neuronmocap.com/

Most importantly the robot is life size, with a height of 1.8 metres, which although is not critical for embodiment, but is certainly preferred as it seems to be more congruent with human height. In fact, in the study where it is shown that body height does not seem to affect the ownership illusion, they chose a height of 1.8 metres for the 'normal' condition (van der Hoort et al., 2011). Additionally, as mentioned above, it comes preloaded with several hardware and software systems that are relevant for our studies, such as speakers, a microphone and the Skype API. The robot is also fully programmable with the accompanying API that allows full access to all its joints, which is absolutely necessary in order to retarget the participant's real-time movement on to it. Finally, as discussed in Chapter 2, the highly robotic appearance of the Robothespian might actually give us an advantage, as compared to a highly lifelike android robot, given the Uncanny Valley hypothesis (Mori, 1970; Mori et al., 2012; Mathur & Reichling, 2016).

By default the Robothespian is manufactured with only a single built-in webcam on its forehead. This, however, would not be enough for our purposes. Since we require a stereoscopic video stream to be rendered in the HMD, we would need two webcams mounted on the robot at the standard interocular distance. This was a critical requirement as providing this 3D video stream is a fundamental feature without which none of the studies could be run. Thus, a customised Robothespian was ordered for the laboratory with two consumer Microsoft HD-3000 webcams mounted on the robot's forehead. The feed from these two cameras could then be streamed to the HMD of the participant, who would have 1PP from the robot's body.

The legs of the Robothespian are not programmable and are solely for aesthetics. Therefore, the lower half of the robot is fixed in place which inhibits movement in space. However, to implement this feature, specifically translation and rotation on the ground, a programmable platform was purchased for this specific purpose from the Department of Robotics of the Polytechnic University of Catalonia, on which the robot was mounted. The platform is built with electric motors, has two degrees of freedom and can be controlled via UDP messages sent through the network. Using the position and orientation values of the torso of the participant, we could compute their movement in 2D space,

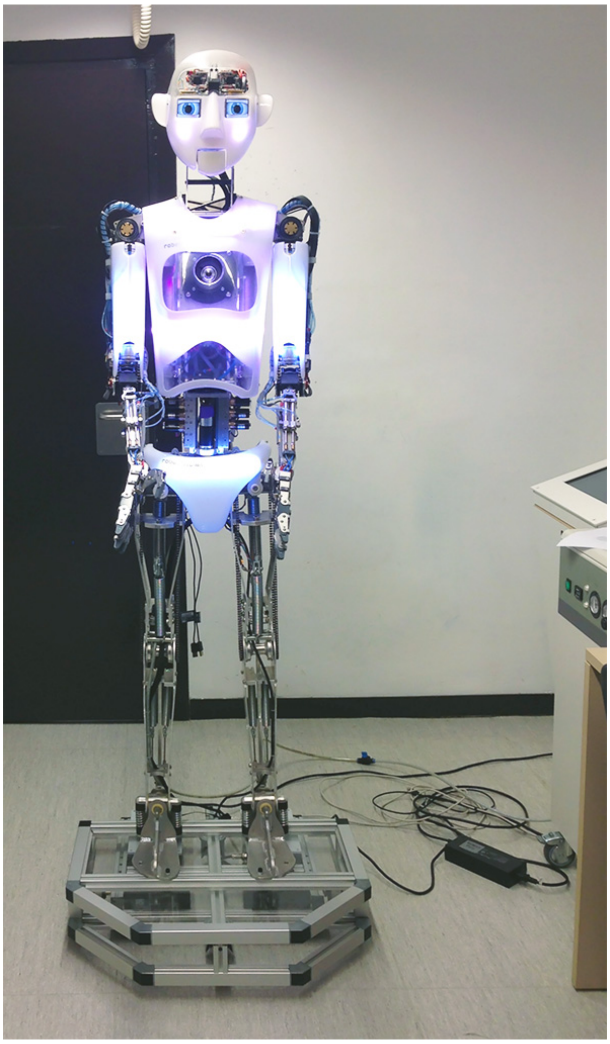

Figure 3.4: The custom-built Robothespian with two webcams on the forehead, mounted on a moveable platform.

which would drive the platform. The method is described in more detail below in Section 3.3. A photograph of the custom Robothespian with two webcams, mounted on the platform is shown in Figure 3.4.

3.2.2 Nao

The Nao, manufactured by Aldebaran Robotics, France[8], is also a humanoid robot, although is much smaller in height at approximately 60 cm. All the joints are operated by DC motors, with 2 degrees of freedom in the head and 5 degrees of freedom in each arm and leg. The Nao was chosen to be the second robot for the study described in Chapter 6. There are several advantages of using this robot for this type of research. The Nao is useful in terms of cost and portability, and moreover, as discussed in Section 2.4, several characteristics of the Nao suggest that it could be used successfully for eliciting FBOIs. Studies have shown that height of the artificial body is not a critical factor with FBOIs being successfully induced with artificial bodies ranging from 0.3 metres to 4 metres (van der Hoort et al., 2011), a range that includes the Nao's height of 0.6 metres, as well as in a virtual 4 year old child-body (Banakou et al., 2013). In terms of appearance, one of the first studies about FBOIs was done with a plastic mannequin, and the exterior of the Nao is completely plastic as well (Petkova & Ehrsson, 2008; Petkova et al., 2011), although no studies were found that used a plastic mannequin of a short height. Finally, the API of the Nao is easy to set up, and allows for highly customisable control over the robot's limbs, and researchers have already developed solutions for real-time motion retargeting with the Nao (Suay & Chernova, 2011; Koenemann & Bennewitz, 2012; Wang et al., 2015). However, the motion retargeting system we used for our studies (Section 3.3) was developed from the ground-up, since we wanted a universal solution for simultaneous control of both the robots and virtual avatars as well.

Contrary to the Robothespian, the Nao is manufactured with two webcams, however they are arranged on a vertical axis rather than a horizontal one, with the lower camera under the chin of the robot. This is done mainly for developing typically autonomous programs with the Nao that allow it to view the ground where it walks, for potentially

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[8] https://www.aldebaran.com/en/cool-robots/nao

avoiding obstacles using computer vision techniques. This feature is especially important for the Nao, as it was used as the official robot for the robots-only football championship, the 'RoboCup' (Kitano et al., 1997). For our purposes, however, this would not work as we require two cameras on a horizontal axis, separated by the standard interocular distance. Thus, a helmet with two Logitech webcams placed appropriately was mounted on top of the robot's head (Figure 3.5).

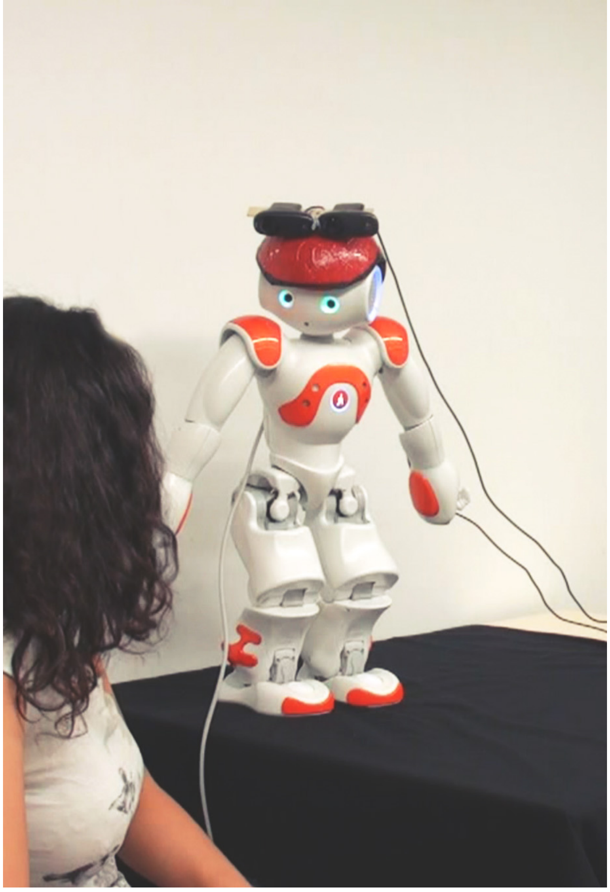


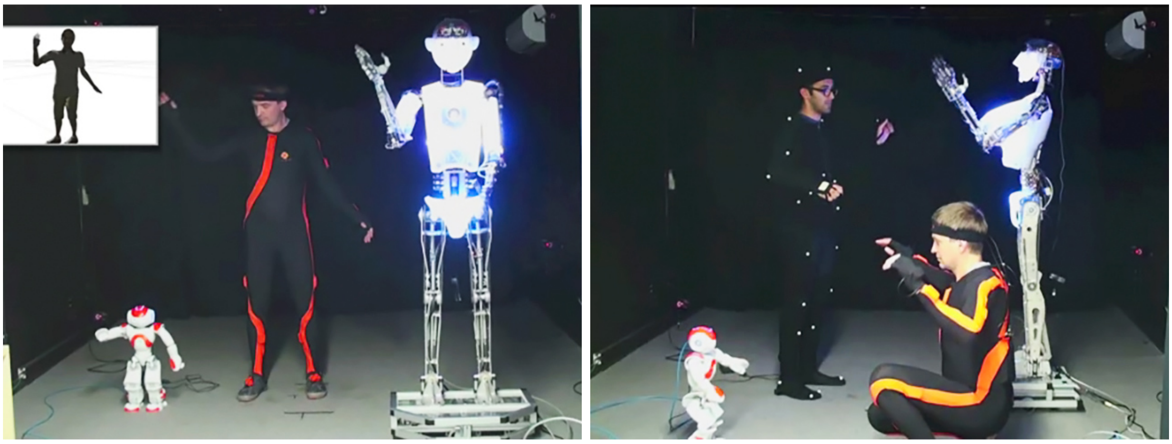
Figure 3.5: The Nao fitted with two webcams attached to a helmet

We have discussed the importance of being able to view a body in 1PP and looking down to see the surrogate body instead of their own increases the feeling of the body-ownership illusion (Petkova & Ehrsson, 2008; Maselli & Slater, 2013; Slater & Sanchez-Vives, 2014). However, with the Nao and the Robothespian, it was not possible to look down at one's own body due to the limitation of the range of the head movement of the robots. To overcome this, a mirror was placed in each of the studies, which was pointed towards the robots, as it has been shown to have great importance in eliciting stronger feelings of the body ownership illusion (González-Franco et al., 2010; Preston et al., 2015).

3.3 Motion Remapping Library

As we mentioned earlier when talking about correlating the participant's movement with the robot to elicit BOIs in Section 2.4.2, an issue that arises with using different body tracking systems with different kinds of humanoid robots is that their tracking data may be represented in different formats. Moreover, since there is no standard based on which these systems are developed, there may be discrepancies in the number of tracked joints or bones, different coordinate systems using either absolute positions or relative positions with respect to a root bone, or even varying bone lengths and their relative rotations. On the other hand, the skeletal structures used by the tracking systems may be completely different from the internal structure of the robots being used. We have already discussed about the huge variability in terms of anatomy, actuator type and dimensions in humanoid robot design (Section 2.4.2).

Because of these issues, we have developed a library that enables us to map the skeleton from a variety of tracking systems to many different types of humanoid skeletons (virtual avatars or humanoid robots) (Spanlang et al., 2013). The library, which is named *HUMAN*, provides specific features useful for mapping different skeletal structures, such as control over the mapping of each bone, specification of the coordinate system, and providing rotational offsets, if required. Building on the character animation library HALCA (Gillies & Spanlang, 2010) (Hardware Accelerated Library for Character Animation), the library allows us to map the movements from any of the compatible tracking systems to a humanoid robot or a virtual avatar in real-time (See Table 3.1 for details). The library also allows control over more than one robot simultaneously. Figure 3.6



(a) (b)

Figure 3.6: Examples of combinations of tracking systems for controlling humanoid robots, using the HUMAN library. The participant in (a) controls both the Nao and Robothespian, and a RocketBox avatar with the Xsens MVN system. (b) shows an example where two participants physically interact with each other's humanoid robot representations. One participant controls the Nao via the Optitrack system, while the other participant controls the Robothespian with the Xsens MVN system.

shows some of the possible combinations of the various tracking systems controlling the humanoid robots that have been discussed above. Although various components of this system have been implemented earlier, such as the immersive teleoperation system by (Nishio et al., 2012). However, their system lacks a full-body tracking system. On the other hand, the paper by (Goza et al., 2004) describes a highly specialised system similar to the one we describe, however, to our knowledge our system is the first time a universal comprehensive solution has been provided, using commercially available technologies.

The HUMAN library is built on an XML based orientation file (XOF) and an avatar skeleton file (XSF) to map the data of the corresponding bones and joints. The XOF file describes the coordinate system transformation from the motion-capture system to the avatar's coordinate system, and maps the corresponding bones with each other. The library uses the XSF format to describe the skeletal hierarchy along with initial transformations.

Although the library was developed initially only for virtual avatar families (such as RocketBox[9] and Daz3D[10]), we incorporated support for mapping humanoid robots specifically for the purposes of carrying out the research presented in the following chapters. However, mapping real-time tracking data to a robot's limbs is very different from doing the same task with an avatar. As mentioned earlier, various robots are built differently, with different types of motors and actuators controlling their limbs, which in turn define the constraints of the system. The degrees of freedom associated with a robot's limb will dictate the degree of accuracy and control the user will have while controlling it. The more closely a robot's limbs have been built to the likeness of a human limb, the more precise the motion can be. Other factors, such as if the robot has the ability to walk, or translate and rotate in a physical space also determine if a real-time mapping of those movements is feasible or not.

The algorithm that has been developed for real-time retargeting modifies orientation and position data for each bone obtained from the tracking system into 'robot friendly' angles. The whole process was developed initially for the Nao robot, but was later adapted for the Robothespian. This was fairly straightforward as the core algorithm of converting data was the same as with the Nao, but with the addition of extra rotational offsets to adapt the values according to the Robothespian's reference frame. Although our solution worked well most of the times, a few movements, especially when the arms were stretched to their extremities would result in discrepancies between the performed movement and the robot's movement. Furthermore, both the robots have angular limits in each of their motors, and any value supplied that is out of range of acceptable movements is ignored. Thus, performing a movement that goes beyond what is physically feasible for the robot also leads to the robot moving all the way to its limit and then stopping, resuming again when the values return into the acceptable range. Although

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[9] http://www.rocketbox-libraries.com/

[10] http://www.daz3d.com/

we have seen that slight amounts of spatial discrepancies could be ignored, these positions for both the robots were identified while developing the system, and were kept in mind while designing the studies in order to deter participants from making these poses.

Finally, a solution was also developed in order to allow the robots to 'walk' around in space. Developing a solution for implementing real-time walking depends heavily on the configuration and physical ability of the robot. While theoretically it seems possible to develop an algorithm that accomplishes it based on the same way as the upper body, practically it is not as straightforward and depends on many factors, such as the walking speed, balance and stability of the robot. Usually, since robots have a low speed, and do not have the same dimensions as the participant controlling it, directly mapping the movement of the legs is not a feasible solution, and also may result in loss of balance, although the solution developed by (Koenemann & Bennewitz, 2012) takes the centre of mass of the robot into account as well, thereby always maintaining the balance. However, even if this were implemented, it would only work for the Nao and not the Robothespian, as the latter does not have programmable legs. Hence, a universal, generic solution for this problem was devised. The algorithm we have developed for translation and rotation in space instead tracks the torso position of the user rather than individually tracking the legs. Initially, the user's torso position (2D coordinates on the X-Z plane) is obtained and at every frame, it is compared with the updated position of the torso. Whenever a robot-based threshold is crossed, the walking mechanism is triggered. The advantage of this algorithm is that it is robust and can be used with any robot that has the ability to move, and does not depend on how the robot moves. It could have any mechanism, such as legs, wheels, a movable platform, and the algorithm would still work. This mapping library, including the section with motion retargeting to humanoid robots was presented at the VRST 2013 conference as a systems paper (Spanlang et al., 2013).

Table 3.1: Motion-Capture systems tested with various avatars and robots.

Tracking Systems	Avatar Families		Humanoid Robots	
	RocketBox	Daz3D	Robothespian	Nao
OptiTrack	✓	✓	✓	✓
Xsens	✓	✓	✓	✓
Kinect	✓	✓	✓	✓
Organic	✓		✓	
Animazoo	✓			

3.4 Software

Managing the tracking systems and humanoid robots, in addition to video and audio streaming requires the use of a software platform where the various aspects can be handled efficiently. For the first two studies (Chapters 4 and 5), a virtual reality toolkit called XVR[11] (Tecchia, 2010) was used. XVR was chosen due to its low cost, and its ability to include external plugins, such as the HUMAN library. Moreover, since it has been developed specifically for building VR applications, it has built-in support for stereo rendering to HMDs and provides an interface for accessing tracking information via network connections, such as VRPN (Taylor II et al., 2001). For the third study (Chapter 6), Unity3D[12] was chosen as the environment instead of XVR. This was done since Unity3D has an intuitive Integrated Development Environment (IDE), which simplified much of the development that was required for building the complex setup for that specific study.

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[11] http://www.vrmedia.it/en/xvr.html

[12] http://www.unity3d.com/

Additionally, similar to XVR, it also provides the ability to use external plugins such as the HUMAN library. The HUMAN library itself was written in C++ and compiled in Microsoft Visual Studio[13]. It was compiled as a Windows Dynamic Link Library (DLL) file so it could be used in XVR and Unity3D as an external plugin.

As mentioned earlier, the stereo cameras mounted on the robots would stream stereoscopic video data to the HMD of the participant in real-time. In the other direction, the participant's body-tracking data would be streamed to the remote robot synchronously as well. Both the streams of data were transmitted through a high-bandwidth Internet connection. It was critical to have all these streams synchronised so that there was no latency or lag in the communication. In terms of network usage, the stereo video streams required the most amount of bandwidth. Thus, the video frames were compressed using the VP8 video codec (Bankoski et al., 2011) prior to streaming. The stereoscopic view was created in the HMD by mapping the appropriate streaming camera image for each eye onto planes placed in front of the participant.

3.5 Audio

Two-way audio communication was provided to participants for all three studies, so they could interact with people present in the remote environment. Wireless Asus HS-1000W[14] headsets were used for carrying out the audio communication. For the studies in Chapters 4 and 5, the audio streaming was enabled via the built-in Skype API[15] of the Robothespian. However, the same technology could not be used for the study described in Chapter 6 since we needed a separate audio stream manager that would allow instant switching between various channels during run-time of the system (See Section 6.2.1.3).

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[13] https://www.visualstudio.com

[14] https://www.asus.com/Headphones-Headsets/HS1000W/

[15] https://www.skype.com/en/developer/

3.6 BEAMING Terminology

As briefly mentioned in Chapter 2, the studies described in Chapters 5 and 6 are based upon the foundations laid out in the BEAMING project[16]. The BEAMING project (Being in Augmented Multimodal Naturally Networked Gatherings) (Steed et al., 2012) involves transmitting a digital representation of a person from one place to another, but where they can be physically embodied in the remote place. Several real-world applications that exploit the underlying BEAMING architecture have been developed in the course of the project, such as performing remote acting rehearsals (Normand et al., 2012b; Steptoe et al., 2012), instruction of a musical instrument, as well as remote medical rehabilitation (Perez-Marcos et al., 2012). It has even supported the teleportation of a human into the cage of a rat, allowing real-time interaction between rat and human, each at their own scale (Normand et al., 2012a). Finally, design considerations for building a fully immersive robotic telepresence setup have also been discussed (Cohen et al., 2011). To ensure consistency while referring to the various concepts involved, certain terms are defined as part of the project, which are also used in the studies to refer to the various system components:

- *Visitor*: The person who ‘travels’ to the remote location.
- *Transporter*: This is the system used to ‘beam’ the visitor - with a high-resolution wide field-of-view and head-tracked HMD, full-body tracking systems and high-end audio devices. This technology is used to capture multisensory data of the visitor, and transmit it to the destination, as well as to digitally display the destination to the visitor.
- *Destination*: The destination is the remote physical location to where the visitor is transported. Here, it is required for the visitor to be represented in some way, for example, as a humanoid robot.

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[16] http://beaming-eu.org

- *Locals*: The people present in the remote destination who can interact with the visitor are referred to as locals. Ideally the locals should not be encumbered by any equipment in order to be able to see and interact with the remote visitor.

3.7 Recruitment and Procedures

Participants recruited for the studies in Chapters 4 and 6 were mainly (although not exclusively) students from the Psychology campus of the University of Barcelona. Prior to starting, participants were provided with verbal and written information regarding the experiment and were informed that they were free to withdraw whenever they desired, and without giving any explanation. The information sheets, consent forms, demographic questionnaires and the post-experiment questionnaires for the experiments can be seen in Appendix A and C, respectively. The questionnaire given to the locals that attended the Tele-Immersive Journalism interviews has been provided in Appendix B. All the experiments were conducted in either Catalan, Castilian Spanish or English, depending on the participant's language of preference, and the documentation was also always available in all three languages. All participant data was kept anonymous, and no personal data was published. Quotes provided by the participants in their post-experiment interviews have also been kept anonymous. Both the experimental studies carried out were approved by the Comissió Bioètica of Universitat de Barcelona.

* * *

“Blinking, Jake slowly sits up on the gurney. He looks down at his avatar body, touching his chest with one hand. He stares at his legs, eases them off the gurney and… His blue feet touch the concrete floor, taking his weight. Jake stands, feeling the strength in his legs. His expression is child-like with wonder.”

James Cameron

Avatar, 2009

4

Robot Control using BCI and Eye Tracking

This Chapter presents the study related to the first hypothesis: *It is possible to induce the full-body ownership illusion over a remote robotic body with a highly robotic appearance. Moreover, it is possible to induce feelings of agency over the robotic body, even with non-manual control.* As we discussed in detail in Chapter 2, it has been shown that the full-body ownership illusion over a mannequin body is possible (Petkova & Ehrsson, 2008; Petkova et al., 2011). Moreover, the illusion has also been successfully elicited using a Geminoid HI-1 robot (Nishio et al., 2012; Ogawa et al., 2012), although the robot used in these experiments was specifically built to resemble a human. Our primary objective was to investigate whether it is possible to induce the BOI over a robotic body with a highly ‘robotic’ appearance. Instead of providing participants with direct control over the limbs of the robot, we chose to compare two indirect methods of control, an SSVEP-based BCI and an eye tracker. The motivation for this decision was based on the fact that we wanted to develop the concept of a real-world application, where this setup could be used to provide a physical surrogate for people with reduced mobility. The methods and results of this study were presented at the 1st VERE PhD Symposium in 2011 and later published in the journal *Presence: Teleoperators and Virtual Environments* (Kishore et al., 2014). A video of the experimental setup and procedure can be seen at: https://youtu.be/iGurLgspQxA.

4.1 Introduction

As discussed in Section 2.2.1, the illusion of ownership over a static mannequin body that substituted the real body was first shown by (Petkova & Ehrsson, 2008). Following from this work, we have also seen that the same type of body ownership illusion can be achieved with a virtual body in immersive virtual reality (Slater et al., 2010). Evidence suggests that 1PP over the virtual body can be a sufficient condition for the illusion (Maselli & Slater, 2013), but that synchronous movement between the real and virtual body can also contribute strongly to the illusion (Banakou et al., 2013; González-Franco et al., 2010; Peck et al., 2013). Moreover, we also discussed that in a direct comparison between synchronous visuotactile stimulation and synchronous visuomotor stimulation, that the latter wins out (Kokkinara & Slater, 2014).

In the experiment presented, the participants had a 1PP from the point of view of the robot; thereby, substituting the robot body for their real body in the sense that when looking toward the mirror, participants saw the robot body instead of their own. It was uncertain whether the FBOI would be induced in a robot with a humanoid, but also highly robotic appearance, as some results suggest that the body has to be humanlike in form and appearance (Section 2.4.1). Furthermore, motivated by the enabling situation, i.e. where the person for which the system is intended cannot manually control such a humanoid robot by moving his or her limbs (e.g., quadriplegics) we limited the control of the robot to abstract methods. This forms a highly critical difference between the presented experiment and the study by (Nishio et al., 2012; Ogawa et al., 2012), where direct correlation between hand movements was provided, although in a more recent study BCI-based control was also developed with the Geminoid HI-1 robot (Alimardani et al., 2013; Alimardani et al., 2015).

The relationship between body ownership (this is my body that is moving) and agency (I am responsible for moving my body) has been the subject of many studies (Kalckert & Ehrsson, 2012; Sato & Yasuda, 2005; Tsakiris et al., 2007). The general view is that although there is a dissociation between ownership and agency in the sense that one can be diminished without affecting the other, it is also the case that the very factor that induces agency (direct control of a limb or body) has been shown to induce an ownership illusion over a virtual hand that moved in synchrony with the real hand (Sanchez-Vives et al., 2010) and even when the hand was moved by a BCI (Perez-Marcos et al., 2012). Therefore, one of the primary focuses of this paper was to examine the extent of body ownership induced by embodiment in a robot body, where there might or might not be a sensation of agency achieved through an abstract control method.

Two existing technologies to control the robot by nonphysical means were tested: a Brain-Computer Interface and eye tracking. Both are established paradigms and appropriate for usage in immersive settings such as the one in our experiment (Friedman et al., 2010). We elected to use the real-time BCI paradigm, Steady-State Visually Evoked Potential (Wang et al., 2006). An SSVEP-based BCI was chosen because it has been shown to be usable by most people (Guger et al., 2012), can differentiate multiple commands, including an idle state, and does not require extensive training to achieve proficiency (González-Franco et al., 2011; Guger et al., 2003). SSVEP functions by users visually observing stimuli that are continuously blinking at different frequencies; these frequencies are replicated in the visual cortex and can be detected with scalp EEG (Electroencephalogram).

An alternative technology that also uses the human visual system, eye tracking, holds great potential in this domain, but has been explored mostly in desktop settings or in real-world settings that do not include the complication of HMD hardware (Majaranta et al., 2011). Eye tracking works by focusing the eye on a particular screen position; items can include an extra triggering mechanism. The de facto standard triggering mechanism requires the user to focus on a point for an extended period, in order to signify the ‘click’. Although it is a common view that eye tracking is a viable method and would be a much simpler substitute for SSVEP, however, the two methods have not been directly compared in an HMD in an immersive setting.

4.2 Materials and Methods

The experiment was designed to expose participants to remote embodiment in a humanoid robot, seen in Figure 3.4, to see whether the BOI could be induced in this body. The experiment can be considered a between-subjects design with a single binary factor: SSVEP-based BCI and dwell-based Eye Tracking (ET).

Twenty able-bodied participants (mean age = 20.9, SD = 2.1, 10 men, 10 women) were recruited from the university campus. One participant could not complete the task, due to calibration of the eye tracker not being possible after 20 minutes of trying, and was excluded from the analysis. All subjects were naive to the experimental conditions and gave informed written consent. They were paid 5 € for their participation.

4.2.1 Materials

A customised Robothespian humanoid robot manufactured by Engineered Arts was used for this experiment. The exact specifications and the technical hardware details of the Robothespian that was used are described in Section 3.2.1. The two webcams (Microsoft HD-3000) in its forehead, positioned with a standard interocular distance, provided the 3D stereoscopic view of the environment, with four overlaid boxes that acted as triggers. Four poses were preprogrammed for the purpose of this experiment; when triggered, the robot moved to the selected pose and would stay in that pose until the idle state was triggered, taking it back to the resting position. This was implemented by modifying the motion retargeting library to include triggers for predefined poses. In both control methods, the robot gestures were activated by interacting with overlain boxes. The exact specification and design rationale of the boxes is explained in the following sections.

Participants viewed the remote location via the head-tracked NVIS nVisor SX111 HMD, the exact specifications of which are mentioned in Section 3.1.1. Head tracking was used in our experiment on two grounds. Many disabled and paralysed patients have preserved head movement, although they lack control over the rest of the body. Another factor is that able-bodied participants do move their heads, and a lack of correlated head movement would have likely contributed to simulator sickness. Figure 4.1 shows the physical setup.

4.2.2 SSVEP Setup

In the experiment presented, we leveraged existing SSVEP technology from Guger Technologies OG. The technical aspects of the SSVEP setup, including the classification and performance characteristics, have been presented in (Guger et al., 2012). Eight active electrodes were located over the visual cortex (PO7, PO3, POz, PO4, PO8, O1, Oz, O2), the ground electrode was located on the FPz, and the reference on the right earlobe. The electrodes fit under the HMD, without compromising the signal, since the HMD weight is distributed over the fronto-parietal junction, across the top of the head. The internal bandpass filter of the g.USBamp was set to 0.5 to 60 Hz.

The HMD was driven at a constant update rate of 60 frames, leading to a maximum stimulus frequency of 60 Hz. After experimentation, four stimulus frequencies were chosen: 8.57, 10, 12, and 15 Hz. The visual stimuli were boxes, chosen because they are common in existing SSVEP experiments. The boxes were displayed over the video stream and extended over 3.5° of FOV. All boxes were placed at least partially into the overlapping areas of the stereoscopic pair, as preliminary tests indicated that SSVEP

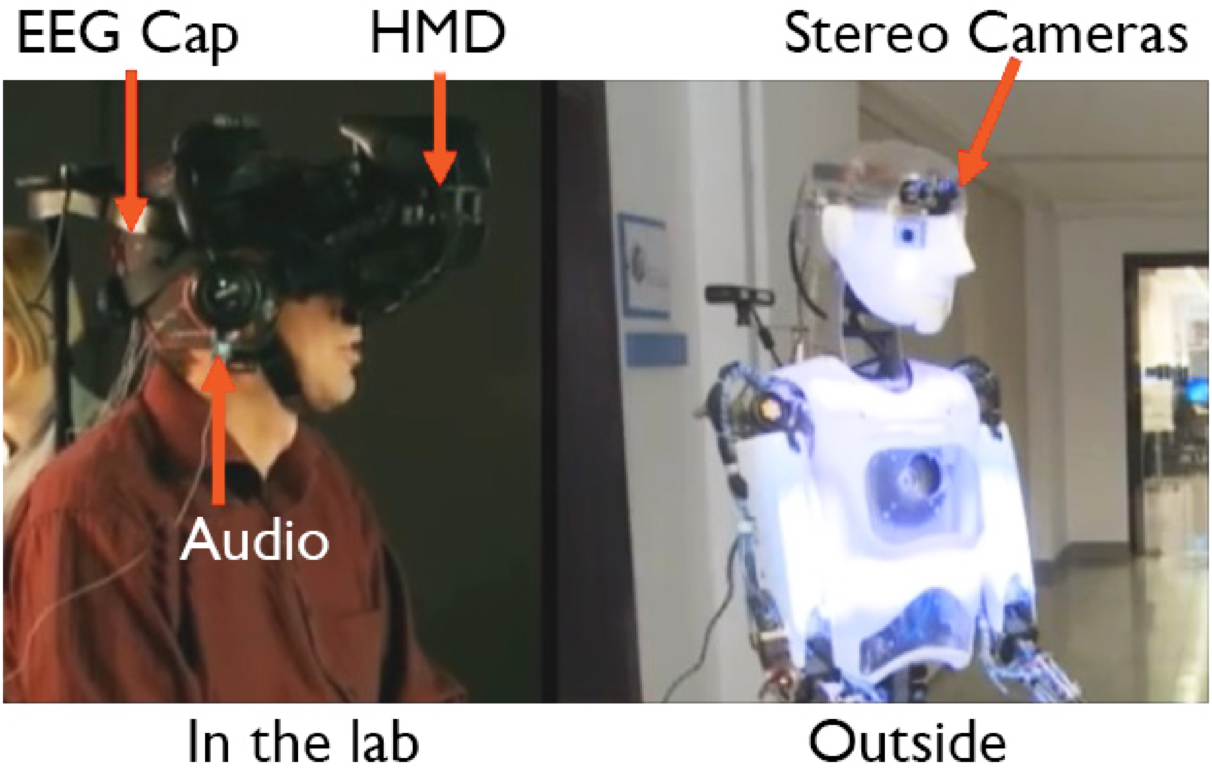

Figure 4.1: Experimental setup: on the left, the participant in the lab, fit with the HMD and the EEG cap (only for the SSVEP condition) and the headset for communication; on the right, the robot in the outside area with the stereo camera.

classification was better when they were seen in both eyes, and it was more comfortable to view. The boxes were laid out in an equally spaced cross with an extent of 6.2° FOV.

The SSVEP training was based on a minimum energy parameter estimation algorithm and classified with a Linear Discriminant Analysis (LDA) into one of the four classes using the same procedure as explained in (Guger et al., 2012). The data obtained from the training session for the classifier was also recorded in the HMD. During the training, each stimulus was viewed for 8 seconds, a total of six times, then an SSVEP offline error rate was calculated based on the minimal error of classification after 6 seconds of continuous observation of the stimuli using the training data. During the experimental session, a real-time, zero-state classifier was used. A 3 second window was used for classification and was evaluated every 200 ms. The multi-class LDA calculated scores for each class, as explained in (Kapeller et al., 2013). Those scores were normalised using a Softmax transform (Volosyak, 2011). A threshold based on the 95% confidence interval was used to accept or reject the classification.

4.2.3 Eye Tracking Setup

The HMD was factory fit with a ViewPoint Eye Tracker by Arrington Research[1] in the right eye. This tracker is specifically made for use in HMDs. The initial calibration was done following the procedures described in (Borland et al., 2013). Control of the robot gestures was performed by dwelling on the same boxes as the SSVEP condition, although since there was no need for them to be blinking in this condition, they were displayed statically. A dwell time of 1 second was chosen for the trigger to limit the number of false positives, that is, the Midas' touch issue (Penkar et al., 2012). A short in-world training was developed for this, optimising participant performance on this particular control setup. A cone was temporarily displayed on screen, pointing in the detected gaze direction. Participants were advised on how they could slightly adjust the location of their gaze, in order to trigger the gestures more accurately. The cone originated in front of the right eye. It was helpful for learning to use the tracker, but was also uncomfortable to view and blocked participant's vision; therefore, it was removed prior to starting the experiment.

4.3 Scenario and Procedure

The basic scenario was a social, robotic telepresence setup. Participants saw the remote physical setting via a stereo HMD, where the stereo-paired images were produced by

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[1] http://www.arringtonresearch.com

two cameras mounted just above the eyes of the robot, which was physically located just outside of the laboratory where the participants were seated. A mirror was placed on a table directly in front of the robot, such that the participants were able to see the majority of the robot body reflected, a setup that has been shown to be effective in inducing BOI (González-Franco et al., 2010; Preston et al., 2015). The participant interacted with the experimenter in the remote space.

The same procedure was followed for both SSVEP and eye-tracking conditions, with the exception of the initial, condition-dependent setup. Participants were familiarised with the equipment and the robot. They were shown the overlay interface, consisting of four boxes seen in front of the remote scene, for triggering the gestures, and were informed of each gesture. The calibration of the system per condition was then undertaken.

In the SSVEP condition, participants were instructed about how to control the SSVEP interface. Although four subjects reported having experience with EEG, none was experienced with SSVEP. The EEG cap was mounted and the HMD donned. The SSVEP training was performed as outlined in Section 4.2.2. The HMD was removed during offline generation of the classifier. Up to three trainings were performed and the classifier with the lowest error was used; if the participant achieved a classifier error of less than 15% in any training session, that classifier was used without further training. Once the classifier was trained, the HMD was placed again for the experimental session. In the ET condition, initial calibration was performed as outlined in (Borland et al., 2013). Training with the full interface was performed with a cone, as previously described.

At this point, the main task started for both conditions, and the procedure was the same for both. Video streaming from the two robot eye-positioned cameras was started, along with the sound connection between the spaces. Participants were encouraged to move their heads and look around and were greeted by the experimenter who was now in the external space with the robot.

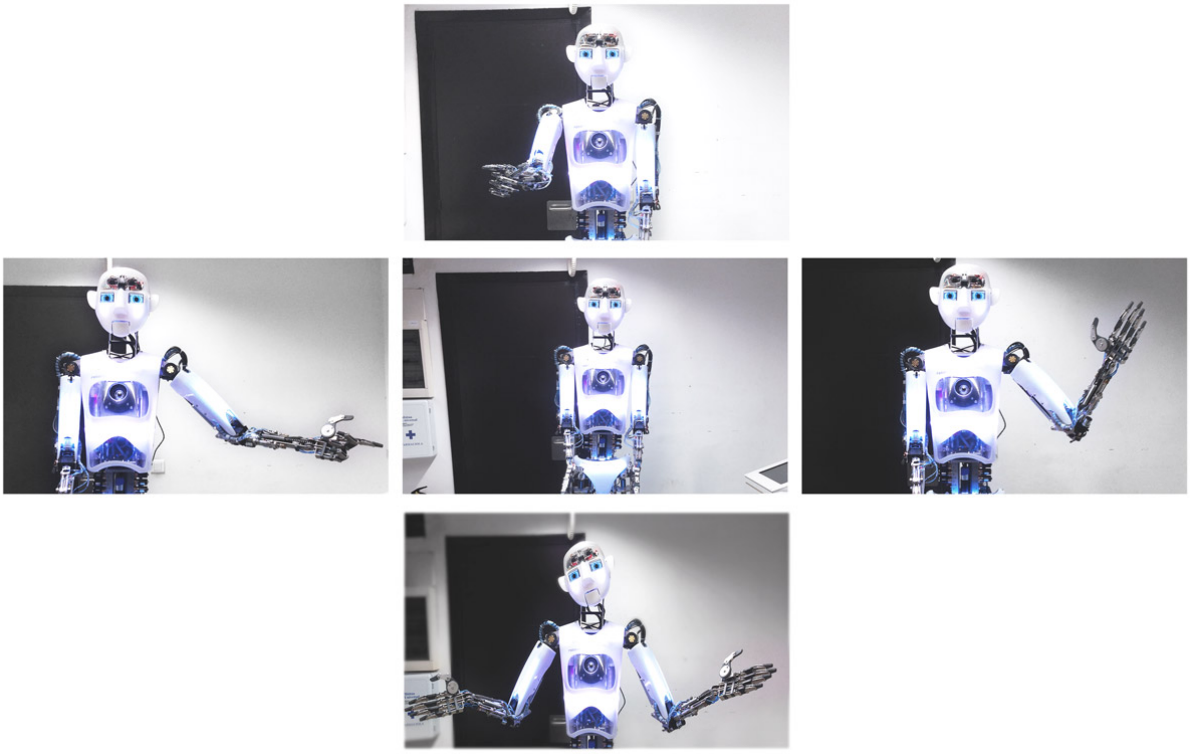

Figure 4.2: The boxes that overlay the video stream triggered the corresponding robot actions: when the left box was selected, the robot pointed to the left; when the upper box was selected, the robot pointed to the front; with the right box, the robot waved hello, and the lower box triggered the 'I don't know' gesture. The idle robot state was triggered by looking anywhere away from the four boxes.

Four robot actions were created specifically for the experiment, as illustrated in Figure 4.2. These actions were chosen for their simplicity and for their appropriateness as gestures in a social setting. Now embodied in the robot, participants were again instructed informally about how to trigger each of the gestures. Then the skill test was started, where participants were asked to trigger each of the four actions four times. The experimental setup is shown in Figure 4.3. The participants' performance was measured during this part of the experiment. After the Skill Test, the experimenter left to return to the laboratory. The session was then ended, and the equipment was removed from the participant. The participant then answered the post-session questionnaire.

Figure 4.3: View from the robot eyes. Boxes overlain on the real life streaming that allow the robot control in both conditions. In this image we can see the mirror facing the robot, the control boxes that the participant used to trigger the gestures, and the experimenter that interacted with the robot.

4.4 Measures

A custom post-experiment questionnaire was used to access four main components of the participant experience: BOI, Place Illusion (PI), agency, and interface usability. All questionnaire responses were recorded on a Likert scale, and data were considered ordinal. The central experience questions can be seen in Table 4.1. BOI was addressed by variations of standard questions (González-Franco et al., 2010; Slater et al., 2010): *body*, *robot body mine*, *mirror me*, and *2 bodies*. The question *arm me* was added, since the arm was the only part of the body that could be seen directly. PI as mentioned in Section 2.1 is a subcomponent of presence and refers to the feeling of being in present in the place presented (Slater, 2009). Questions *PI seen*, *PI person*, and *direct interaction* addressed this concept. Two questions addressed the feeling of Agency: *robot body mine* and *control robot*.

A secondary goal of this experiment was to contrast the relative performance of two established control methods and any impact they might have on the experience of BOI and PI. As such, the measures implemented did not focus on the technological performance characteristics of the methods; instead, the measures focused on the participant's perceived ability to use the interfaces via self-report methods. This was assessed with a set of questions, as listed in Table 4.2. The participant was asked to trigger each of the movements that the robot could perform with four trials each. If the participant was able to trigger the designated movement, it was counted as a successful trial. If another movement or no movement at all was triggered, the trial was marked as failed.

The social experimental scenario made it difficult to access the ground truth, thereby precluding the usage of traditional measures for these technologies, such as false positive rates. Since our focus was not on the technologies per se, we omitted such measures. However, we report the classifier error of each training session for the SSVEP condition, since the data was readily available.

4.5 Results

The task performance results are shown in Table 4.3. Performance on the skills test, in terms of total count of gestures triggered, was not significantly explained by condition (Zero-Inflated Negative Binomial Poisson Regression: count component: $\beta = .05$, $Z = .2$, $p = .8$, zero inflation component: $\beta = 18.7$, $Z = .0$, $p = 1.0$).

Table 4.1: Post-experiment Questions Related to BOI, Place Illusion, and Agency. Responses were given on an anchored 7-point Likert scale, where 7 is 'strongly agree' and 1 is 'strongly disagree'.

Body	I felt as if the body I saw might be my body.
Standing	I felt like I was standing.
Robot body mine	I felt like I controlled the robot body as if it was my own body.
Mirror me	Even though it didn't look like me, when I looked in the mirror, I felt as if the body I saw might be my own.
Arm me	Even though it didn't look like me, when I saw the robot arm moving, I felt as if the arm I saw might be my own.
2bodies	I felt that I had two bodies.
Machine	I felt I was turning into a machine.
PI seen	I had the feeling that I was on the landing outside.
Control robot	I felt in control of the robot body.
Direct interaction	It felt like I was directly interacting with the person who approached.
PI person	I felt like I was in the same space as the person who approached.
Communicate	I felt like I was able to communicate effectively with the person who approached.

Responses to the questions about the participant's experience are shown in Figures 4.4 and 4.5. A representative question for each concept (BOI, PI, Agency) was used in the analysis, since a visual inspection of the data indicated similar trends existed in all questions for each concept. Analysis of the BOI relevant question *body* revealed

Table 4.2: Post-Experiment Questions Related to the Experience of Using the Interface. Responses were given on an anchored 7-point Likert scale, where 7 is 'strongly agree' and 1 is 'strongly disagree'.

Control method	I felt I could control the interface.
Focus	I had difficulties visually moving my focus between the interface and world.
Box distracted	I was often distracted from the environment by the interface.
Frustrated	I became frustrated trying to use the interface.
Difficult	It was difficult to control the interface.
Distracted	I found the interface (squares) distracting.
Concentrated	I had to highly concentrate to use the interface.
False executed	Actions I did not intend to select were executed often.

a significant effect by condition, Wilcoxon rank sum: $W = 19$, $n_1 = 10$, $n_2 = 9$, $p = .03$. Participants in the SSVEP condition reported higher levels of body ownership. Analysis of the PI relevant question *PI seen* found no effects by condition. PI (*PI seen*) and BOI (*body*) were significantly correlated, Spearman's ρ: $r_s(9) = .49$, $p = .03$. Logistic regression analysis on the question *body* indicated the Agency question *control robot* as an additional explanatory factor, $coeff = 1.1$, $z = 2.6$, $p < .01$. This suggests that agency influenced the reported level of BOI.

4.6 Discussion

The results can be considered along two axes: the illusion of body ownership in the remote robot and the usability of the methods.

Table 4.3: Performance on the Skill Test - Note that Participant 12 did not complete the task. Column 3 shows the SSVEP classifier error rate calculated during pre-session EEG training of the real-time classifier used (see Section 4.2.2). Column 4 shows the number of correctly triggered gestures during the skill test. In total, 16 trials were performed.

Participant	Condition	SSVEP classifier error rate (%)	Skill Test: Number of successfully triggered gestures
1	SSVEP	20.0	4
2	SSVEP	5.0	13
3	SSVEP	25.0	3
4	SSVEP	10.0	8
5	SSVEP	10.0	10
6	SSVEP	0.0	16
7	SSVEP	15.0	11
8	SSVEP	5.0	14
9	SSVEP	40.0	1
10	SSVEP	0.0	16
11	ET		8
13	ET		10
14	ET		12
15	ET		11
16	ET		5
17	ET		0
18	ET		0
19	ET		11
20	ET		7
Mean (SD)	SSVEP	13.0 (12.5)	9.6 (5.4)
Mean (SD)	ET		7.1 (4.6)
Mean (SD)	All		8.4 (5.1)

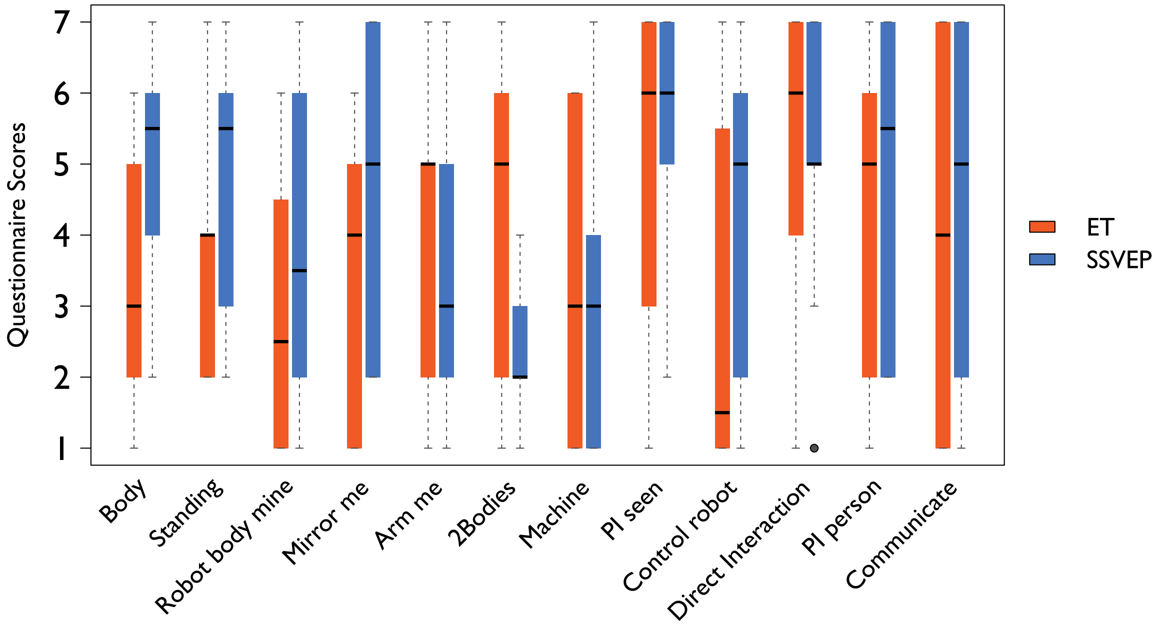

Figure 4.4: Responses per condition to all questions on embodiment and place illusion as provided in Table 4.1. Responses were given on an anchored 7-point Likert scale, where 7 is 'strongly agree' and 1 is 'strongly disagree'. Error bars represent the standard error and dots are statistical outliers.

4.6.1 Body Ownership Illusion

This study aims to contribute to recent work investigating the full-body ownership illusion, and is unique in several aspects. It embodies the participant in a full-sized, remote humanoid robot. Earlier in Chapter 2 we described the study by (Ogawa et al., 2012), which investigated the ownership illusion in a remote humanoid robot, the Geminoid HI-1. In their study, participants controlled the movement of one of the robot's hands, seen from different viewpoints. They assessed ownership through a single question about the hand and measured GSR response to a threat to the robot hand. Our study differs in a number of regards: we provided a fully head-tracked setup which provided correlated head movements, and asked a series of previously published ownership and

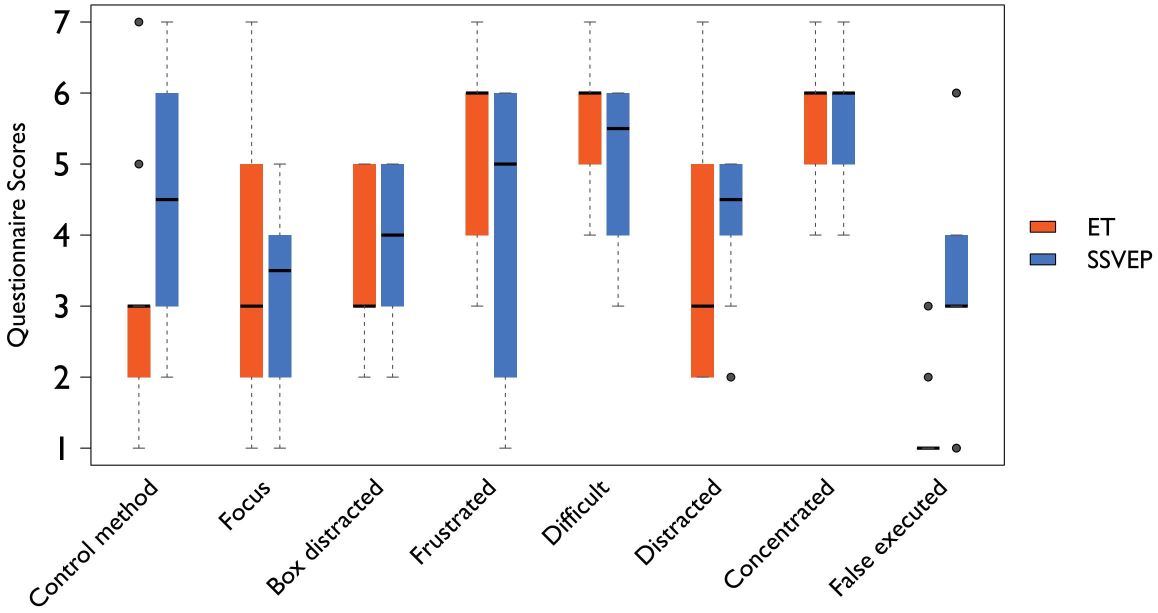

Figure 4.5: Responses per condition to all questions with respect to the experience of using the interface as provided in Table 4.2. Responses were given on an anchored 7-point Likert scale, where 7 is 'strongly agree' and 1 is 'strongly disagree'. Error bars represent the standard error and dots are statistical outliers.

agency questions about full-body ownership. Additionally, participants were in a non-congruent posture in our experiment, and the control of robot actions was through an abstract control mechanism, either a SSVEP-based BCI or eye tracking.

Globally, participants reported high levels of BOI ($median = 5, IQR = 3.5$). A difference in the subjective feeling of body ownership illusion by condition existed. Notably, the responses were higher for the SSVEP condition, with a median score of 5.5 ($IQR = 1.75$). We might presume this is due to differences in agency, which has been linked to body ownership as discussed below; however, no statistically significant differences existed in the levels of control by condition and the level of perceived control did not interact with condition in regression analysis of the BOI. Visual inspection of the question *control robot* provides some support for a link with heightened perceived agency in the SSVEP condition. This suggests that further investigation is warranted with a larger sample size and more controlled study to investigate this specific link.

Research on the rubber hand illusion has suggested that body parts must be human in form and appearance in order to induce the ownership illusion, and this was also one of our main concerns regarding inducing FBOIs with a humanoid robot (Section 2.4.1). Our results seem to reinforce the idea that the humanoid morphology is the critical component rather than the visual appearance for induction of the full-body ownership illusion.

Agency has been linked to body ownership in both theoretical frameworks (Jeannerod & Pacherie, 2004; Tsakiris et al., 2007) and experimental results (Kalckert & Ehrsson, 2012; Tsakiris et al., 2006). Our experiment introduces new evidence to this connection, by showing the effect of an abstract, non-manual, control mechanism of some body movement gestures. In previous setups, agency has been introduced in the form of visually correlated movements of the extracorporeal limb or body in synchrony with physical movements. In those studies, two methods to investigate agency have been used: the movement is either congruent (agency) or non-congruent, or active motor movements (agency) are compared with passive motor movements. Our study has taken a different approach, providing agency not through movements of the body but through the physical manifestation of intentions to perform an action. A previous study by (Perez-Marcos et al., 2009) demonstrated mental control of an embodied body part (a hand) by a nonphysical method, namely a motor imagery BCI. More recently, (Cohen et al., 2012) and (Alimardani et al., 2013) also demonstrated a similar setup in terms of controlling a robot using a BCI interface. Similar to our results, they found that this method helped induce the BOI. While our SSVEP setup also functions over mental input, our work differs in that the efferent system is not a functional part of the interaction method. In all the studies mentioned above, (Perez-Marcos et al., 2009; Cohen et al., 2012; Alimardani et al., 2013), the task was such that motor imagery was congruent with the visual stimulus. Since motor imagery has been linked to the efferent system (Grush, 2004), it is unclear whether it is necessary to create a motor plan of the same action that is seen in order to induce ownership. Our results suggest that the efferent system may not need to be involved, but a more rigorous investigation is warranted. Consequently, this setup also provides a platform for investigating this question about the role of the efferent system in agency and the BOI.

4.6.2 Usability

Although not a strict scientific comparison of the technologies, the experiment allows a measure of comparison of the usability of two fairly standard setups. Overall, the results of this study suggest that both SSVEP and eye tracking seem to be possibilities for immersive control in an HMD. In terms of usability of the interface, the two methods differed in various aspects. There was no indication of differences in task success during the skill test or in the questionnaire responses about the interfaces. This was true even though the eye tracker had a much shorter delay in triggering gestures (1 second vs. 3 seconds with SSVEP). Perhaps the usability indicator with the most impact is that two of the ET participants did not succeed in triggering even a single gesture; all SSVEP participants triggered at least one coherent gesture during the skill test. Although counter to our *a priori* expectations, these observations are in line with recent findings by (Kos'Myna & Tarpin-Bernard, 2013), who found similar performance results in a more traditional desktop setting. The poor eye-tracking results in our experiment are somewhat surprising. The success of the technology in desktop settings (Majaranta et al., 2011), and the common view that it would be more successful than BCI, led us to expect that eye tracking would outperform the BCI system. We used commercial eye-tracking technology specifically designed and sold for use in HMDs, ensuring a quality setup. Our results and experience were not as expected, but it must be noted that there were technological differences in our setup compared to existing literature.

Another important factor in our experience of using these technologies was the physical properties of the HMD used. Our results suggest that SSVEP-based BCI combined with the HMD caused only minimal interference and discomfort. During pilots, we found that it was possible to take off the HMD during the off-line classifier generation step and then later replace it with only a minimal degradation in quality for the experiment. This proved to be a critical difference with the eye tracker, which required the HMD to remain affixed during and after calibration. The calibration process often took extended periods of time, during which the 1.3 kg weight of the HMD could have caused discomfort to the participants.

4.7 Conclusion

We have shown that the full body ownership illusion can be induced over a remote humanoid robot, where the body is highly robotic in appearance. This provides further evidence that matching form rather than appearance to the body is necessary for induction of the BOI. Additionally, the BOI was induced with two different abstract controls of the movements of the substitute body; thereby, the BOI was maintained in the presence of non-congruent bodily motions in the remote body, which are believed to break the illusion. Further investigation is required to verify and understand the impact of this finding. The two methods for triggering the gesturing, SSVEP-based BCI and eye tracking, proved to be tractable for immersive control of a humanoid robot in a social telepresence setting. This is the first study that directly compares these methods in an HMD. However, future research should investigate the relative advantages of these technologies in a more controlled experiment to provide more insight into these findings, particularly in an immersive HMD setting. Furthermore, one could consider combining the two technologies to potentially obtain even better results.

Finally, we have also successfully demonstrated a potential application of a highly immersive embodied robotic telepresence system that allows the operator to feel ownership and agency over the robot without actually moving their own body. Given this result, one can assume that when actually provided with direct control over the robot's body via real-time body tracking would elicit an even stronger illusion, which would lead to a substantially more powerful experience. In the next Chapter we describe such a system, and discuss a case-study that was carried out where such a system was used in the context of journalism.

* * *

"Using this instrument, you can 'work' in another room, in another
city, in another country, or on another planet.
Your dangerous job becomes safe and pleasant."

Marvin Minsky
Telepresence, 1980

5

Tele-Immersive Journalism using Robotic Embodiment

In Chapter 4 we showed that it is possible to induce the illusion of full body ownership over a humanoid robot, even with non-matched body posture and indirect methods of control. However, as discussed in Section 2.4.2, an even higher degree of the illusion can be elicited if, along with 1PP, participants are also provided with direct control over the limbs of the avatar or surrogate body. Furthermore, by matching the posture of the robot with that of the participant at all times we also provide synchronous visuoproprioceptive feedback. In addition, we provide a stereoscopic video stream of the remote destination and two-way audio streaming between the participant and locals. By combining all the aspects discussed above - allowing someone to see a remote location from 1PP of a remote body, have the ability to hear, touch, interact with people, and move the remote body naturally in the remote space as if it were their own - we can simulate a type of virtual teleportation - or in science fiction terms, *'Beaming'*.

This Chapter addresses the second hypothesis of this thesis: *By embodying someone in a remote robotic body, they can be physically represented in the remote location by using the robot as a surrogate. This setup can be used as an application for tele-immersive journalism.* We first discuss the development of the system, and then focus specifically on developing a solution in the context of journalism - where either the journalist beams to a remote location embodied in a humanoid robot, or an interviewee beams to the location of the journalist. The paper about the details of the system and subsequent case-study has been accepted in the journal *IEEE Computer Graphics and Applications*, and is in press at the time of writing this thesis (Kishore et al., 2016). A video of the technical setup and demonstration of the case-study can be seen at: http://youtu.be/ry6dmWB34qI.

5.1 Introduction

So far, we have discussed the various conceptual and technological subcomponents of this system individually. Regarding conceptual discussion, in Chapter 2, we provided a detailed review of telepresence with respect to commercially available telepresence robots, and pointed out the lack of a truly immersive embodied remote telepresence system. We have also discussed the concept of FBOI in detail, with special focus on the potential factors that may affect the illusion with a humanoid robot. From the previous Chapter we have learned that although the Robothespian looks highly robotic, its humanoid morphology is sufficient enough to override its appearance, which allows participants to feel ownership over its body. To our surprise we also found that even having a non-congruent posture between the robot (standing) and participant (sitting) did not break the illusion. Furthermore, even with an indirect method of control over the robot body we were able to elicit feelings of agency. Thus, if we follow existing literature and the knowledge gained from our previous study, we have good reason to believe that if we were to remove these discrepancies of posture and indirect control, we would be able to elicit an even higher degree of FBOI and agency.

On the other hand, in Chapter 3 we provided a description of all the individual technologies that we use for robot control, such as body tracking and motion retargeting, although we did not use it for our previous study (except for the head). However, now we discuss how to combine all the conceptual and technological components, by relying on the terms that were defined in the BEAMING project (Section 3.6), into one comprehensive system for an immersive telepresence setup. Furthermore, our confidence about inducing a FBOI with our setup gives us motivation to develop a real-world application that utilises the system for a relevant purpose.

The area we chose to apply this technology is that of journalism. We envision a system where a journalist can act as a visitor and travel instantaneously to a remote location, where they can be embodied in a humanoid robot and go about their job using their surrogate body. While a study by (de la Peña et al., 2010) refers to immersive journalism as providing the news to the audience via an immersive medium, we refer to our concept as *tele-immersive journalism*. The reason we decided to apply this system specifically for journalism is because travelling to various locations in order to report stories is a fundamental aspect of the profession. However, travelling to certain locations may not be an option, for example during a natural disaster, or an ongoing violent situation in times of war, or certain locations where conditions are extremely inhospitable. Using robots in the remote location instead of physically travelling can be used as an alternative in these cases. A few setups already exist where robots have been deployed for carrying out tasks in hazardous situations (Lin & Kuo, 1997; Hasunuma et al., 2002; Hirabayashi et al., 2006; Bell, 2012). By providing a journalist with the ability to 'travel' anywhere in the world by being embodied in a humanoid robot, and giving them a natural way of controlling their surrogate body may allow them to carry out their job as if they were physically there. Furthermore, humanoid robots can also be customised according to the situation, based on appearance, race or even gender, in order to better connect with the people being interviewed (Nowak & Rauh, 2008), although as we discussed in Chapter 2, designing robots that are highly lifelike may end up causing a feeling of revulsion amongst the people interacting with the robot due to the Uncanny Valley hypothesis

(Mori et al., 2012; Mathur & Reichling, 2016). Finally, it has also been shown that simply having a physical presence, albeit robotic in appearance, tends to be preferred by the locals as well, as compared to a representation on a screen (Pan & Steed, 2016). Similar results were also reported in a study with the Geminoid HI-1 robot (Sakamoto et al., 2007). Furthermore, another study with the same robot revealed higher scores of BOI when participants teleoperating the robot were interacting with someone in the remote space (Nishio et al., 2013), thus showing a positive effect of having a social interaction on BOI over the robot.

In the next section we describe the setup of our system. We give an overall description of the setup of the technology, but we do not go into the technical details of each component since that has been provided in Chapter 3. The relevant sections where the details of each component can be found have been mentioned wherever appropriate.

5.2 Materials and Methods

This section is divided into two parts, based on the physical location of the two components of the system - The *Transporter* and the *Destination*.

5.2.1 The Transporter

The Transporter is the part of the system that the visitor uses to transport themselves to the remote destination. This can be considered from two points of view. The first is what is required to display the remote destination to the visitor. For this purpose, a stereoscopic 3D video feed from two cameras separated by a standard interocular distance at the destination is streamed in real time via the Internet to the HMD worn by the visitor. The HMD that has been used for the various applications of this system is the NVIS nVisor SX111 (Section 3.1.1), although the Oculus Rift has also been successfully incorporated in the system as well. The audio captured from the destination is also streamed to the transporter in real-time and played back through high quality headphones (Section 3.5).

The second aspect concerns transferring the visitor's behaviour to the humanoid robot representing the visitor at the destination. To provide the visitor with the most natural method of controlling the robot, the limb motions of the visitor are tracked in real-time. Similar to the setup in the previous study, the head of the visitor is tracked by an Intersense 900 (Section 3.1.2), which is attached to the HMD itself, while the body can be tracked by a variety of full-body motion capture systems. For our system, we have used the Xsens MVN Inertial Motion Capture system (Section 3.1.3.1) most frequently, although other commercially available systems such as Arena Optitrack (Section 3.1.3.2) or Microsoft Kinect can also be used. These tracking systems have been used to capture the position and orientation of each limb of the visitor in real-time. Additionally, they also supply spatial information of the visitor with respect to the world. Once we have this information, it is used as an input for a system that was developed specifically to convert this tracking data and map it to the humanoid robot at the destination, in real time (Spanlang et al., 2013). Thanks to this control method, participants have the ability to move the robot's body by moving their real body.

The audio, video and motion capture streams are transferred from the Transporter to the destination using a high-bandwidth Internet connection. Similarly the stereo video stream from the remote cameras, and the audio stream are transferred back to the visitor's Transporter. As discussed earlier, since the stereo video streams require the most amount of bandwidth, they are compressed using the VP8 format prior to streaming (Bankoski et al., 2011). Since it is possible that the head and body of the visitor might be tracked using different tracking systems, at each frame an entire packet is constructed with new values of motion data. Finally, this array of integer values is sent at each frame to update the limb angles of the robot at the destination. The limb values of the robot are updated depending on the maximum refresh rate of the robot. The intermediate values between the current position of the limb and new set of values are interpolated by the robot's internal processor. Since the rate at which new values are streamed is

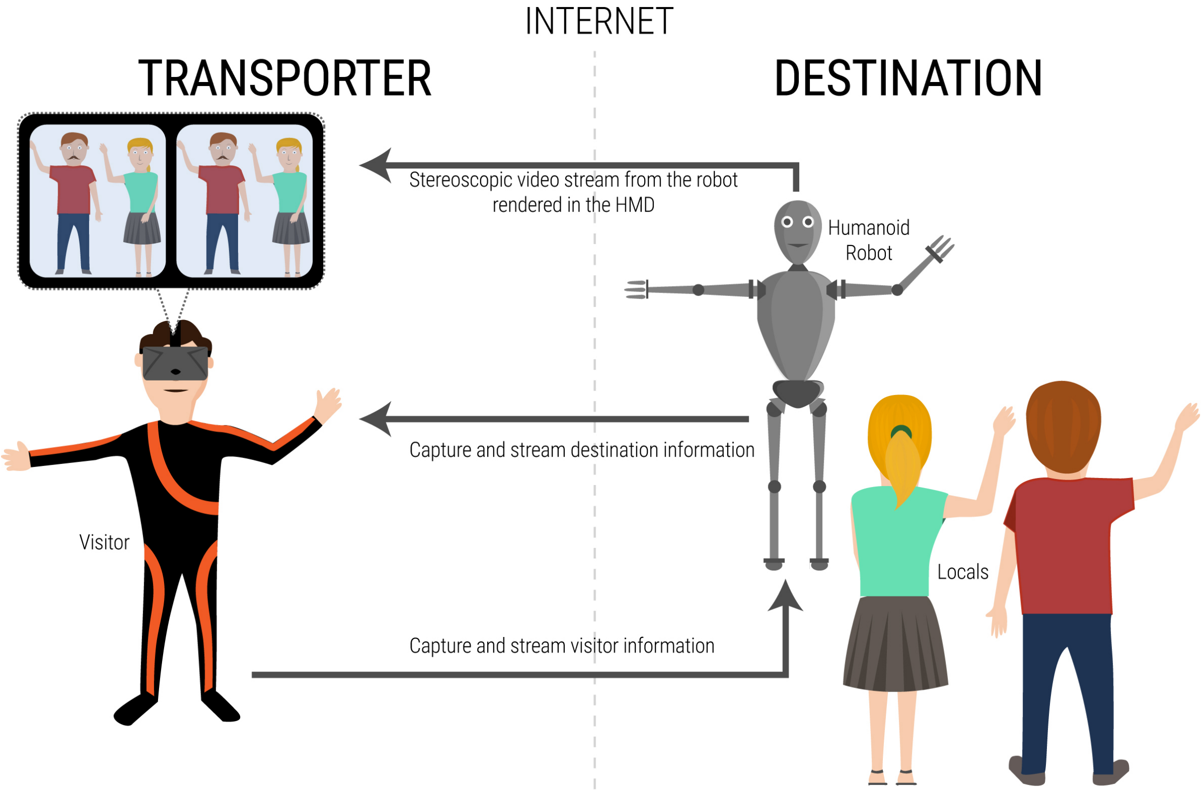

Figure 5.1: An illustration of the BEAMING schema. The visitor is physically located at the Transporter, where they are fully body-tracked and are wearing a Head Mounted Display (HMD). The body-tracking information of the visitor is captured and streamed to the Destination over the Internet, where it is mapped on to a humanoid robot. The robot is used by the visitor as their physical surrogate at the Destination. The locals are the people present at the Destination who can interact with the robotic representation of the visitor. Two cameras separated by the standard inter-ocular distance are mounted on the humanoid robot's head that stream video in stereoscopic 3D directly to the HMD donned by the visitor.

much higher than the refresh rate of the robot the robot will always work with the latest motion capture data, however, the interpolation will always lead to smooth movements. However, this does mean that it might miss small subtle movements in between such updates. Although the refresh rate of the robot used for this application was high enough to not display any noticeable issues.

5.2.2 The Destination

At the destination, the visitor is represented by a robot through which they can interact with the locals in a natural way, and without encumbering the locals with the requirement to use or wear any special equipment. Hence, the essential component of the setup at the destination is the humanoid robot that acts as the surrogate body for the visitor. The robot that we have used for the system is the Robothespian (Section 3.2.1). Due to the lack of sensors in the hands of the robot, haptic feedback to the visitor when the robot's hand is touched is not possible. However, the locals can physically interact directly with the robot itself (for example, shake hands) which would not possible using traditional means of remote communication. Furthermore, as we discussed earlier, having a physical presence in the destination can be beneficial for both, the visitor and the locals.

To allow the visitor to see from the robot's perspective, feed from two cameras mounted on the robot is streamed to the transporter, and rendered in the HMD of the visitor, who therefore can see the destination in stereo. Since the head of the robot is also directly mapped and controlled by the head movements of visitors they can update their view by simply moving their head. When looking at a mirror in the destination the visitor will see a reflection of the robot body - which due to the real-time motion capture and mapping moves as they move. This has been shown to increase the degree of FBOI, both in physical reality and in IVR (González-Franco et al., 2010; Preston et al., 2015).

The lower half of the robot is fixed in place, thus, the robot cannot walk on its own. However, to facilitate movements, specifically translation and rotation on the ground, a programmable platform was purchased for this specific purpose, on which the robot was mounted. Using the method described in Section 3.3, new values for the position and orientation of each limb in the upper arm and head are sent to the robot at every frame. Additionally, the torso of the visitor is also tracked and this information is used to compute the movement of the visitor in 2D space, which is subsequently streamed to the platform concurrently. Figure 5.1 shows the schema for this system.

Through this setup, the visitor is able to see the remote destination in stereoscopic 3D, and has head-based sensorimotor contingencies since the head of the robot moves in correspondence with the visitor's head moves. The sensorimotor contingencies contribute to provide a rich multisensory experience and enhance the sense of presence in the remote location (Slater, 2009). Furthermore, the movement of the arms of the visitor and the robot are congruent, which can also be seen by the visitor through the 'eyes' of the robot, engendering agency.

5.3 Tele-Immersive Journalism - A Case Study

The system has been used several times for the purposes of tele-immersive journalism, and has been extensively demonstrated in the media. The following section has been divided into two parts - The first section is about the times when the system was used by journalists as a means to understand the functioning of the system itself. This led to several articles and videos about the system being published in popular news media. The second part of this section however describes the case-study where the system was used for the first time by a journalist to cover a story not about the system itself, but about other issues.

5.3.1 Tele-Immersive Journalism used for news about the system

The BBC was the first news channel to cover the system, where they carried out an interview using the system itself. The journalist was present at University College London (the destination). A Robothespian was located there that represented the remote visitor (the interviewee, Dr Sanchez-Vives) who was physically located in Barcelona, Spain, and was beamed to London, where she was interviewed about the system[1].

The system was also used by TV3 based in Catalonia and the Spanish Newspaper La Vanguardia, where the relationship between interviewer and interviewee was reversed. This time, the two journalists were physically present in Barcelona, Spain, and were beamed to University College London where they controlled the Robothespian, and conducted an interview about the system with one of the researchers located in London. The news article was printed in La Vanguardia[2] while TV3 aired it as part of a science documentary[3].

While the demonstrations mentioned above were a first of their kind and received widespread news and media coverage, the interviews had always been about the system itself. The first time that this setup was used by a journalist to not just experience or showcase the system, but to actually apply this technology for conducting interviews about other issues was by journalist Nonny de la Peña.

5.3.2 Tele-Immersive Journalism used to report news

In a session that lasted for about three hours, Nonny de la Peña beamed to Barcelona, Spain from Los Angeles, USA, and conducted two sets of interviews. The first was with a researcher (Dr Javier Martínez Picado) whose team had recently discovered an important result in HIV research. The second was to conduct a debate amongst three students who were pro-, anti- or neutral about Catalonia's bid for independence from Spain. An image from the debate session can be seen in Figure 5.2. The debate was led and moderated by her remotely, i.e., as embodied in the robot. This event was broadcast live on Barcelona TV and an impromptu interview was also conducted where a journalist from

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[1] http://www.bbc.com/news/technology-18017745/

[2] http://www.lavanguardia.com/vida/20120520/54296167703/teletransporte-barcelona-londres.html

[3] http://blogs.tv3.cat/quequicom.php?itemid=48881

Figure 5.2: An image from the Tele-immersive Journalism debate session. Journalist Nonny de la Peña is embodied in the Robothespian, and moderates a debate amongst three students regarding Catalonia's independence.

BTV asked Nonny de la Peña, while embodied in the robot, about future applications of this technology[4].

Nonny de la Peña utilised the system once again, when she beamed from London to Barcelona to conduct an interview with Dr. Perla Kaliman about her research and book regarding types of food and cooking that are good for the brain (Kaliman & Aguilar, 2014). In this case the interview using this system was published in traditional news media. The article, which focused solely on the substantive issue of food for the brain rather than the system that was used, was published in the newspaper Latino LA[5].

In this case the visitor (the journalist) was physically present at University College London where we had set up a laboratory as a Transporter system. The Transporter was equipped with the same HMD used for previous setups, the NVIS nVisor SX111. Since this HMD weighs about 1.3 Kg, a long uninterrupted session could be uncomfortable.

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[4] https://www.youtube.com/watch?v=FFaInCXi9Go

[5] http://latinola.com/story.php?story=12654

Therefore, the session was carried out in parts, with regular breaks of 5-10 minutes at the discretion of the visitor. The body of the visitor was tracked in real-time by the Xsens MVN motion capture suit, and an Intersense 900 head tracker was used to track the orientation of the visitor's head. High-quality headphones and microphone were used to facilitate two-way audio communication.

The destination was the University of Barcelona, Spain. A Robothespian with specifications as described earlier was used as the physical representation of the visitor. The speaker and microphone built in to the robot provided the necessary hardware for the audio communication. Additionally, a mirror was also placed in front of the robot. The setup explained above can be seen in Figure 5.3.

5.3.3 Reports of the Experience

Six people who took part during the course of the two sessions that included the interview with the HIV researcher and the debate about Catalonia returned a questionnaire. This was based on standard questions related to telepresence to judge the extent to which they felt as if they were in the same physical space as the journalist with whom they were interacting. Additionally, other questions related to Human-Robot Interaction with a humanoid robot were included from the standard NARS (Negative Attitudes Towards Robots Scale) questionnaire (Nomura et al., 2004; Nomura et al., 2006; Tsui et al., 2010). These questions were aimed at retrieving information about how comfortable locals felt while interacting with a robot, and if they perceived the experience to be positive.

All questions were scored on a 7-point Likert Scale, with 1 being total disagreement and 7 being total agreement with the statement. The questions and the scores are shown in Table 5.1, and Figure 5.4 shows a summary graph. Three out of the six respondents recorded a score of at least 4 in response to how much they felt as if they were interacting with a person rather than a robot (Q1), with 4 people scoring at least 4 that they felt that

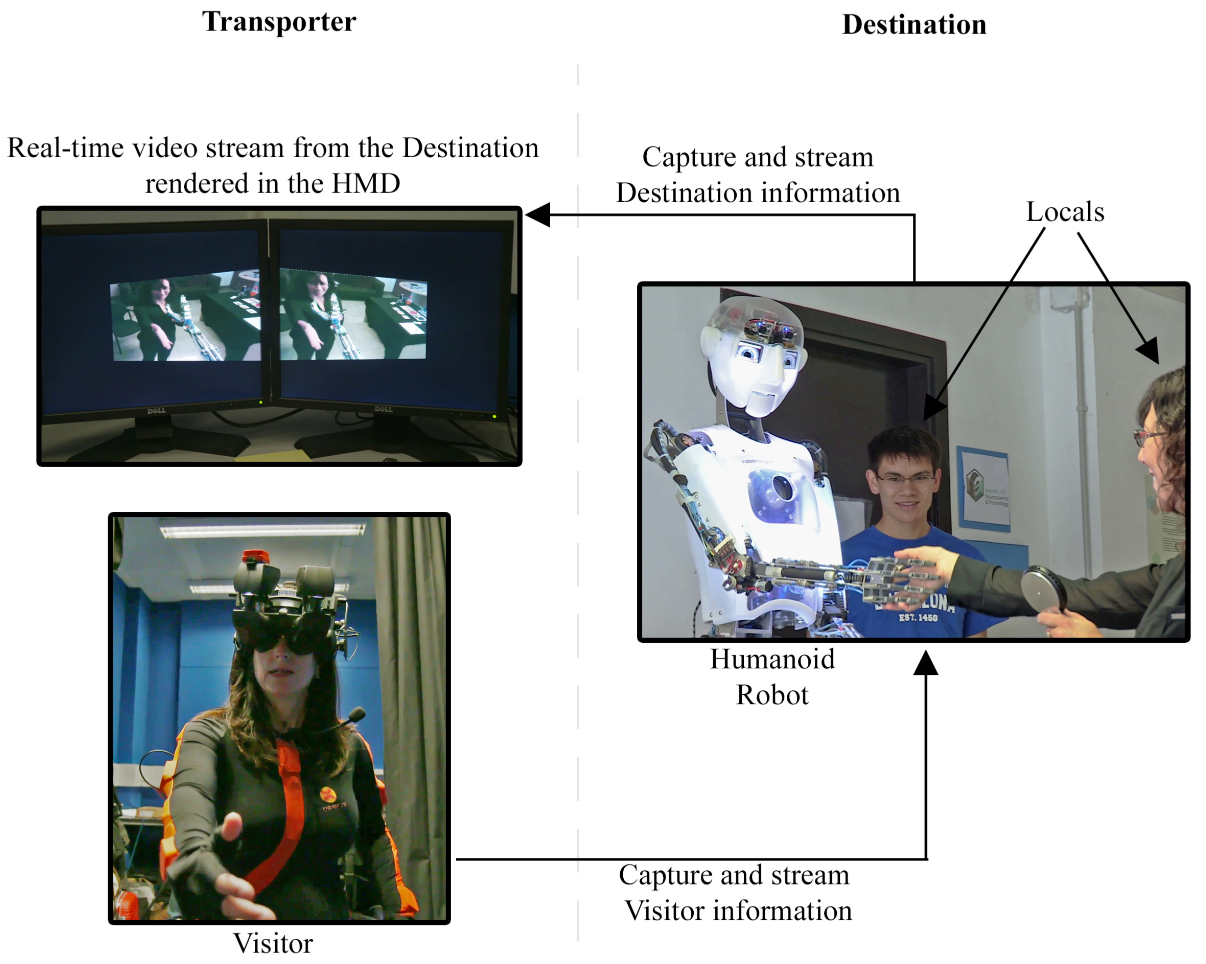

Figure 5.3: The specification of the setup used for the immersive journalism interview. The visitor, journalist Nonny de la Peña, wore an Xsens body tracking suit and an NVIS nVisor SX111 HMD, with an Intersense 900 head tracker. At the destination she was represented by a custom-built Robothespian with two Microsoft HD-3000 webcams separated at a standard interocular distance, manufactured by Engineered Arts. She could view the Destination in stereoscopic 3D via the HMD. The entire communication and exchange of data took place through a regular Internet connection.

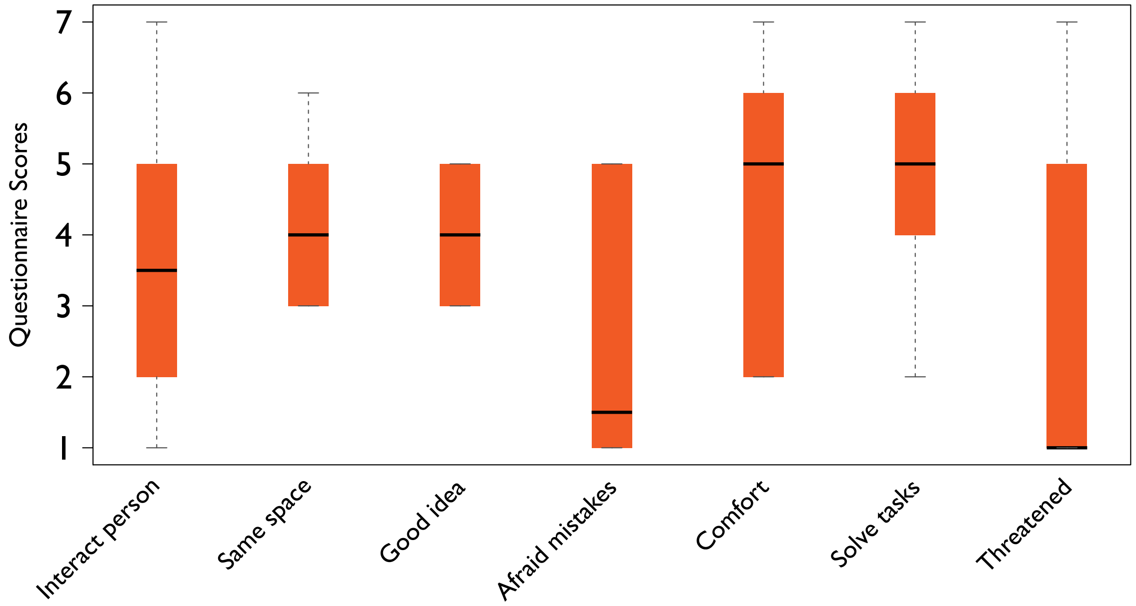

Figure 5.4: Box-and-whiskers plot for the questionnaire responses of the locals. Questions and detailed data are available in Table 5.1. Responses were given on an anchored 7-point Likert scale, where 7 is ‘strongly agree’ and 1 is ‘strongly disagree’.

there were in the same space as the person controlling the robot (Q2) and that they were comfortable in the presence of the robot (Q5). Five out of six people scored at least 4 regarding the feeling that they would be able to solve tasks together with the robot (Q6). In relation to negative aspects only two participants scored at least 4 regarding their fear of making mistakes or breaking something (Q4), and similarly two felt threatened by the robot (Q7). Finally four out of six scored at least 4 in agreement with the idea of using the robot for journalism (Q3). No general conclusions can be drawn from this small sample, and the variation between individuals was high, but given that this was the first ever trial of this type of human-human social interaction via a robot, and given the fact that there were no facial expressions (a feature greatly missed and commented on by the HIV researcher interviewed), the results are encouraging for future applications.

On the other hand, journalist Nonny de la Peña reports that she “approached the task at hand with the same intention as when doing an interview with her biological body

Table 5.1: Questionnaire responses of all six locals for each of the questions in the questionnaire. A score of 1 means 'Totally disagree' and 7 means 'Totally agree' with each of the statements. L1 – L6 are the six participants that responded to the questionnaire. Figure 5.4 shows a boxplot of the questionnaire responses.

Question	L1	L2	L3	L4	L5	L6
I felt as if I was interacting with a real person, and not a robot. (*Interact person*)	7	1	5	3	2	4
I felt as if the person controlling the robot was in the same physical space as me. (*Same space*)	5	4	4	3	3	6
I think it is a good idea to use a robot for journalism purposes. (*Good idea*)	3	3	4	5	5	4
I was afraid to make mistakes or break something while interacting with the robot. (*Afraid mistakes*)	1	2	5	1	5	1
I was comfortable in the presence of the robot. (*Comfort*)	7	2	5	6	2	5
I feel I could solve tasks together with this robot. (*Solve tasks*)	7	4	5	5	6	2
I felt threatened by the robot. (*Threatened*)	1	1	1	1	7	5

rather than conducting the conversation on the phone or through Skype. The interview questions were prepared prior to the event and included reading background information and exchanging emails as would typically be done in preparation for reporting any piece. On the day of the interview, prior to donning the Xsens motion capture suit and HMD, de la Peña reviewed her research and committed interview questions to memory.

There were constraints for de la Peña in operating the robot body, such as overcorrection from head turns or hand movement and a viewpoint that was much taller than her normal height." While describing her experience she says,

> *"I can only describe the experience as trying to do a sit up for the first time - you have a concept of how to do it but no muscles to actually perform the task. My entire being had to work in a unified effort to occupy and embody a 'second' self so I could conduct the type of interviews I have done over the past twenty years."*

However she mentions that "within approximately fifteen minutes of initiating the experience, she began to adopt the robot body as a natural parallel of her biological body. The connection became so intense that after the first session, it took thirty minutes to stop feeling as if her biological body was still driving the robot body. Moreover, in the second reporting session with Dr. Kaliman, she was more readily able to adapt the stance that allowed her to control the robot's movements utilising the Xsens suit."

De la Peña also indicates that "for several months afterwards when she recalled the experience, her body involuntarily adopted the most comfortable position for matching the robot to her natural body stance. For example, her arms would bend at the elbow, with her hands outstretched ready to wave, shake hands or gesture. Her head would look upright and her back would stiffen in order to more readily walk forward, back or to swivel from left to right. She also reports some strange and distinct connections to her 'robot-self'." Regarding this feeling she says,

> *"When I first saw the interview with my robot-self in Barcelona, I was unexpectedly and strangely upset about the viewpoint of the TV crew camera because I was seeing it from the wrong angle! I actually jumped up from my desk and walked away. I had to force myself to sit back down to watch the whole video. I still cannot define for myself why this view made me so feel so uncomfortable."*

Moreover, she also describes watching the BBC video report of Dr. Sanchez-Vives driving an identical robot. She reported that she “felt the disturbing sensation as though someone were inside and occupying her own personal body.”

Finally, de la Peña notes that “her ability to report was enhanced in comparison to conducting interviews with current video-based technologies. Using the robot as an extension of her ‘self’, she was able to shake hands, make eye contact or adjust viewpoint to address unique individuals as well as to ‘walk over’ and see materials provided by an interview subject. She could also act as a director by arranging the locals into the organisation and location that she wanted - by pointing directly into the space, and talking to individuals and groups. By using her biological body in a similar way as if she were actually present on scene, she had a freedom to engage with the interview subject and the other locals in ways not possible with traditional videoconferencing or the telephone or even other telepresence setups.”

5.4 Discussion

We have presented a novel system that significantly advances beyond existing telepresence robot setups by combining theoretical and practical knowledge from the fields of cognitive science and computer science. This system not only allows a person to immediately interact with people in a remote destination, but it also can invoke a feeling of owning a physical body, thereby giving the illusion of really being there in a physical sense. Additionally, the method of controlling this body is direct - the robot limbs and torso are moved by moving the corresponding parts of the real body. Thus, the robot body can be used for gestures and integrating other forms of non-verbal communication in the experience as well. This substitution of the real body by a surrogate robotic body allows someone to see, move and interact with the environment approximately like they would if they were physically present at the destination.

The main bottleneck in terms of cost and accessibility is the hardware involved. Thanks to advances in the field of gaming hardware with the recent proliferation of low cost and high quality head-mounted displays at consumer prices some of the critical elements are widely available. This not only helps in lowering the financial cost, but also allow visitors to hold longer, uninterrupted sessions as the fatigue would be less with the new lighter generation of HMDs. Another consumer device that can be used to advantage is the Microsoft Kinect. The current version of the device is already capable of full-body real time tracking, and consequently, can be used in our system to drive the robot remotely. One advantage the Kinect has over Xsens is that the Kinect uses markerless tracking. The Xsens, which is based on inertial tracking, requires the visitor to put on a special suit and perform a pre-calibration every time. The Kinect on the other hand uses computer vision techniques to detect and track users without any additional equipment. In addition, the Kinect has been used for teleoperation of the Nao robot as well (Suay & Chernova, 2011). This consumer oriented approach is technically already possible with our system by using, for example, an Oculus Rift with a Kinect, albeit with lower quality motion capture. By combining a good quality, reasonably priced and portable HMD with a markerless and portable full-body tracking system the transporter side of the system can be constructed to be both cost-effective and portable.

While it is already economically and practically possible to have a portable transporter system, there is still some way to go before we have low-cost life-sized humanoid robots available commercially and universally. The cost and time required to deliver and set up a life-size humanoid robot such as the Robothespian is still relatively high. However, the system that we have developed has already been integrated and successfully tested with the Nao robot. As the field of humanoid robotics gains momentum commercially, the feasibility and advantages that this system offers will vastly improve. The algorithm that has been used to map movements of the visitor to the robot is modular and can be extended to allow compatibility with a new robot easily, as long as the structure of the robot is humanoid. This allows us to continuously enhance the system as these robots become available. Furthermore, newer robots are being developed with a plethora of sensing devices and systems that provide rich information regarding the state of the robot. For example, the Nao comes pre-built with touch-based sensors on its hands, which could be used to drive vibrotactile devices attached to the visitor's hands. The sensor could be used to simulate tactile feedback when the visitor uses their hand to touch an object or shake a local's hand. The addition of visuotactile feedback along with 1PP, visuomotor correlation and head-based sensorimotor contingencies would deliver an even stronger illusion of FBOI.

5.5 Conclusion

We have described the details of the system that we have developed for providing an immersive embodied telepresence experience. In addition to a technical description of the system, we have also demonstrated an application by adapting the system to the context of journalism, with several instances where it was used successfully to report news stories about the system itself, and in two cases for covering real news stories as well. We have provided a detailed account of the visitor's experience and have produced questionnaire data regarding the locals' experience of interacting with a remotely controlled robot.

This information tends to confirm our hypothesis that by embodying a visitor in a remote surrogate body in a telepresence setup can greatly enhance the experience for both, the visitor and the locals. By providing the visitor with congruent multisensory data in terms of controlling the robot body by moving their own and being able to talk and hear through the robot, we elicit a high sense of the body ownership illusion and agency. Thus, by making the robot body as the source of all associated sensations of the visitor, we are able to provide the visitor with an embodied physical presence in the destination, which in a sense can be understood as a form of virtual teleportation, or beaming.

While we have demonstrated the system's abilities successfully in a real-world application, it is important to assess its performance in a more controlled environment. However, replicating this setup in a laboratory would not be as revealing, since the study described in Chapter 4 has already provided us with several clues regarding social interaction using the system. Thus, as a way to extend the functionality of the system and to test its effectiveness at the same time, we demonstrate a system that allows a visitor to be in multiple places at the same time. In the next Chapter, we give a technical description of how this is implemented, followed by a study that was run using this system.

* * *

"In one and the same day, Pythagoras was present at Metapontum in Italy, and Tauromenium in Sicily, and discoursed in common with his disciples in both places, though these cities are separated from each other by many stadia both by land and sea, and cannot be passed through in a great number of days."

Iamblichus

Vita Pythag. XXVIII, ca. 250 - ca. 330

6

Multi-Destination Beaming

In Chapter 5, we successfully developed and demonstrated a system that enables someone to be beamed to a remote physical location where they and are in control of and feel ownership over a robotic body. In order to build on this foundation, the next question was to see whether it is possible for someone to be present not in one, but three remote locations simultaneously, with each remote destination equipped with a robotic or virtual body that could be inhabited and be fully controlled by the visitor, thereby giving them the illusion of ownership and agency over each of them. This Chapter discusses the hypothesis: *Extending the setup in the previous hypothesis, it is possible for someone to be in three distinct locations simultaneously and can perform tasks in each location, by embodying a physical (or virtual) surrogate body.*

Instead of describing the system in detail, which has been discussed in Chapter 5, the following sections describe how the system was extended to include multiple destinations. Following the description of the *Multi-Destination Beaming* setup, a study is described where participants could be in three distinct remote locations (two physical and one virtual) simultaneously, where they were in full control of a different humanoid robot at each physical location and an avatar in the virtual location. They could see, hear and interact with the people present in all three remote locations and had to perform predefined tasks. A video of the concept of the system itself, the experiment and the procedure can be seen at: https://youtu.be/oh1B6C3JggQ.

6.1 Introduction

Before we begin discussion of the system or the study that was run, we must ask a fundamental question related to bilocation. Is it possible to be in more than one place at the same time? According to 2nd century philosopher Iamblichus, Pythagoras was reported to be in two different places separated by a large distance, seen having a discussion with his disciples in both places simultaneously (Iamblichus & Taylor, 1926). Not limited only to Greek philosophy, multiple instances of bilocation (and even multilocation) have been reported over the centuries as part of folklore, mysticism and in various religious texts, with most examples considered to be miraculous or divine events. However, none of these alleged events have any scientific basis, and moreover one person being in multiple places simultaneously is physically impossible. Although one has to admit that today, in this increasingly fast paced world, the ability to be present in two (or more) different places at the same time and being able to interact with people and carry out tasks at both places simultaneously could be extremely useful.

While being in two locations simultaneously is physically impossible, it can be simulated partially by leveraging the concept of telepresence. The concept of bilocation, in terms of presence with respect to virtual environments has been studied in the past (Gooskens, 2010) and it has been shown that humans distribute their 'self' over two distinct places (Wissmath et al., 2011). In their study, participants experienced a virtual rollercoaster and were continuously asked about the extent to which they felt present in either their real location or the displayed virtual location. Their results show that participants were successfully able to distribute their self over these two distinct places, with the sum of their ‘divided’ self adding up to roughly 100% at all times. Although we found no studies that attempted to study the phenomenon over three or four places.

On the other hand, in the field of telepresence robots as well there have been attempts at implementing a system that lets an operator monitor up to four robots in different physical locations (Glas et al., 2008). Though they had positive results regarding the experience of the teleoperator in controlling four robots simultaneously, the system presented was a traditional desktop-based computer comprised of a screen and a keyboard/mouse. Thus, the key feature still lacking, regardless of the number of remote teleoperators, is the crucial feeling of body ownership. We hypothesise that by extending our current system and introducing multiple remote locations, each equipped with a remote surrogate body that the visitor can own, the phenomenon of multilocation can be simulated virtually.

The way we extend the system to include more remote destinations is by letting the participant be at any one location at any given point, and giving them the ability to instantaneously switch between the various possible destinations by pressing a trigger. While the participant is present in one destination, it is important to have a sensible method of engaging the remote surrogate representations currently unoccupied by the participant in the other destinations. Hence, a proxy system has also been developed based on the concepts defined by (Steed et al., 2012; Friedman et al., 2013), which tracks the locations not currently inhabited by the participants, and takes over their remote representation in order to continue performing the tasks in those locations in a logical fashion. To test its efficacy, a study was carried out with a fully functioning system and a simplified version of the proxy for use in a social interaction. Participants could be in three distinct destinations (two physical locations and one virtual environment) simultaneously, where they were in full control of a different humanoid robot at each physical location and an avatar in the virtual location. They could see, hear and interact with the people present in all three remote locations and had to perform predefined tasks.

6.2 Materials and Methods

Since the objective of the hypothesis being discussed in this Chapter was to add remote destinations to the system built in Chapter 5, the Transporter used was exactly the same, as discussed in Section 5.2.1. The main additions were in terms of the destinations and a proxy system to engage the physical representations at each destination unoccupied by the visitor, which are described below.

6.2.1 The Destinations

Two types of possible destinations have been implemented in the system – Physical and virtual. A physical destination is an actual remote location, while a virtual destination is a collaborative immersive virtual environment that the visitor and locals share. For the sake of consistency, we will refer to the two physical destinations as PD1 and PD2, while the virtual destination will be referred to as VD3.

6.2.1.1 Physical Destinations

Similar to the destination described in Section 5.2.2, the key factor that dictates the setup is that the interaction between the visitor and locals has to be natural, and not constrained by intrusive equipment and cables. Thus, the only essential component in the physical destinations is the humanoid robot that represents the visitor. The robot used for PD1 was the Robothespian. On the other hand, PD2 was equipped with a Nao robot (see 3.2.2 for specifications).

As mentioned earlier, the cameras mounted on the heads of the robots lead to a stronger feeling of agency and head-based sensorimotor contingencies as the view of the cameras changes based on the visitor's head movement. However, since it was not possible to look down at one's own body due to the limitations of the range of the head movements of both robots, a mirror was placed at both PD1 and PD2 pointed towards the robots.

6.2.1.2 Virtual Destination

The biggest advantage with a virtual destination is that it can be completely customised based on requirements of the task to be carried out. It could be indoors or outdoors and with as many avatars present as the number of locals in the scenario. VD3 was designed as a room with one avatar experienced from first person perspective representing the visitor, and another seated avatar as the local. The visitor experienced visuomotor synchrony with respect to the movements of their avatar. The virtual environment was rendered in Unity3D, which was also used to manage all the communication between the transporter and the three destinations. The entire VD3 setup was developed based on previous embodiment studies that have successfully elicited a high degree of FBOIs over virtual avatars in IVR (Banakou et al., 2013; Kilteni et al., 2013; Peck et al., 2013).

6.2.1.3 Destination Manager

An underlying server was developed that would be able to detect and manage the switching of the destinations by the visitor. The server would keep track of the destination the visitor was currently in and would stream the appropriate video feed to the HMD and connect the audio streams together, while letting the proxy audio take over at the other destinations. This way the visitor would have a stereoscopic view and two-way audio streaming with whichever destination they would be in at any given point in time. Similarly, the movements of the visitor would also be streamed only to their current destination, with the proxy system controlling movements of the other representations.

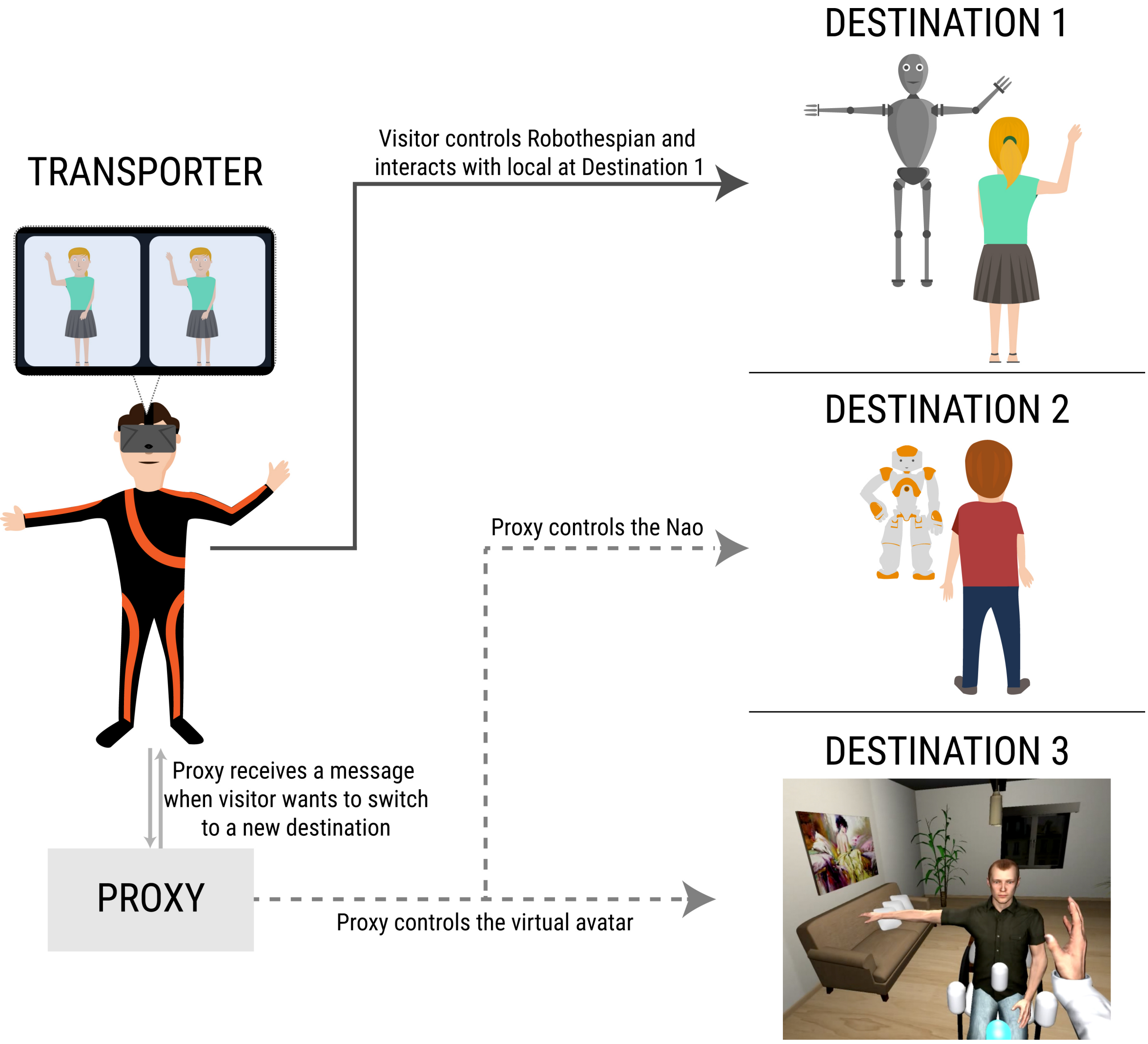

Figure 6.1: An illustration that describes the schema of the setup. The visitor can be in one destination at any given point, and is in full control of the robot (or avatar) present there. Concurrently, the proxy system is in control of the other two visitor representations in the other destinations. A message is sent to the proxy when the visitor wants to switch to another destination, which tells the proxy to take over the destination previously occupied by the visitor.

6.2.2 The Proxy

A critical feature that gives the visitor the ability to be in three different places simultaneously and perform tasks at each destination is the proxy system. While the visitor is only at one destination, the other two destinations are running concurrently as well, where an artificial agent known as the proxy continues interacting with locals and attempting to solve tasks as best as possible. The visitor has the option to switch to any of the other destinations instantaneously and take over the robot or avatar in that destination. At the instant of the switch, the proxy hands control over to the visitor and takes over the representation that the visitor has just left in the previous destination. According to the system described in (Steed et al., 2012), a 'communication proxy' is defined not as an autonomous virtual agent, but as a customised agent based on the models of the owner's behaviour, aware of the owner's goals and preferences. Consequently, a long-term vision for the proxy has been described as being able to replace the person in various real-life contexts by capturing aspects such as verbal and non-verbal communication styles and personality. An example of a prototype of the proxy for a substitute teacher has been described in (Friedman et al., 2013), which has three modes of operation: background, foreground and mixed-mode of operation. During the background mode, when the visitor is actively engaged at a destination, the proxy simply records its owner's behaviour such as skeleton tracking, in the background, and this collected data provides the main source of behaviour model when the proxy is in control.

Based on this vision of the proxy, a simplified version was developed for the purposes of the study. Before beginning the experience, the visitor was made to record a few generic sentences such as:

- *"Oh! I forgot what I was saying!"*
- *"I really can't remember what I was going to say. This has never happened before you know!"*
- *"By the way, my favourite movie is <Visitor's favourite movie>. What's yours?"*

- *"Anyway, forget about me, what's up with you?"*

If the proxy would detect that the visitor was not in a certain destination, it would play back the statements in random order and at random times. Additionally, pre-recorded 'idle' animations were also loaded in the 'Animation Library' of the proxy system, which would be streamed to the unoccupied robot or avatar. As soon as the visitor would switch their destination, the proxy would hand over control of the corresponding visitor representation, and take over the newly unoccupied representation instantly, playing the pre-recorded sentences and skeletal animations.

6.3 Scenario and Procedure

In order to test the efficacy of the system, an experiment was designed with two main objectives in mind. The primary question addressed by the experiment was whether the system could be used successfully and efficiently as a tool for interaction by a participant present at three remote locations simultaneously. The subsequent question concerned the quality of the experience. Specifically regarding the possibility of eliciting a full body ownership illusion in the remote representations and if that assists in creating a stronger experience of being physically present in the same location as the locals. Furthermore, to test the merit of the proxy system, it was important to observe the interaction from the perspective of the local as well.

A total of 41 participants (mean age = 27, SD = 10.5, 17 males, 24 females) were recruited, with each session involving two participants – one visitor and one local (21 visitors; 20 locals). The last session was run with a confederate acting as the local instead of a participant. Each session involved the visitor beaming to three destinations, two physical and one virtual. As mentioned earlier, PD1 was equipped with the Robothespian, PD2 with the Nao and VD3 with an avatar. The experiment was designed for social interactions, and the tasks were designed accordingly. This was done following the theme of the other two studies presented here, as a reported increase in FBOI was shown when participants were in control of a Geminoid HI-1 robot and engaged in a social conversation with a local (Nishio et al., 2013). The visitor would start with PD2 in all cases, and would have a casual, friendly conversation with the local there. For this reason, each visitor and local were recruited in pairs so they knew each other beforehand, and would be able to talk to each other comfortably. Next, at PD1, the visitor would have to give a talk on any topic that they preferred. They were told beforehand to prepare a five-minute talk on any subject they liked. At PD1, a confederate was present to listen to the talk, and interact with the visitor depending on the situation. In VD3, the visitor would have to help a virtual avatar that was seated in front of them to perform a simple exercise with their right arm. The local-avatar at VD3 was controlled by the experimenter, as the task was straightforward and there was no scope for further interaction other than performing the exercise. The main reason for adding the virtual destination was to observe whether the visitor would be able to cope with performing tasks at three destinations, with one of them being virtual.

Each session followed the same sequence - The visitors would begin at PD2 and would begin a friendly conversation with the local. After two minutes they would automatically be switched to PD1, and then two minutes later to VD3. After that, the cycle would repeat again in the same order and the visitors would visit each destination a second time. The decision of switching the destinations could have been given to the visitors, but instead was switched automatically after a fixed amount of time for the purposes of experiment, since all tasks are open-ended and thus needed a time limit. While the visitor was at PD1 and VD3, the local participant at PD2 would continue interacting with the Nao humanoid robot, at that point being controlled by the proxy. The main reason behind visiting each destination a second time was to show the visitor that the interaction had continued even after they had left. Before beginning the experiment, the visitor was given a brief description of the system and was informed about the tasks that they would have to perform. They were also told that they would be automatically switched from one destination to the next after two minutes. The local was not informed

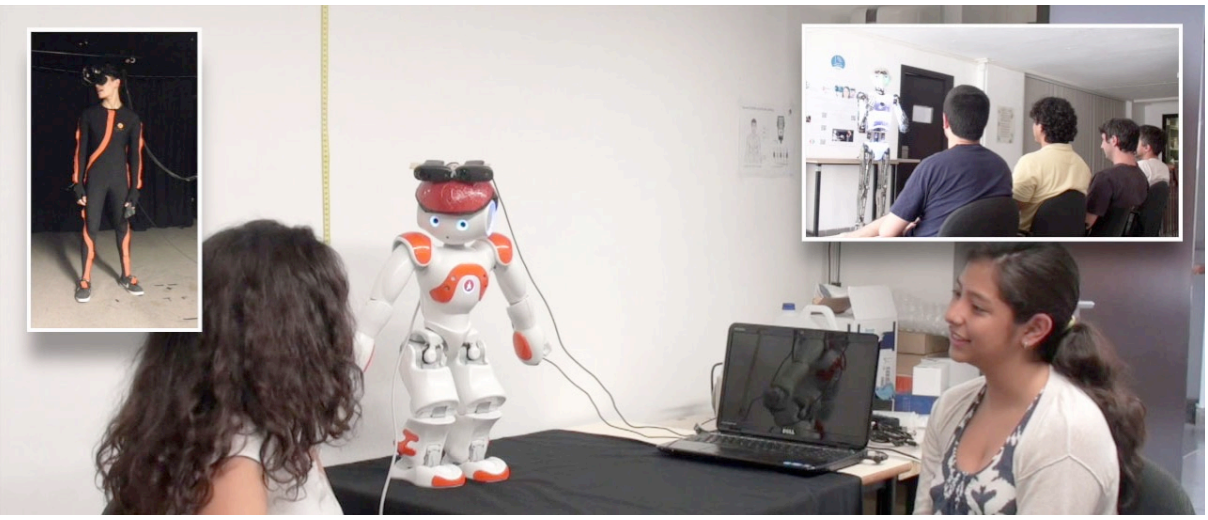

Figure 6.2: The visitor (top-left corner) is currently in PD2 having a social interaction with a friend. The visitor controls the robot's head, and consequently, the view of the destination by simply looking towards the desired direction. Meanwhile, the Robothespian at PD1 continues interaction with the locals via the proxy (top-right corner).

of this otherwise they would expect the proxy to take over, which would break the interaction. Both the participants (visitor and local roles) were interviewed and given questionnaires after the experience. Following is an explanation of the measures used and the results of the responses received.

6.4 Measures

Using the described setup, our main focus was on finding out whether the system was effective in allowing the visitor to perform tasks in three distinct places simultaneously. The question of usability was approached from several perspectives, which are detailed as follows. Visitors were asked to assess their feeling of presence, specifically place illusion (PI) (Slater, 2009), degree of success with which they could cope with the tasks as well as their physical and psychological comfort level while using in the system, along

Figure 6.3: Images from the transporter and all three destinations. Clockwise from left; (a) The visitor wears the Xsens Inertial motion capture suit and the NVIS nVisor SX111 HMD at the transporter; (b) PD1 where the visitor gives a talk to four locals, while embodied in the Robothespian; (c) PD2 where the visitor is in control of a Nao and engages in a friendly, social conversation with a friend; (d) VD1 where the visitor assists a local in performing an exercise, while embodied in a virtual avatar.

with their overall rating of the system's usability (Table 6.1). In addition to the questions related to task performance, the visitors were also asked questions related to the body ownership illusion and agency twice, once for each robot (Table 6.2). The embodiment questionnaire was not given for VD3 since high ownership illusions and high levels of agency have been reported in various previous studies using the exact same setup (Banakou et al., 2013; Kilteni et al., 2013; Peck et al., 2013). The locals were asked two questions regarding their experience (Table 6.3). Questionnaires were administered in paper form immediately after the experiment, and in the same laboratory where the experiment took place. All responses were on a seven point Likert scale anchored with 'Strongly disagree' and 'Strongly agree'. After finishing the questionnaire, the experimenters conducted an oral interview with both participants as well.

Table 6.1: Questions Related to PI, Copresence, Task Performance, Comfort and System Usability. Responses were given on an anchored 7-point Likert scale, where 7 is 'strongly agree' and 1 is 'strongly disagree'.

Copresence	How much did you feel you were physically with the other people?
PlaceIllusion	How much did you feel you were in the places that were displayed?
CopeTasks	How much did you feel you were able to cope with the tasks?
AccomplishTasks	How much did you feel you were able to accomplish the tasks?
PhysicalComfort	Could you rate how physically comfortable you felt while inside the system?
PsychologicalComfort	Could you rate how psychologically comfortable you felt while inside the system?
Usability	How much would you use this system if you really had to be at 3 different places at the same time?

Table 6.2: Questions Related to Body Ownership Illusion and Agency. Responses were given on an anchored 7-point Likert scale, where 7 is 'strongly agree' and 1 is 'strongly disagree'.

MyBody	I felt as if the body I saw might be my body.
Agency	I felt like I controlled the robot body as if it was my own body.
MirrorBody	When I looked in the mirror, I felt as if the body I saw might be my own.
ArmMine	When I saw the robot arm moving, I felt as if the arm I saw might be my own.
TwoBodies	I felt that I had two bodies.
Machine	I felt I was turning into a machine.
ControlBody	I felt in control of the robot body.

Table 6.3: Questions related to the local participant experience. Responses were given on an anchored 7-point Likert scale, where 7 is 'strongly agree' and 1 is 'strongly disagree'.

Copresence	How much did you feel you were physically with the other people?
InteractLocal	How much did you feel you were interacting with your friend?

The question of FBOI over the two robots was addressed through questions *MyBody*, *MirrorBody*, *ArmMine*, *TwoBodies* and *Machine*, agency was assessed via two questions, *Agency* and *ControlBody* (Table 6.2) while Place Illusion was assessed by *PlaceIllusion* and *Copresence* (Table 6.1). The question *ArmMine* was asked since the arms were the only part of the robot that were visible directly by looking down. Task performance ratings were measured using questions *CopeTasks* and *AccomplishTasks*. Finally, questions related to overall usability and comfort level of the system were assessed through *PsychologicalComfort*, *PhysicalComfort* and *Usability* (Table 6.1). The experience of the local was evaluated through two specific questions: Similar to the visitor, *Copresence* was used to assess the local's feeling of being with another person in the same space. *InteractLocal* was used in order to evaluate performance of the proxy system (Table 6.3).

6.5 Results

Box-and-whiskers plots corresponding to the questionnaire responses of the visitors are shown in Figures 6.4 and 6.5. Based on the responses to the question *CopeTasks*, the system was effective in giving participants the feeling that they could cope with the tasks *(median = 6, IQR = 2)* regardless of the destination, and that they could also accomplish the tasks *(AccomplishTasks) (median = 6, IQR = 1.75)*. There are clearly no differences in responses for *CopeTasks* which suggests that the type of representation in the various destinations did not make any difference to their task performance.

Participants gave high scores for both, place illusion *(PlaceIllusion)* for each of the three destinations as shown in Figure 6.4 *(median = 5, 5, 6; IQR = 2, 2.25, 1.25 for PD1, PD2, VD3 respectively)*, as well as for the feeling of being in the same space *(Copresence)* as the locals *(median = 6, 6, 5; IQR = 2, 2, 3.25)*. No significant differences were found between the responses to the copresence ratings between the physical and virtual destinations *(Wilcoxon signed rank test: Copresence(VE) - Copresence(Nao): Z = -1.43, p > 0.05; Copresence(VE) - Copresence(RT): Z = -1.75, p > 0.05)*. Similarly, the differences in responses for PI with respect to the physical and virtual destinations were not statistically significant either *(Wilcoxon signed rank test: PlaceIllusion(VE) - PlaceIllusion(Nao): Z = -1.62, p > 0.05; PlaceIllusion(VE) - PlaceIllusion(RT): Z = -1.17, p > 0.05)*.

Furthermore, visitors gave very high scores for the physical and psychological comfort felt while using the system *(PhysicalComfort: median = 6, IQR = 1.25; PsychologicalComfort: median = 6, IQR = 2)*. Finally, the question regarding their overall evaluation of the usefulness of the system was also met with an extremely positive response as participants gave high scores for using the system in the real world to be in three different places at the same time *(Usability: median = 6, IQR = 1)*. Similarly, the local participants also had the illusion of being with the visitors as well, *(Copresence: median = 5, IQR = 2)* and gave a positive response to the question regarding that the robot they were interacting with was in fact, a surrogate representation of their friend *(InteractLocal: median = 5, IQR = 1)*.

Regarding the body ownership illusion over the two robots and sense of agency, participants gave positive responses for the relevant questions in the questionnaire and the post-experience interview as well. The differences in scores for the questions *MyBody* and *TwoBodies*, with respect to the two robots were not statistically significant *(Wilcoxon signed rank test: MyBody(RT) - MyBody(Nao): Z = -0.159, p > 0.05; TwoBodies(RT) - TwoBodies(Nao): Z = -0.552, p > 0.05)*. Moreover, participants gave high scores for both questions regarding agency, for both robots. The question *Agency* had exactly the same scores for both robots *(median = 5, IQR = 3)* while *ControlBody* had a higher median score for the Nao *(median = 6, IQR = 2)* than the Robothespian *(median = 5, IQR = 2)*.

6.6 Discussion

The discussion of the results is presented in two parts – The first section relates to the characteristics and efficacy of the system, such as task performance, physical and psychological comfort and the overall usability ratings of the system. Additionally, the responses by locals can also be taken into account here, since they provide insight about the ability of the proxy system and the influence of a physical representation of the visitor in the destination. The second aspect of the discussion is related to the visitor's body ownership illusion and feeling of agency over the two remote humanoid robots, and the significance of those in terms of the system's performance.

6.6.1 System Performance

Prior to the experiment, the main concern regarding the system had been that the visitors might find it difficult to keep up with being at three different places simultaneously, and coping with three different tasks. However, most did not express any complaint regarding the same in the interviews or in the questionnaires. On the contrary, they seemed comfortable with the idea as shown by questionnaire results (Figure 6.4, *CopeTasks* and *AccomplishTasks*). It is understandable that there are no significant differences according to destination type for the variable *CopeTasks,* since the tasks were mainly related to verbally interacting with the locals. If the tasks had been more physically oriented, the difference in dimensions of the robots or lack of haptic feedback in case of the virtual destination would have been more important.

Although, responses were not statistically significant, median scores of the questionnaire data related to copresence shows a slight trend towards both the physical destinations performing slightly better than the virtual destination. This is to be expected since the visitors interacted with real locals in PD1 and PD2, while in VD3 the virtual local was automated, instead of being a representation of a real person. On the other hand, median scores for place illusion are higher for the virtual destination as compared to the two physical destinations, which could be attributed to the higher resolution and higher frame rate of the rendered environment as compared to the lower quality video stream. It has been shown that display parameters such as frame rate have an effect on the degree of place illusion (Barfield & Hendrix, 1995; Sanchez-Vives & Slater, 2005). Additionally, visitors had much higher freedom of movement in the virtual environment with the avatar, while in the physical destinations they were constrained by the limited

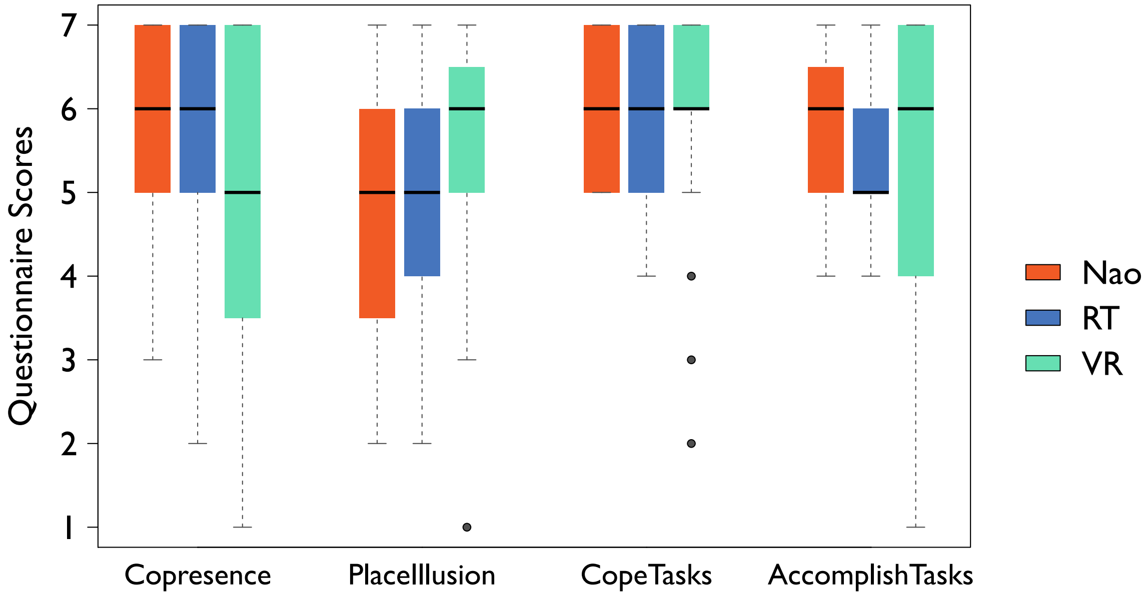

Figure 6.4: Responses to questions on Place Illusion and Task Performance per destination, as provided in Table 6.1. Responses were given on a 7-point Likert scale, where 7 is 'strongly agree' and 1 is 'strongly disagree'. Error bars represent the standard error and dots are statistical outliers.

range of movement of the robots. The responses in the post-experience interviews were mostly positive, with comments such as:

> *"I was in 3 different places with 3 different people."*

> *"I felt transported to 3 different destinations, I had conversations with 2 individuals and prompted physical exercise to a patient."*

Furthermore, regarding the moment they were transported from one destination to the next, most participants answered that they could cope with it very easily, even though for this experiment the switching was done automatically, which would typically be under the visitor's control. A participant commented,

> *"I felt like switching from one environment to another was seamless - it didn't feel weird or artificial."*

In addition, it can also be said that the system was comfortable enough to use for the purpose of performing tasks in three locations, given the high scores to the questions related to comfort and usability. These high scores for physical comfort are in spite of the fact that the HMD used for the system weighed 1.3 Kg and the participants had to don a full-body tracking suit before the start of the experiment.

Furthermore, local participants also gave high scores to the question related to copresence *(Copresence: median = 5, IQR = 2)* suggesting that the physical presence of the visitor was important for the interaction. This is similar to the results of the study by (Pan & Steed, 2016) where they found that the physical presence of a robot was better for communication, than a video or a virtual avatar. The local participants strongly expressed the feeling of being together with their friends during the experience, with comments such as,

> *"I was able to talk and feel the very strong presence of my friend. I could talk with her as if she was there with me and the movements of the robot reminded me of her gestures. From the movement of the head, I was able to understand what my friend was seeing."*

This statement particularly highlights the advantages of having a physical representation in the remote destination, instead of screen or desktop-based systems that do not allow people to express physical gestures and other non-verbal forms of communication. Furthermore, with a median score of 5, the question related to the effectiveness of the proxy system provides a satisfactory evaluation, since the response given by the locals was regarding the entire experience, including the times when they were actually interacting with the proxy representation. Even though many locals didn't immediately realise the moment the visitor had left their destination, they did eventually catch on to the fact that they were not present anymore. One participant said,

> *"I was talking with my friend about things we are currently working on together. At some point it was strange to notice that the context of the conversation changed out of the blue and I later realised that I was not really interacting with my friend anymore, rather with a pre-recorded audio of him."*

However, one local did not realise the change throughout the experience, and thought that the visitor was actually saying the statements that were being played back by the proxy. Their post-experience comments were,

> *"We had an informal conversation about Java classes, buying a dog, and holidays. Then my friend told me his favourite movie was The Gremlins and that he forgot something (... that he was saying)."*

From the perspective of the visitors, one commented that they felt as if the locals had not realised that the visitor had left the destination:

> *"I could interact with 3 different people at one time and it felt like all the 3 thought I had not left the space I shared with them at all."*

All participants were asked about overall comments about the system or suggestions for improvement, and most of the answers were related to the hardware limitations of the robots. Many expressed the desire to be able to walk in the destination. This feature has been implemented and used in the case-study described in the previous Chapter, but was disabled for the experiment to reduce the risks to the local participants and to limit damaging of equipment. Furthermore, the tasks had been designed specifically to not involve walking, however the feature was still missed by some of the participants.

6.6.2 Body Ownership Illusion and Agency

Even though overall the visitors claimed to have felt a sense of body ownership and agency, there is a minor difference in the median scores between the two robots, likely

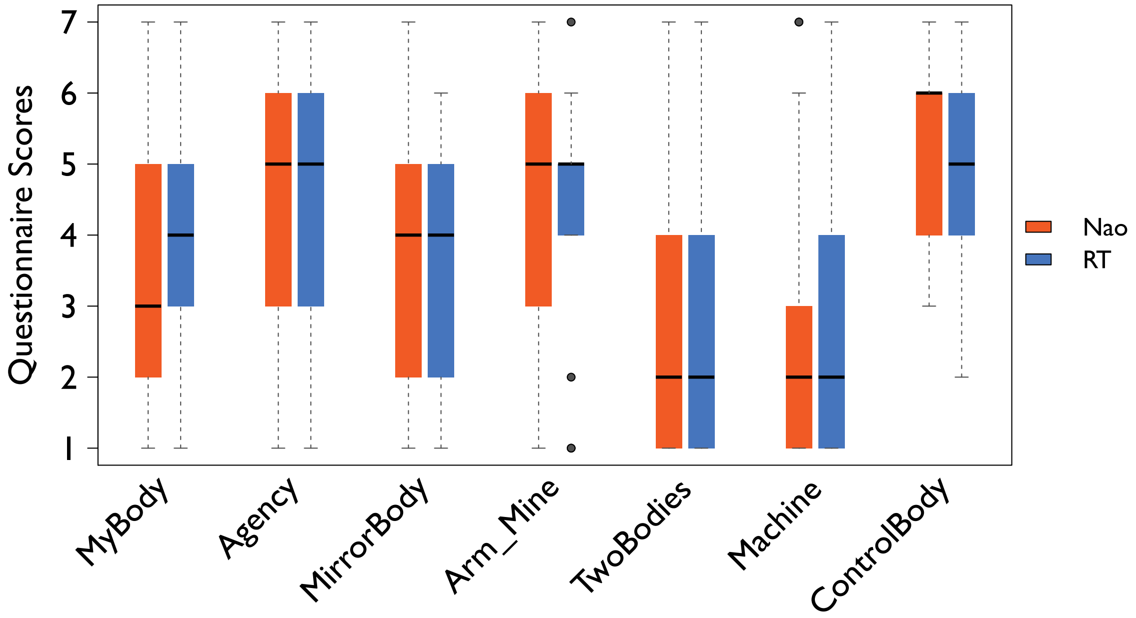

Figure 6.5: Responses to questions on BOI and agency per robot, as provided in Table 6.2. Responses were given on a 7-point Likert scale, where 7 is 'strongly agree' and 1 is 'strongly disagree'. Error bars represent the standard error and dots are statistical outliers.

due to the differences in physical dimensions and movement mechanisms. A participant mentioned,

> *"I did feel more like myself with the bigger robot, and less like myself with the smaller. I am unsure whether to attribute this only to the size of the robot, or not."*

Regardless of that however, the difference between the BOI scores for the two robots is not significant, which suggests that BOIs can be elicited regardless of robot size, as long as first person perspective is provided, in addition to head-based sensorimotor contingencies and visuomotor correlation of limbs. This has also been shown earlier in a study by (van der Hoort et al., 2011) where they were able to induce ownership over bodies of varying sizes. Although we were able to successfully elicit a BOI over the two robotic bodies, the median score for the variable *MyBody* is at the midpoint

(Robothespian: median = 4, IQR = 2). This could be due to several reasons, such as the appearance or dimensions of the two robots. Another reason may be due to the fact that participants could not look down to view their ‘robotic’ body from 1PP due to constraints in the movement of the neck of the robots, and the main visual feedback they had with respect to ‘owning’ the robot body was via the mirror placed in front of both robots at the destination. This is also corroborated by visual inspection of the data, which shows similar scores for the question *MirrorBody* and *MyBody*. The only time when the visitors had a direct view of their robotic body was if their robotic arm would enter their field of view, while embodied in the robot. The evidence of this can be seen in the responses to the question which asks if the arm they saw was their own, with higher scores *(ArmMine: Robothespian – median = 5, IQR = 1; Nao – median = 5, IQR = 3)* than any other questions related to body ownership.

With respect to agency, exactly the same scores for the question *Agency* for both robots show that as long as the mapping and motion retargeting of the visitor’s movements on to the robots is fairly accurate, the dimensions seem to not matter, a finding similar to the study by (Banakou et al., 2013). However, some differences could arise depending on the hardware installed in the robots, with the Nao’s control mechanism built with DC motors for all joints, whereas the Robothespian’s arms having pneumatic motors. Although we do not see any difference in the responses to the question *ControlBody*, we suspect that the construction of the robot could influence the feeling of agency, since the electrical motors in the Nao with higher sensitivity may allow for a finer degree of control over the subtle arm movements, while the pneumatic motors of the Robothespian might be unable to represent these small movements made by the visitors and only tend to move once the movement is more noticeable. A follow-up study that focuses on the effect of the control mechanism of various humanoid robots on the feeling of agency could provide insight regarding this question.

6.7 Conclusion

We have successfully shown that people were able to cope with being at three different places at the same time and were able to carry out tasks successfully by using our Multi-Destination system. While all telepresence applications follow a one-to-one approach, we have developed a highly immersive system that allows the participant to be in three separate locations at the same time, and allows complete two-way interaction with the locals at each location. To our knowledge, this is the first time such a system has been developed. Thanks to the proxy system, the interactions are able to continue even if the visitor is not present in the destination.

Although we carried out the study with a simplified version of the proxy, it has the potential to be developed into a much more intelligent system, with a much higher degree of autonomy. The proxy could be task-based, so it could have appropriate behaviour depending on the tasks that the visitor is required to perform. It could have the ability to 'learn' new tasks according to the need, such as performing repetitive movements, or for example, learning a speech that the visitor needs to give. This could allow the visitor to do other activities while their surrogate robot gave the speech, and with a press of a button they could go to their destination and check on the proxy, in case it was required. The proxy itself could also somehow have a way of contacting the visitor in case they were unable to solve some issue on their own and needed the visitor's intervention. Finally, although we have demonstrated the possibility of self-localisation in three distinct places simultaneously, a proper analysis of this question as part of a follow-up study is important.

* * *

"It is change, inevitable change, that is the dominant factor in society today. No sensible decision can be made without taking into account not only the world as it is, but the world as it will be…"

Isaac Asimov

Asimov on Science Fiction, 1981

7

Conclusions

7.1 General Discussion

In this thesis, we have drawn inspiration from several concepts across multiple fields, such as telepresence, teleoperation, self-perception and bodily illusions, in order to develop a novel system which allows a participant to be virtually teleported to a remote destination instantaneously. In the remote location they are embodied in a humanoid robot, which allows them to not just see and hear from the robot's perspective, but also allows them to move its body as if it were their own, thereby making them feel ownership over the robot body, thus making the robot the source of all their associated sensations.

By manipulating various aspects of this system, we conducted three studies, which were discussed in Chapters 4, 5 and 6. Given the results that we observed, we are in a position to defend the hypotheses that were laid out at the beginning of this thesis.

I. **Hypothesis 1:** *It is possible to induce the full body ownership illusion over a remote robotic body with a highly robotic appearance. Moreover, it is possible to induce feelings of agency over the robotic body, even with non-manual control.*

Several concepts related to BOIs have been studied with rubber hands, mannequins, avatars in IVR as well as a few cases of android robots, but there is a lack of conceptual knowledge regarding eliciting FBOIs with a robot of a highly robotic appearance. It is important to discover this information, as it could be used to develop real-world immersive telepresence applications with commercially available humanoid robots for various purposes. As an example of a potential scenario, an application could be developed, which would allow disabled patients that have lost control of their limbs to feel ownership of a robotic body, in order to carry out tasks. Indirect control methods such as BCI have been demonstrated with humanoid robots, although none of them offer an immersive and versatile solution for robotic embodiment.

We first developed such a system by taking into account the various requirements and constraints involved. Subsequently, we carried out a study with 20 participants, in order to test whether we would be able to elicit a FBOI over a remote humanoid robot. In addition, we compared two abstract methods of control in an immersive environment for controlling the robot, BCI based SSVEP and eye tracking.

Our results provide evidence that it is in fact possible to induce feelings of body ownership over a humanoid robot with a robotic appearance, even if the postures of the participants and robot are incongruent. Corroborating results from existing studies, our results also show that having a humanoid morphology is more crucial than visual appearance for eliciting the illusion. However, significant differences were found in reported BOI based on control method, with a higher reported score for the BCI condition. This could be due to the reported level of agency, which was also higher for the BCI condition based on visual inspection of the data.

II. **Hypothesis 2:** *By embodying someone in a remote robotic body, they can be physically represented in that remote location by using the robot as a surrogate.*

    As we saw that it is possible to induce a feeling of body ownership over a robotic body, even with abstract controls and incongruent postures, the next question we posed was what would happen if we were to fix these discrepancies. Previous studies have shown that with visuomotor correlation and head-based sensorimotor contingencies provided from a 1PP of an artificial body can lead to high feelings of body ownership over that body. However, no such study has been carried out where all these concepts are combined in the context of a humanoid robot. Several robotic telepresence setups provide the operator with a physical representation at a remote location, although none of them provide a fully immersive experience. On the other hand, many solutions have been developed for remote teleoperation of a humanoid robot using natural body movement, but not in the context of an immersive embodied remote telepresence experience.

    By extending the capabilities of the system we developed, we provided a participant with full control over the robot's limbs by using their own natural movement, in addition to the previously mentioned aspects such as 1PP and head-based sensorimotor correlation. Consequently, this direct mapping of the participants' movements onto the robot also led to both entities having congruent poses at all times, all of which when combined lead to a highly immersive experience where the participant is embodied in and physically present in a remote location. In order to test the system, we developed a real-world application in the context of journalism. We ran several instances of the setup as part of a case-study to analyse the functionality and efficacy of the system. Several news articles were published as a result of this, both discussing the system itself as well as articles not related to the technology at all, but focusing on the news story that was covered using the system.

III. **Hypothesis 3:** *Extending the setup in the previous hypothesis, it is possible for someone to be in three distinct locations simultaneously and perform tasks in each location,* *by embodying a physical (or virtual) surrogate body.*

Given the results of our previous experience, we were interested in extending this system further to allow the visitor to be in not one, but three distinct destinations. The concept of bilocation (and multilocation) has been studied partially with respect to virtual environments, and there exist certain telepresence setups as well that allow an operator to control multiple robots in different locations. However, to our knowledge there has been no research that combines the concept of FBOI with multiple artificial bodies simultaneously.

Therefore in order to observe the experience of having one visitor be present and embodied in three distinct locations simultaneously, we updated our system and carried out a study with 42 participants. In the study, one visitor could 'travel' to three locations - two physical and one virtual, and in each destination they would be in control of a surrogate robotic (Robothespian or Nao) or virtual body. This was done by allowing the visitor to be in one destination at any given point, with the ability to instantaneously switch to the other destinations. A proxy system and an underlying network server were also conceived and developed to control the remote representations of the unoccupied destinations and to manage the entire scenario. Thus, each session was run with two participants - one visitor, to test the main hypothesis regarding coping with being in three places at the same time, and one local, to test the efficacy of the proxy system.

Our results show that participants were successfully able to cope with the tasks in three places at the same time, and that the system was physically and psychologically comfortable and usable in such a scenario. They reported feelings of BOI and agency over both robots, although we did not find significant differences between the two, even though there is a big difference in height of the two robots, with the Robothespian at 1.8 metres, while the Nao is only 0.6 metres. This is in line with existing literature that states that ownership can occur with artificial bodies of very large and very small dimensions. These results have potential for further developing this system, especially the proxy so as to make it viable for use in real-world scenarios.

7.2 Contributions and Limitations

There are two main contributions of the research presented here. Firstly, we have demonstrated development of a method to develop a fully immersive embodied telepresence setup with a humanoid robot. We have also been able to evaluate its functionality and effectiveness, and have tried to gain understanding about the system's potential to be used as a viable application for real-world scenarios. Secondly, we have also developed further conceptual understanding regarding body ownership illusions with humanoid robots. Not only does this give us clues about using humanoid robots for the purposes as described here, but also provides us with insight related to the theoretical framework regarding these concepts, which could be used to further understand the relationship of the body and the brain.

More specifically, in the *BCI-ET Study* we show for the first time a full body ownership illusion being elicited in a humanoid robot. Furthermore, we have also developed a prototype of an application that could have immense potential with disabled and paralysed patients to give them the ability to feel ownership of a robotic body and drive it using indirect control methods. Although we found the two control methods (SSVEP BCI and eye tracking) to be similar in terms of task performance, we did not go into too much detail about the relative advantages of these technologies. A more controlled experiment that investigates various aspects of each control method, specifically in an immersive environment would provide us with clues regarding which method could be more appropriate for what type of scenario. Additionally, these technologies could also be combined together where eye-tracking and SSVEP data work synchronously to provide even more robust control.

As part of the *Tele-Immersive Journalism* case-study, we have developed a fully immersive system where a participant can be embodied in a humanoid robot located in a completely different place. Using commercially available technologies, we developed the system that included real-time body tracking, motion retargeting on humanoid robots, stereoscopic video streaming, and two-way audio streaming, all carried out over a regular Internet connection. By applying this technology to a real-world scenario, we carried out the first instance of tele-immersive journalism, where journalists beamed several hundred miles to different cities instantaneously and carried out their job through a humanoid robot that they felt to be their own body. Since this was meant to be a case-study and a demonstration of the system as a real application, we made no quantifiable observations regarding BOI and agency with the humanoid robot. We based our presumptions on existing literature and our own findings from the previous study, which were corroborated through anecdotal observations of the visitor's experience, though it would have been even more useful to have objective data. However, it would be better to design a simple study with this system rather than running it as an application of tele-immersive journalism, which could be extremely complex due to the variance in the scenarios.

Finally, in the *Multi-Destination Beaming* study we extended our system to include multiple destinations and showed that it is physically and mentally possible to cope with being in three different places, carrying out three completely unrelated tasks. This setup demonstrates progress in terms of currently existing technology, since most telepresence systems work with a *one-to-one* scheme, i.e. one operator driving one remote robot. Furthermore even the systems that do allow for control over multiple robots do not provide the participant with a truly immersive, embodied experience. In addition, the setup also gives us clues regarding the theoretical concept of self-localisation and multilocation over different destinations. Although we analyse this through two questions regarding coping with and accomplishing tasks, a more in-depth study that focuses on understanding self-localisation and the continual distribution of self while using the system could be very informative. Finally, although we demonstrated our setup as a proof-of-concept, the system is still lacking in certain aspects, especially in terms of the proxy. Development of the proxy by applying concepts from various computing fields such as artificial intelligence would lead to a much more powerful ‘assistant’ that could manage the unoccupied destinations much more convincingly.

7.3 Future Work

The work that we have demonstrated in this thesis provides a foundation that holds great potential in terms of further research that can be carried out. In the same vein as the studies that we have carried out, the future work can be continued in both directions, related to technological applications of tele-immersive embodiment as well as theoretical studies regarding self-perception and body representation.

In terms of perceiving an artificial body as one’s own, a very interesting phenomenon has been observed, which was also mentioned briefly in Chapter 2. Some studies in IVR reported that participants embodied in virtual bodies that were culturally or physically distinct from their own resulted in temporary higher level behavioural and attitudinal changes, according to the type of avatar. Studies showed participants embodied in casual dark skinned bodies played the drums with more freedom than when embodied in formal light skinned bodies (Kilteni et al., 2013). Participants embodied as Dr. Sigmund Freud were able to provide a better counselling to their problems than when embodied as themselves (Osimo et al., 2015). More remarkably, being embodied in black avatars led to a reduction in the participants’ implicit level of racial bias (Peck et al., 2013).

These results are extremely interesting and give us inspiration going forward with BOI studies carried out with artificial bodies. Given these results, there is a strong motivation to study the higher-level behavioural aspects and implicit changes in attitude as a result of embodiment in a humanoid robot. Over the years as humanoid robots have gained popularity and momentum, it has become very important to understand these underlying psychological behaviours of people who interact with these robots. There have been many studies in the field of *computer anxiety* (Heinssen et al., 1987), a disorder that prevents people from using computers, but knowledge is lacking in terms of robots. Several researchers have attempted to study attitudes of people towards robots, based on gender, culture and nationality (Nomura & Kanda, 2003; Bartneck et al., 2005; Nomura et al., 2005) using different scales and measures. In addition to computer anxiety, popular media, such as news and movies, often portray robots as evil entities taking over the world. This can end up causing an even stronger bias among people against use of humanoid robots in daily life. Thus, a series of experiments that would aim to investigate the implicit bias people may have against robots would be very insightful as to the current attitudes that people may have. The hypothesis of the study would be to see if implicit bias against robots can be reduced by self-association, in a way similar to previous racial-bias studies by embodying the participants in a robot and asking them to perform a task. It is believed that synchronous control over the robot body and a successful task performance will lead to a significant reduction in implicit bias against robots, as compared to the participants that perform the asynchronous condition (Peck et al., 2013; Maister et al., 2015).

A study that attempts to answer that question has been designed, and is in its pilot phase at the time of writing this thesis. The experiment has been designed to be carried out over two phases. In the first phase, participants will be asked to fill in the Negative Attitude towards Robots (NARS) questionnaire (Nomura et al., 2006) in order to have an explicit measure of their initial bias. Immediately after, they would be given some reading material regarding humanoid robots in the news. The salience document presented to them will contain excerpts from articles talking about negative aspects of humanoid robots, such as reduction of jobs due to automation, and threats of artificial intelligence. This would be done to make the participant aware of the situation, and to motivate them to think about this topic. But since the document might cause a bias, after they are done reading they would be given distracting tasks such as finding words in a word puzzle. Finally after finishing the distractor tasks, they will be asked to perform an Implicit Association Test (IAT). The IAT has been used in several studies, and it involves classifying words and/or images into different categories. The implicit bias is calculated by measuring the differences in response times and errors during classification (Greenwald et al., 1998). The IAT for this study has been designed using similar images and words as described in (MacDorman et al., 2009) where they used the test to observe a difference in bias against robots in participants from Japan and the United States. All of the above would give us a baseline about their implicit and explicit bias with respect to robots.

A few days later, the participants would come for a second session, where they would be asked to perform a simple task while embodied in the robot. The task consists of moving their head and arms following a set of pre-recorded instructions for a total of 9 minutes, which consists of a set of two training periods that last 3 minutes each, and a final movement task of 3 minutes more. According to their condition, they might have synchronous or asynchronous visuomotor correlation, although they will always have synchronous head-based sensorimotor contingencies. At the end of the experience, they would be asked to fill the NARS questionnaire and take the IAT again. Another measure, based on previous studies on proxemics could also be used, which involves clicking a photograph of the participant and the robot. The minimum distance that the participants choose to maintain between themselves and the robot will be recorded. This procedure will be done at the end of both sessions, and the difference in the distance between the participant and robot, before and after the embodiment experience, could potentially give us another measure to analyse the behavioural change. The observation of proxemics is a common measure in the field of human-robot interaction and has been used in several previous studies (Walters et al., 2005; Walters et al., 2006; Oosterhout & Visser, 2008; Mumm & Mutlu, 2011).

The research that we have carried out, and the ideas that we have put forward are a step in the right direction, but we have just begun to scratch the surface of the immense potential that this subject holds. With technological innovations growing at an exponential rate, we have unprecedented computational power that allows us to develop paradigms related to improvements not only in areas of robotics, but also towards understanding the internal processes of the brain, in terms of perception of the self and the surroundings.

Science fiction literature has always stretched one's imagination to the extreme regarding where robotic technology could lead us, and most of them admittedly have a depressing tone about a dystopian future. But these ideas, including the negative ones also provide inspiration, and give us clues about potential pitfalls which should be kept in mind. For example, the famous three laws of robotics that Isaac Asimov defined in his science fiction short story 'Runaround' (Asimov, 1942), kickstarted an extraordinarily diverse series of discussions and debates regarding ethics and design philosophies in the field of robotics and artificial intelligence (Clarke, 1993; Murphy & Woods, 2009).

According to our vision, the system discussed in this thesis could be transformed into diverse configurations based on the requirements. It could be useful in areas such as healthcare, not only for disabled patients but also for medical doctors to attend to patients remotely without travelling. It could also become a viable tool in general, for immersive interaction in real-world scenarios for remote communication and would immensely reduce the need for travelling over long distances. Not only would this save time, but it would be extremely beneficial in conserving the environment as well. In a few decades from now, we imagine a scenario where there would be surrogate-robot docking stations all over the world, where anyone could connect to whichever robot they wanted, and more substantially, as many robots as they wanted, and teleport to many locations instantaneously. It may seem far-fetched today, but that is what makes it truly exciting.

⁂

A

BCI-ET Study Material

In this appendix, we present the documents that were used for the BCI-ET study described in Chapter 4.

The materials are provided as follows:

- The information sheet that was given to the participants on arrival.
- A consent form that was designed in accordance with ethical recommendations. Participants were asked to sign this form as a way of giving consent to being a participant in the experiment.
- An anonymous demographics questionnaire.
- The Post-experiment embodiment and Control method questionnaires.

The forms presented here are in Castilian Spanish, but documentation was also available in English and Catalan, if desired by the participants.

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INFORMACIÓN DEL EXPERIMENTO

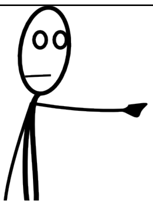
Este experimento forma parte de una serie a través de la cual intentamos aprender cómo responden las personas a las experiencias de telepresencia a través de robots. El objetivo principal es la utilización de estos sistemas para personas con limitación de movimientos.

Te pondrás un casco de Realidad Virtual que te mostrará un mundo a través de los ojos del robot, podrás activar cuatro movimientos del robot mediante dos técnicas diferentes. Se realizarán dos sesiones en días separados para cada una de las técnicas.

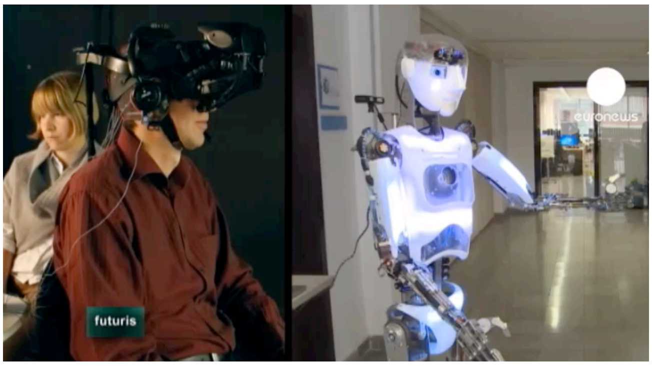
En una sesión llevarás un gorro de EEG, con solo 8 electrodos, con el que mediremos su actividad cerebral. Para instalar el gorro necesitaremos poner un poco de gel en tu pelo. Está técnica te permitirá activar los comandos del robot observando fijamente los cuadrados que parpadean a diferentes frecuencias. El cerebro humano reproduce las frecuencias en el cortex visual y nosotros seremos capaces de saber a qué cuadrado estás mirando. Es muy importante que estés concentrado en el cuadrado objetivo sin prestar atención los otros parpadeos, sino no podremos descifrar tu objetivo. Haremos un entrenamiento antes de empezar para que aprendas a usar esta tecnología.

En la otra sesión (sin EEG), controlaremos hacia donde miran tus ojos, con la técnica de captura de movimientos. Esta técnica te permitirá activar los comandos del robot simplemente observando hacia los cuadrados.

Los comandos serán los siguientes gestos:

			
"no se"	"señalando a la izquierda"	"señalando en frente"	"hasta luego"

En la imagen inferior puedes ver a una persona con todo el equipo. Y el robot haciendo uno de los gestos.



El experimento consiste en aproximadamente 1 hora (sesión EEG) y 45 minutos (sesión movimientos).

Si tienes alguna pregunta ahora, por favor pregunta.

MUY IMPORTANTE: notifíquenos si ha tenido algún ataque epiléptico anteriormente.

Recuerda que eres libre de abandonar el experimento en cualquier momento y sin dar explicaciones.

eventLAB
Neuroscience
& Technology

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Campus de Mundet - Edifici Teatre
Passeig de la Vall d'Hebron 171, 08035 Barcelona, Spain

CONSENTIMIENTO INFORMADO DEL PARTICIPANTE

El voluntario deberá leer y contestar cuidadosamente las siguientes preguntas:

¿Ha leído toda la información sobre este estudio? SI/NO

¿Ha tenido la oportunidad de preguntar y comentar cuestiones sobre el estudio? SI/NO

¿Ha recibido respuestas satisfactorias a todas las cuestiones? SI/NO

¿Ha recibido la suficiente información sobre este estudio? SI/NO

¿Qué investigador le ha hablado sobre el estudio? ……………………….

¿Ha comprendido que usted es libre de abandonar este estudio?

- En cualquier momento SI/NO
- Sin dar ninguna razón SI/NO

¿Ha comprendido y aceptado los riesgos asociados con el uso de la Realidad Virtual? SI/NO

¿Está de acuerdo en tomar parte en el estudio? SI/NO

¿Está de acuerdo en ser grabado en vídeo? SI/NO

¿Está de acuerdo en ser grabado en audio? SI/NO

¿Está de acuerdo con que pongamos gel en su pelo? SI/NO

¿Está de acuerdo con que le contactemos en dos semanas para preguntarle sobre su experiencia? SI/NO

Yo certifico que no padezco epilepsia.

Yo certifico que no conduciré ni coches, ni motos, ni bicicletas ni usaré ningún tipo de máquinas complejas que puedan ser peligrosas para mí o para otros, durante las tres próximas horas después de acabada la experiencia.

Firmado………………………………………………………… **Fecha**……………………………

Nombre en mayúsculas……………………………………………………………………………………

En caso que usted desee hacer alguna pregunta o comentario de este estudio en el futuro por favor contacte con:

Mel Slater

EVENT Lab for Neuroscience and Technology
Facultat de Psicologia, Universitat de Barcelona, Departament de Personalitat, Avaluació i Tractaments Psicològics,
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La información obtenida de su experimento nunca será publicada individualmente. Los datos serán analizados en grupos y aquellos comentarios verbales, en el caso que se publiquen, serán presentados de forma anónima.

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INFORMACIÓN DEMOGRÁFICA

ID (a rellenar por el investigador)	
Edad	
Género	○ Masculino ○ Femenino
Ocupación	Estudiante ○ Investigador ○ Trabajador ○ Otros ○
¿Está tomando alguna medicación?	○ Si ○ No Si afirma, especifique cual:
¿Tienes visión normal o corregida a visión normal?	○ Si ○ No Si afirma, especifique cual:
¿Ha consumido más de dos unidades de alcohol en las últimas 6 horas? *(2 unidades de alcohol = 1 cerveza o 2 copas de vino)*	○ Si ○ No
Por favor indica tu nivel de experiencia en Realidad Virtual (ninguna experiencia) 1○ 2○ 3○ 4○ 5○ 6○ 7○ (experiencia extensa)	
Por favor indica tu nivel de experiencia con juegos 3D en ordenador: (ninguna experiencia) 1○ 2○ 3○ 4○ 5○ 6○ 7○ (experiencia extensa)	
Por favor indica tu nivel de experiencia con Interfaces Cerebro Ordenador BCI: (ninguna experiencia) 1○ 2○ 3○ 4○ 5○ 6○ 7○ (experiencia extensa)	
¿En qué categoría de jugador de videojuegos dirías que estás?	○ No jugador: Casi nunca juego a videojuegos ○ Jugador casual: Juego para relajarme y disfrutar ○ Jugador Core: Normalemente juego a videojuegos con una curva de aprendizaje más pronunciada, o juegos que requieren mayor dedicación o con complejos desafíos tácticos. ○ Jugador Hardcore: Normalmente juego videojuegos de mucha acción y extremadamente competitivos que requieren un nivel de dedicación superior, o destreza para poder progresar.

Por favor indica como de acuerdo estás con las siguientes afirmaciones sobre tu experiencia:

	Completamente en desacuerdo						**Completamente de acuerdo**
He sentido como si el cuerpo que veía pudiera ser mi cuerpo.	○	○	○	○	○	○	○
He sentido como si estuviera de pie.	○	○	○	○	○	○	○
He sentido como si controlara el cuerpo del robot como si fuera mi cuerpo.	○	○	○	○	○	○	○
Aunque no se parecía a mí, cuando miraba el espejo, he sentido como si el cuerpo que veía pudiera ser el mío.	○	○	○	○	○	○	○
Aunque no se parecía a mí, cuando he visto moverse al brazo del robot, he sentido como si el brazo pudiera ser el mío.	○	○	○	○	○	○	○
He sentido que tenía dos cuerpos.	○	○	○	○	○	○	○
He sentido que me estaba convirtiendo en una máquina.	○	○	○	○	○	○	○
He sentido que estaba en el lugar que veía.	○	○	○	○	○	○	○
He sentido que controlaba el cuerpo del robot.	○	○	○	○	○	○	○
Parecía como si estuviera interactuando directamente con la persona que se acercó.	○	○	○	○	○	○	○
He sentido que estaba en el mismo lugar que la persona que se acercó.	○	○	○	○	○	○	○
He sentido que era capaz de comunicarme de manera efectiva con la persona que se acercó.	○	○	○	○	○	○	○

Por favor, indica el nivel de validez de las siguientes afirmaciones sobre tu experiencia de este método para controlar el robot (método de interacción):

	Completamente en desacuerdo						**Completamente de acuerdo**
He sentido que podía controlar el método de interacción con los cuadrados.	○	○	○	○	○	○	○
He tenido dificultad moviendo mi foco visual entre los cuadrados y el mundo.	○	○	○	○	○	○	○
A menudo el método de interacción me distraía del entorno.	○	○	○	○	○	○	○
Me he frustrado de intentar usar el método de interacción.	○	○	○	○	○	○	○
Era difícil controlar el robot.	○	○	○	○	○	○	○
Los cuadrados me distraían.	○	○	○	○	○	○	○
Me tenía que concentrar mucho para usar el método de interacción.	○	○	○	○	○	○	○
A menudo se ejecutaban acciones que yo no quería seleccionar.	○	○	○	○	○	○	○

B

Tele-Immersive Journalism Material

In this appendix, we present the questionnaire that were given to the local participants in the various demonstrations of the Tele-Immersive Journalism case-study described in Chapter 5.

The materials are provided as follows:

- A questionnaire regarding their interaction experience with the journalist embodied in a humanoid robot.

The questionnaire presented here is in Castilian Spanish, but was also available in English and Catalan.

Cuestionario acerca de la experiencia

Sentí como si estuviera interactuando con una persona real, y no con un robot.

○	○	○	○	○	○	○
(Totalmente en desacuerdo)						(Totalmente de acuerdo)

Sentí como si la persona que controlaba el robot estuviera en el mismo espacio físico en el que yo estaba.

○	○	○	○	○	○	○
(Totalmente en desacuerdo)						(Totalmente de acuerdo)

Creo que es una buena idea usar a un robot para propósitos de periodismo (por ejemplo entrevistas).

○	○	○	○	○	○	○
(Totalmente en desacuerdo)						(Totalmente de acuerdo)

Tenía miedo de cometer errores o romper algo cuando interactuaba con el robot.

○	○	○	○	○	○	○
(Totalmente en desacuerdo)						(Totalmente de acuerdo)

Estaba cómodo con la presencia del robot.

○	○	○	○	○	○	○
(Totalmente en desacuerdo)						(Totalmente de acuerdo)

Siento que pudiera realizar tareas conjuntas con este robot.

○	○	○	○	○	○	○
(Totalmente en desacuerdo)						(Totalmente de acuerdo)

Me sentí amenazado por el robot.

○	○	○	○	○	○	○
(Totalmente en desacuerdo)						(Totalmente de acuerdo)

¿Tienes otros comentarios que quieras agregar?

C

Multi-Destination Beaming Material

In this appendix, we present the documents that were used for the Multi-Destination Beaming study described in Chapter 6.

The materials are provided as follows:

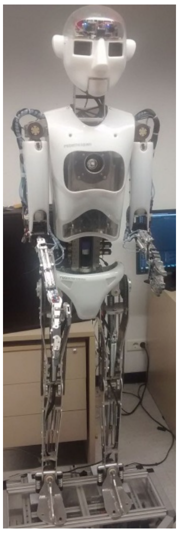
- The information sheet that was given to the participants on arrival.
- The Post-experiment embodiment and task performance questionnaires for the visitors.
- The Post-experiment interaction quality questionnaires for the locals.

The consent form and demographic questionnaires used in this study were the same as the ones presented in Appendix A. The forms presented here are in Castilian Spanish, but documentation was also available in English and Catalan, if desired by the participants.

INFORMACIÓN DEL EXPERIMENTO

Este estudio forma parte de una serie a través de la cual intentamos aprender cómo responden las personas a las experiencias de realidad virtual.

En este estudio se pondrá un traje de cuerpo entero con el cual se reflejarán sus movimientos. Además, deberá ponerse un casco de realidad virtual (HMD) que le mostrará un mundo virtual. La siguiente imagen le muestra una persona llevando el HMD y el traje de cuerpo entero.



El experimento consiste en una aplicación donde podrás ver e interactuar con personas de un escenario remoto a través de unos robots. Los participantes usarán un casco de realidad virtual y auriculares para comunicarse y realizar una tarea en colaboración con otras personas localizadas en destinos remotos. Un sistema de captura de movimiento permitirá a los participantes controlar el robot al moverse.
Se tiene que hacer un breve discurso de 3 minutos (mas o menos), sobre el tema de su elección, para presentarlo a través del robot que se ve arriba.

La duración total de experimento será de aproximadamente 60 minutos (incluyendo cuestionarios y una breve entrevista al final de la sesión). La participación será compensada con 5 euros.

El estudio se llevará a cabo en el laboratorio de realidad virtual del Campus Mundet, Edificio Teatro, Facultad de Psicología, UB.

Por calquier problema ponerse en contacto con Pierre Bourdin al correo electrónico pierre.bourdin@gmail.com

Requisitos indispensables para poder participar en el experimento:

- Mayor de 18 años y menor de 50
- No haber tomado alcohol, ni medicación que afecte la percepción el día del experimento.

Si tiene alguna pregunta ahora, por favor pregunte.

Recuerde que es libre de abandonar el experimento en cualquier momento y sin dar explicaciones.

Post-Experiment Questionnaire - Visitor

ID:

Indica hasta qué punto estás de acuerdo con las siguientes afirmaciones sobre tu experiencia. Cada afirmación debe ser contestada con una de las siguientes opciones:

0 Totalmente en desacuerdo, (o dependiendo de la pregunta, Nunca, De ningún modo, etc…)

1 Bastante en desacuerdo

2 En desacuerdo

3 Ni de acuerdo ni en desacuerdo

4 De acuerdo

5 Bastante de acuerdo

6 Totalmente de acuerdo, (o dependiendo de la pregunta, Todo el tiempo, Totalmente, etc…)

Durante el experimento hubo momentos en los que:

Q1 ¿En qué medida has sentido haber estado en los lugares que se muestran?

a) Robot pequeño
(Nunca) 0 1 2 3 4 5 6 (Todo el tiempo)

b) Robot grande
(Nunca) 0 1 2 3 4 5 6 (Todo el tiempo)

c) Entorno virtual
(Nunca) 0 1 2 3 4 5 6 (Todo el tiempo)

Q2 ¿Sentías que estabas con otras personas (la sensación de estar con otras personas)?

a) Robot pequeño
(Nunca) 0 1 2 3 4 5 6 (Todo el tiempo)

b) Robot grande
(Nunca) 0 1 2 3 4 5 6 (Todo el tiempo)

c) Entorno virtual
(Nunca) 0 1 2 3 4 5 6 (Todo el tiempo)

Q3 ¿Hasta qué punto eras capaz de hacer las 3 tareas?

a) Robot pequeño
(Nunca) 0 1 2 3 4 5 6 (Todo el tiempo)

b) Robot grande
(Nunca) 0 1 2 3 4 5 6 (Todo el tiempo)

c) Entorno virtual

(Nunca) 0 1 2 3 4 5 6 (Todo el tiempo)

Q4 ¿En qué medida has sentido haber logrado las tareas?

a) Robot pequeño
(Nunca) 0 1 2 3 4 5 6 (Todo el tiempo)

b) Robot grande
(Nunca) 0 1 2 3 4 5 6 (Todo el tiempo)

c) Entorno virtual
(Nunca) 0 1 2 3 4 5 6 (Todo el tiempo)

Q5 ¿Podrías calificar el nivel de confort tanto en relación al bienestar físico y al bienestar psicológico?

a) bienestar físico:
(Incómodo) 0 1 2 3 4 5 6 (Cómodo)

b) bienestar psicológico:
(Incómodo) 0 1 2 3 4 5 6 (Cómodo)

Q6 ¿En qué medida usarías este sistema si realmente tuviste que estar en 3 lugares diferentes al mismo tiempo?

(De ningún modo) 0 1 2 3 4 5 6 (Totalmente)

Q7	¿Podrías describir lo que ha pasó?
	____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________
Q8	¿Qué se tendría que cambiar, para que considerases este tipo de sistema como una solución real al problema de tener que estar en varios lugares diferentes al mismo tiempo?
	____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________
Q9	Otros comentarios (opcional)
	____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________

Post-Experiment Questionnaire - Local

ID:

Indica hasta qué punto estás de acuerdo con las siguientes afirmaciones sobre tu experiencia. Cada afirmación debe ser contestada con una de las siguientes opciones:

0 Nunca, (o dependiendo de la pregunta, Totalmente en desacuerdo, etc…)

1 Bastante en desacuerdo

2 En desacuerdo

3 Ni de acuerdo ni en desacuerdo

4 De acuerdo

5 Bastante de acuerdo

6 Todo el tiempo, (o dependiendo de la pregunta, Totalmente de acuerdo, etc…)

Durante el experimento:

Q1	¿En qué medida has sentido que estabas con otras personas? (la sensación de estar con otras personas)								
(Nunca)	0	1	2	3	4	5	6	(Todo el tiempo)	
Q2	¿En qué medida tenías la sensación de interactuar con tu amigo?								
(Nunca)	0	1	2	3	4	5	6	(Todo el tiempo)	

Q3	¿Podrías describir lo que ha pasó?
	____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________
Q4	Otros comentarios (opcional)
	____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________

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Declaration

I herewith declare that I have produced this work without the prohibited assistance of third parties and without making use of aids other than those specified; notions taken over directly or indirectly from other sources have been identified as such. This work has not previously been presented in identical or similar form to any examination board. The dissertation work was conducted from 2011 to 2016 under the supervision of Professor Mel Slater at the University of Barcelona.

Barcelona,

This dissertation was finished writing in Barcelona on Saturday 28 May, 2016

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