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**A design-led approach for transferring the
embodied skills of puppet stop-motion
animators into haptic workspaces**

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2013

Abstract

This design-led research investigates the transfer of puppet stop-motion animators' embodied skills from the physical workspace into a digital environment. The approach is to create a digital workspace that evokes an embodied animating experience and allows puppet stop-motion animators to work in it unencumbered. The insights and outcomes of the practical explorations are discussed from the perspective of embodied cognition. The digital workspace employs haptic technology, an advanced multi-modal interface technology capable of invoking the tactile, kinaesthetic and proprioceptive senses. The overall aim of this research is to contribute, to the Human-Computer Interaction design community, design considerations and strategies for developing haptic workspaces that can seamlessly transfer and accommodate the rich embodied knowledge of non-digital skillful practitioners.

Following an experiential design methodology, a series of design studies in collaboration with puppet stop-motion animators led to the development of a haptic workspace prototype for producing stop-motion animations. Each design study practically explored the transfer of different aspects of the puppet stop-motion animation practice into the haptic workspace. Beginning with an initial haptic workspace prototype, its design was refined in each study with the addition of new functionalities and new interaction metaphors which were always developed with the aim to create and maintain an embodied animating experience. The method of multiple streams of reflection was proposed as an important design tool for identifying, understanding and articulating design insights, empirical results and contextual considerations throughout the design studies.

This thesis documents the development of the haptic workspace prototype and discusses the collected design insights and empirical results from the perspective of embodied cognition. In addition, it describes and reviews the design methodology that was adopted as an appropriate approach towards the design of the haptic workspace prototype.

Acknowledgements

I would like to specially thank my supervisors, Prof John Lee and Dr Mark Wright, for giving me the opportunity to conduct this research in the very first place, and for supporting me along the way with insightful comments, advice and hours of helpful discussions.

I am particularly thankful to the group of animators with whom I co-designed the haptic workspace, Steve Warne, Annelise Wimmer and Anna Spearson for the creative, exciting and resourceful collaboration and for their enthusiasm over this work. I would also like to thank the digital animators, Thaleia Deniozou, Amy Bogin, Greg Telakis and Heida Vigfusdottir, and the animators who participated in the evaluation study, Cat Bruce, Kate Howley, Adam Gierasimiuk and Claire Lamond for their attentive comments and observations. These collaborations would not have been possible without the constant support and irreducible interest from Donald Holwill, Head of the Animation Department at ECA at that time and Neil Kempsey, Senior Animation Technician. Their insightful comments and suggestions have been inspiring and encouraging. I am also grateful to Sophia Lycouris, Penny Travlou and Ann Marie Shillito for their valuable guidance.

Many thanks go to Nikos Chatzinikolaou, Thomas Koeppe and Nikos Tsorman for helping me with the numerous lines of code, and to Owen Green for his methodical proof reading.

I have been very fortunate to have had a lot of support and useful advice from my friends and colleagues: Vangelis Lympouridis, Beatriz Cantinho, Dora Zachou, Natasa Fytrou, Martina Kyriazi, Mayte Beltran, Sonia Matos, Nearchos Panos, Stavroula Fylachtou, Harris Pappachristopoulos, and Maria Androulaki, thank you all for your friendship and for being who you are. Special thanks go to my parents and brother for the continuous support.

I am wholeheartedly thankful to my love, and traveling companion, Yiannis Mattheakis. It has been a long and challenging process and you have patiently shared it with me. This thesis is dedicated to everyone who has supported my efforts in different ways over the years, and particularly to the memory of E. and D.

Mariza Dima
Edinburgh, August 2012

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

(Maria Dima)

Do, or do not. There is no try.

Master Yoda

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Introduction

Non-digital skilled practitioners use their body and their senses in order to interact with physical materials. Equally, practitioners trained to work with digital media have developed skills in using a wide range of digital tools which ease the developing process. While the nature of the non-digital practitioners' work is explicitly embodied, as bodily and sensorial cues support skillful interaction with their physical materials, the work of the digital practitioners does not in most cases involve multi-sensory and body-driven actions. The workspaces of digital practitioners are digital environments, virtual platforms for creation and production involving digital tools and objects which are abstract and intangible.

Little change has been made regarding the way we physically interact with digital workspaces, as has been highlighted by both McCullough (1998) and Jorgensen (2005). Consequently, digital workspaces cannot facilitate the intuitive ways in which non-digital practitioners interact with physical artefacts nor accommodate their embodied skilled knowledge. In this thesis, I illustrate the difference of embodied skillful work in physical and in digital workspaces in the context of Animation production, in particular between puppet stop-motion animators and digital character animators.

Through my research, I have explored the transfer of the embodied skills of non-digital puppet stop-motion animators into a digital environment by designing and developing a prototype digital workspace. The prototype workspace was designed with the aim to evoke an embodied animating experience and allow puppet stop-motion animators to work in it unencumbered. I carried out this design-led research from the perspective of Human-Computer Interaction (HCI), with a focus on interface design. My motivation has been to explore a way of recording and preserving in the rapidly digitalized world the rich body of tacit embodied knowledge and experience that is manifested in well-established non-digital practices.

My exploration was led by practical studies in which I ask:

- What are the interface design considerations for transferring the embodied practice of puppet stop-motion animation into a digital environment?
- How can we design a digital workspace that successfully transfers and accommodates the embodied skilled knowledge of puppet stop-motion animators?

The latest developments in digital technologies have made possible the multi-sensory interaction with digital media. These technologies are designed to exploit the human motor-sensory and kinesthetic abilities and, by enriching the interaction space with bodily and sensory cues, they have the potential for creating new vocabularies for skilled practitioners in digital workspaces. In my practical explorations, I employed haptic technology which is a promising technology for enabling embodied interaction with three-dimensional virtual artefacts. In contrast to generic two-dimensional devices, haptic devices are operated through three-dimensional gesture and convey tactile, kinesthetic and proprioceptive cues to the user.

I have followed a design-led methodology to develop a prototype haptic workspace for producing stop-motion animations. As the notion of embodiment was central to my research, the design and development of the haptic workspace was theoretically framed by an embodied approach to cognition. This approach considers cognition as deriving from people's continuous embodied and situated activity within the world. It highlights the embodied nature of this activity and emphasizes the fact that being in the world is intimately connected to acting in the world.

My design methodology was based on the experiential approach to design, presented in detail in Chapter 2, that places collaboration between designers and users in a dialogic relationship in which participants' previous knowledge and experience are brought together to form new knowledge. This experiential approach is grounded on a holistic appreciation for the design process which encourages designers to explore the multiple processes that take place during design. Adopting this perspective, I established collaborations with puppet stop-motion animators, students and professionals, with whom I co-designed the prototype haptic workspace.

Beginning with an initial haptic workspace prototype, a series of design studies helped refine the initial design, adding new functionalities and introducing new interaction metaphors which were always developed with the aim to create and maintain an embodied animating experience. Each design study that I present in later chapters was a small intervention in the standard work flow of the puppet stop-motion animators. Within the experiential design framework, I propose the use of multiple streams of reflection as a highly important design tool for capturing, understanding and articulating design concepts, empirical results and theoretical considerations. Throughout the design process I constantly reflected upon and triggered the animators' reflection on three aspects of our collaborative design process: their use of each haptic workspace prototype in terms of interface design, how the haptic workspace accommodates their existing skills and its appropriation in their existing practice, and my own design and research practice.

Through the design studies, I sought to research in depth the transfer of different aspects of the puppet stop-motion animators' embodied skills into the haptic workspace from the

perspective of embodied cognition. At each stage of its development, the haptic workspace encompassed design considerations and the empirical insights that derived from the design process. These are both outlined and discussed in the thesis with the aspiration to provide an initial set of design strategies and concepts and set a basis for further explorations in this and similar contexts.

As the haptic workspace augments the digital environment haptically, I extended my investigation to include a digital animator in an attempt to explore the haptically-enabled animating experience from her perspective. In addition, I sought to explore the differences between the two techniques and, more importantly, the areas in which they converge. Although the main focus of my practical explorations was to design the haptic workspace, after the completion of the design studies I carried out a short evaluation of the prototype. The evaluation was a small-scale evaluation, which explored the potential of the haptic workspace to successfully transfer the embodied skills of the puppet stop-motion animators and carry forward their artistic intentions.

Thesis Outline

This thesis is written in six chapters. The first chapter sets the context of the research and the second chapter introduces the design methodology that was followed in the practical studies. The third chapter describes the design studies that were carried out and explains the links between each study and its preceding one. The fourth chapter presents a short evaluation of the haptic workspace prototype that was carried out after the design studies were completed. The fifth chapter discusses in depth the three interrelated research contributions: the interface design insights derived from the studies, the design methodology that was followed and the haptic workspace prototype as a tangible outcome of the research. Finally, the sixth chapter gives a summary of the research and discusses further directions.

Chapter 1

Background

This research is set to investigate the transfer of the embodied skills of puppet stop-motion animators from the physical to a digital workspace that evokes an embodied animating experience. As such, the relevant theoretical discourse that frames it, addresses notions of cognition, mediated bodily action and embodiment in both spaces. In this chapter I intend to lay out the context of the research and introduce the research methodology that was followed during the practical work.

The chapter begins with an introduction to the technique of puppet stop-motion animation emphasizing the embodied nature of the puppet stop-motion animators' skills. This is followed by a description of the technique of digital character animation, which has evolved in parallel to the physical technique and uses digital workspaces for animation production. After I detail the tools and media used in digital character animation, I highlight the different dimensions of embodied activity that each technique presents. This difference introduces difficulties for puppet stop-motion animators to work in digital animation workspaces unencumbered.

Having stressed this point, I introduce and discuss the concept of embodiment in digital workspaces and particularly in virtual environments. Much of the users' experience in a virtual environment is influenced by how they cognitively experience and access the environment. After reviewing two major approaches to cognition, Objective and Embodied cognition, and their influence in the design of Human-Computer Interaction (HCI), I will focus on Embodied Cognition, which considers embodiment as central to its theoretical framework. I will then discuss the use of interfaces for accessing virtual environments, and focus on Enaction, a concept that pertains to embodied cognition.

In the last section, I will discuss enactive interfaces, as my practical work involved the design of a digital workspace that uses such an interface. I will particularly focus on enactive interfaces that use haptic technology, which was the technology employed in my practical explorations. I will review examples of research projects that have designed haptic interfaces to support skilled activity in digital workspaces, with particular emphasis on projects which

have used haptic interfaces for animation.

1.1 The technique of puppet stop-motion animation

1.1.1 Introduction

Animation uses the principle of rapidly displaying a succession of two or three dimensional still images in order to create the illusion of their movement. Cinematic space is used to communicate the story to the audience as the sequence of images that define the story is imprinted into film. An example of 2-D animation elements can be hand-drawn characters while 3-D elements can be sculpted figures or real world objects. Many techniques for arranging and projecting a sequence of images have been developed since the inception of the practice which may be generally categorized into Hand-drawn (or Cel-animation), Stop-motion and Computer-Generated or Computer animation.

Hand-drawn animation involves the succession of drawn images, while in the technique of Stop-motion a physical object is moved and photographed in different poses or positions. Each pose differs slightly from its previous so that the movement follows a smooth choreographed path, otherwise, the final motion will not be appealing to the eye. The physical objects that can be used are made of various materials such as clay, paper or sand. The process is sometimes named after the material that is used, for example clay, cut-out or sand animation respectively. In puppet stop-motion, the protagonists of the story are puppets, not necessarily human-like, made of various materials with an internal armature that acts as a skeleton. By manipulating the skeleton, puppet animators set the figure in motion. The materials that are most often used is foam latex, silicone, glass fiber, moulded clay and plasticine. The last two give the models the ability to deform. Puppet stop-motion animators use cinematic space to communicate the story to the audience. Various tools allow them to capture the different poses of puppets as images, place the captured images on the preferred sequence and playback the sequence to create the illusion of movement.

Before the age of the cinematic movie camera and projector, one of the first animation tools was Phenakistoscope, invented in 1831 by Joseph Plateau. The Phenakistoscope consisted of a disc with figures drawn around the disc in a circle. The disc had slots around the edge through which the figures could be viewed using a mirror. A refinement of the Phenakistoscope was the Zoetrope, built in 1834 by William Horner and followed by Emile Reynaud's Praxinoscope in 1877. The Praxinoscope consisted of an inner and an outer cylinder. A strip of pictures was placed inside the outer cylinder, so that each picture is reflected by a set of equally numbered mirrors on the inner cylinder. When the outer cylinder rotated, the rapid succession of reflected pictures gave to the viewer who looked at the inner cylinder the illusion of a moving picture.

With continuous improvements, the final version of the device, *Theatre Optique*, used a lantern to project the moving images onto a screen. The advances in cinematography, pioneered by the Lumiere Brothers, led to another device capable of manually capturing between 16 and 20 frames per second. The beginning of stop-motion as an art form can be credited to Alfred Clark, a pioneer of cinematography who was one of the first to realise that the cinematic movie camera could be stopped during filming of a scene in order to replace or move an object, before it was started again. This observation enabled him to replace the actress with a puppet in his 1895 short film *The execution of Mary, Queen of Scots* in order to portray the execution with realism. George Melies (Ezra, 2000) and a few of his contemporaries like Segundo de Chomón (Tharrats, 1988) experimented with the cinematic movie camera and created stop-motion films. According to Bendazzi (1995),

If animation comes into play not when its techniques were first applied but when they become a foundation for creativity, then the first animated film could very well be *Matches: An Appeal*, by the Briton Arthur Melbourne (1899).

Melbourne is credited with the creation of the second puppet stop-motion film in 1908, *Dreams of Toyland*¹. Nowadays, digital cameras are used for capturing the puppet's poses and digital software are deployed for the arrangement and playback of the sequence (e.g. *DragonTM*) as well as for post production purposes such as the addition of digital visual effects (e.g. *Adobe After EffectsTM*). These software are an example of the two-dimensional digital workspaces. They allow functions such as composite layering of captured images and the preview of the frame sequence at any moment during the process so that the animators can easily make adjustments or corrections without the need to complete the whole sequence first. With the advent of digital technology and the advances on the field of Computer Graphics most of the traditional animation techniques became computer-assisted. For example, the traditional technique of hand-drawn animation used a sequence of hand drawings, each one differing slightly from its previous, traced on transparent acetate sheets. Nowadays, the hand drawings are not traced into cels but they are scanned and digitally painted in the computer. Apart from providing assistance to existing animation techniques, the move to digital workspaces has created new techniques which produce 2-D and 3-D *computer-generated* animation. The term denotes that the animation process is carried out entirely in the computer using exclusively digital workspaces and tools and, consequently, different skills.

1.1.2 Digital workspaces for animation

Digital workspaces are virtual spaces, usually displayed on a computer screen, which provide digital tools for the creation and production of digital content. The dimensions of those spaces

¹The first stop-motion film was 'The Humpty Dumpty Circus' (USA, 1897) by Albert E. Smith and J. Stuart Blackton. No copies exist.

are defined by the nature of the work. Digital painting or writing, for example, require a two dimensional space, while digital 3-D character modeling requires a three dimensional environment. Since the puppet stop-motion animators work in three dimensional space manipulating 3-D physical puppets, I focused on designing a three dimensional digital workspace.

A *virtual environment*, which is the digital workspace that was developed in this research, is a computer generated three dimensional environment displayed on a computer screen. Virtual environments are often displayed through immersive stereoscopic equipment. According to Ellis (1994),

Virtual environment displays are interactive, head-referenced computer displays that give users the illusion of displacement to another location (Ellis, 1994, p.17)

Since the computer screen is two dimensional, the representation of a three dimensional space is done through methods that create the illusion of perspective. Because virtual environments only appear to be three dimensional, they are known as $2^{1/2}$ - D virtual spaces. The term virtual environment is closely connected to Virtual Reality (VR) which is used to describe a set of systems and applications that use virtual environments and hardware devices including computers, head-mounted displays and data gloves to immerse users in simulated worlds for purposes such as teleoperations, gaming, remote communication, aircraft simulation and heritage sites' walkthroughs.

Amongst the many techniques for digital animation, the one which is concerned with the animation of digital articulated characters is known as digital character animation. Digital character animation was developed in parallel with the advances on computer graphics. It relies on the use of static and dynamic CGI (Computer Generated Imagery) for the creation of digital scenes and models, including articulated characters. The workspace of the digital character animator is a virtual environment. The articulated characters are digitally modeled entities. They consist of two parts, an outer surface that represents the skin, clothes or other items, and an inner skeletal model, called 'rig'. Similar to the puppet's armature in traditional stop-motion, the rig is a hierarchical chain of bones and joints attached to the outer surface and given dynamic properties through various kinematics algorithms. The digital animator manipulates the rig in order to move the skin and thus make the model move (skeletal animation). Rigs are also used for moving, often by deforming, the more detailed parts such as facial characteristics (facial animation).

Key-framing has been employed as the digital equivalent of the image sequence in puppet stop-motion. The key frames store the key-poses of the character as set by the animator from the viewpoint of the camera. The stored poses are in the form of data which can be previewed in the software directly or turned into video format for export in a movie file. Then, adjustable and automatic algorithmic computations of the possible character poses in the frames in-between the key-frames ensure smooth development of the character's motion. One example

of such algorithm is interpolation in which the coordinates of the three dimensional discrete points which comprise two given character poses are used in mathematical calculations to produce new poses in between the two. Interpolation is one of the numerous processes used in digital animation to reduce the time taken to animate and allow animators to experiment with ease. Automation in the creation of motion differentiates the sense of timing with relation to motion that stop-motion animators have as opposed to digital animators. For example, in digital character animation, a movement of the character's arm to reach for a glass can be computed in seconds by advanced algorithms. Stop-motion animators need to calculate in advance all the different steps in between and also predict and represent movement that happens due to physics laws before, during or after the motion.

Another technique that digital character animators employ for smooth motion is Motion Capture. In Motion Capture, instead of manually creating the poses in each frame, animators record the motion of people and apply it to the character. Motion Capture is in part a result of the strong tradition of pursuing realism in CGI development. Motion Capture was developed as a solution to the difficulty that digital animators had in recreating realistically with the currently available software and hardware the biomechanics of bipeds, quadrupedal or of any entity which shares similar complex structures. Motion Capture involves the recording of actors' motion through sensors attached to their bodies. The data is then transferred into the virtual model with a few adjustments needed by the animator. The human-like appearance can be reproduced with highly realistic CGI which over the years becomes more advanced by using sophisticated algorithmic processes and faster graphics/physics cards and processors.

The goal of both the puppet stop-motion and the digital character animation techniques is to infuse life into inanimate characters and make them look convincing to the audiences so that they empathize with them forgetting that they are not real. Many of the elements of the puppet stop-motion technique such as the believability of the characters, the suspension of the audience disbelief and the embedding of personality traits and mannerisms are also encountered in digital character animation. Lasseter (1987) has shown how applying traditional animation principles to digital character animation results in animated characters that engage the audiences. The main difference between the two techniques is the medium and skills they use to bring the characters into life. While the animating experience of puppet stop-motion animators is driven by bodily and sensory actions that manifest themselves in a physical three dimensional space, existing workspaces for digital animation create a disembodied working environment. Numerous small workarounds and interaction metaphors are introduced in digital character animation workspaces in order to simulate the embodied physical interactions with the puppets.

1.1.3 Embodied skills in puppet-stop motion animation

The concept of embodiment reflects our innate way of experiencing the world, being embedded in it, through our body and our senses. We embody much of the knowledge we gain by interacting with the world in this way and this knowledge becomes tacit because it is difficult to formalise and verbalise it. Polanyi (1966) termed this kind of knowledge as *embodied knowledge* and the skills that are acquired in this way *embodied skills*. Embodied skills are evident in the work method of traditional craft practitioners who use skillful hand gestures to work on physical materials either by using tools or by handling materials directly with their hands. Similarly, the nature of the puppets stop-motion animators' skills is strongly based on the bodily and sensorial interaction with the puppets. The technique of puppet stop-motion animation uses skillful hand practice in incredibly creative ways which have fascinated audiences of all ages. Puppet animators develop particular skills around two-handed tactile interaction with the puppets. These skills are the experiential, personal and physical abilities the animators employ in order to perform the necessary actions for the desired result.



Figure 1.1: A puppet stop motion-animator in her studio

Direct tactile manipulation of the puppets is the main method puppet stop-motion animators use to materialize their ideas². The first thing that is built is the armature, a piece of

²The following descriptions are masterfully outlined in the short film, 'The Making of I am Tom Moody' by Will Anderson and Ainslie Henderson. The film documents a behind-the-scenes story of how the puppet stop-motion

twisted aluminium or tin wire which forms the skeleton of the puppet and determines how the puppet will move. During its construction, the animators have already designed in their mind rough sketches of the key poses in which they will eventually place the puppet because these poses determine the structure of the armature such as the size, number and type of joints which will be needed.

The animators' actions, either direct or through the use of tools, drives the creative processes of crafting the motion of the puppet. They usually spend considerable amount of time manipulating the puppets while they experiment with different ways to embody life into it. The handling and *felt* knowledge of the different materials the puppet is made of, its mass, weight and texture enables them to connect to the puppet. A two-way relationship emerges from the continuous handling of and engagement with the puppet. According to animator Jim Danforth,

Human beings enjoy touching, so it's natural that stop motion animators would enjoy touching a tangible object such as a puppet, particularly breathing life into it. If not spiritual, then it is definitely something quite emotional. When I connect to the character, and crawl inside its head, becoming the character, then the performance will germinate. in Purves (2008)

The two-handed practice, occasionally augmented with tools for changing subtle details such as chisels and craft knives, introduces small imperfections in the making of the sequence some of which remain unnoticed and pass on to the film. Purves (2010) comments on the excitement and stress that this possibility causes:

Most animators enjoy the fact that when you animate you don't get the chance to refine. Once you have repositioned a character, you have immediately lost the previous frame. This is both a huge pressure and part of the excitement. This is as near to acting and to animating live with all the adrenalin and thrill that that implies, as it is possible to get. (Purves, 2010, p.33)

The puppet stop-motion animators develop their embodied skills further by establishing a connection with the puppets in experiential ways which are not based on but are assisted by tactile interaction with them. Bringing a lifeless object into life is a very personal process and elements of the animator's personality are embedded in the personality of the puppet. As it is the case with anyone who tells a story through a character, the animator becomes an actor. Similarly to how actors empathize with the character they portray, the animators seek to immerse themselves in the complex of all the attributes that comprise the personality of the puppet's character. One of the first things that animators do when they build the puppet is to position the eyes so that the puppet looks at them as they look at it. By doing so, they immediately establish an intimate relationship with the puppet that sets the basis for a creative

animation 'I am Tom Moody' directed by Ainslie Henderson, an Edinburgh College of Art graduate, was made. URL: <http://vimeo.com/43533906>, accessed 6th August 2012

interaction space between them. The process of embedding mannerisms and behaviours into the puppet aims to create a thinking character whose actions are believable to the audience.

Alongside the development of motion over time, the creation of the surrounding environment is an equally tactile and experiential process. The cameras, nowadays digital, are moved around the scene to provide different viewpoints and the lights are set to create the stage's atmosphere. In most cases, animators shoot from one camera, switching between close-ups and long shots. Each case requires different manipulation of the camera. Acting as a director, the animator moves cameras around to stage sequences from different angles and the way that the camera is moved can reveal the animator's personal animating style. Any visual effects are added to complete the ambiance of the animated film. Before the advent of digital technology which has eased the addition of visual effects, animators would come up with innovative ideas for adding visual effects in physical ways. Nowadays, visual effects, are added using commercial digital software. The post-production process involves the final composition of images, backgrounds and visual effects.



Figure 1.2: The puppet in the physical workspace (left) and the captured image of the puppet on the screen (right)

The above analysis emphasizes the fact that, for puppet stop-motion animators, the experience of animating in their physical workspace is embodied and multi sensory and relies strongly on the interplay of experiential, tacit phenomena and existing knowledge that manifests itself through body-action. Existing digital workspaces for animation do not support this embodied animating experience. A virtual workspace which can accommodate the puppet stop-motion animators' physical knowledge must facilitate its embodied nature. I argue that a first step towards the design of such workspaces is to understand how the animators cognitively experience it through their bodily and sensory-mediated actions.

In the following section, I will introduce the research methodology that framed my practical work which is based in the concept of embodied cognitive experience.

1.2 Embodied cognitive experience of virtual environments

Embodied skills are manifested through bodily action and, conversely, bodily action is used to perceive and make meaningful the physical environment upon which the action occurs. This interplay between physical action and perception together with the participation of the senses and other experiential phenomena, such as emotions, is crucial in forming cognition. Cognition, deriving from the Latin verb 'consistere' which means *to know*, is the knowledge we have of ourselves and of our environment. Throughout the practical studies of my research, I have investigated the puppet stop-motion animators' cognitive experience through the lenses of embodied cognition, an approach to cognition which liberates it from traditional conceptions of the Cartesian mind and body dualism and extends its nature to include the coupled dynamics of the body, the senses and the environment. Embodied cognition is a relatively new perspective in Cognitive science, the field which studies the processes that subsume cognition. The previous dictum for decades in Cognitive Science as an approach to cognition is known as *objective cognition*. Due to its engineering-oriented and quantitative nature, objective cognition was also significantly influential to HCI design.

1.2.1 From objective to embodied cognition

The framework of objective cognition places the mind in analogy to an information processing unit in order to understand the ways that the mind works to turn abstract representational data situated in the brain into meaningful action (Kaptelinin, 1995). This analogy prompts for a view of the human mind as a mechanism with an input, a process and an output, hence the linearity of the model perception-cognition-action. The analogy was further empowered and influenced by the advent of digital computers and research on Artificial Intelligence which was oriented towards linearly structured problem-solving approaches.

Objective cognition holds that cognition derives from a set of discrete mental functions which can be individually identified and measured in a scientific way. Raw perceived data of external reality, or *symbols*, is represented internally in the mind and substitutes specific features or states. The internal representation of external reality is known as a *mental model* (Craik Kenneth (1943), Johnson-Laird (1983), (Norman, 1983)). Mental models are images that are stored in the mind from previous experiences and brought out when necessary (consciously or unconsciously) to conceptualize the creation of meaning in any human activity. According to the objective approach, cognition is considered independent from perception and is the outcome of a rule-based manipulation of mental models which results in motor-sensory action. Concepts are typically represented as propositional structures 'abstracted from the sensory modalities by some process of filtering and transduction' (Hayward, 1998,

p.3).

The application of objective cognition to psychology in order to investigate how people perceive, think, make sense of and learn in a given situation, is known as cognitive psychology. Cognitive psychology has been and still is extensively used in Human-Computer Interaction to predict and evaluate user responses to digital software and hardware systems (Preece et al., 2002, p.602). Evaluation methods are based on the notion of mental models which explain how people make sense of a situation after having passed through perception and cognition³. Through a procedure known as usability study, elements are iteratively integrated into the developed digital system that help users create new, accurate mental models of the interface. The evaluation methods based on mental models have been criticized for being in many ways similar to a laboratory experiment: mainly task-based, controlled and targeted at measuring the usability of a design outcome, product or interface, with quantifiable metrics such as efficiency, efficacy and user satisfaction (Preece et al., 2002). This may be a result of the fact that cognitive psychology suddenly imposed to HCI, a deeply engineering field, the necessity to care for the user. At this point, HCI developers did not have the means to communicate with the users in order to understand their needs. Therefore, 'considering them as a set of cognitive systems and subsystems' (Benyon et al., 2010) might have been the easiest way forward.

According to Wright et al. (2006), characteristic of the cognitive psychological approach is the tendency to control the interaction between the users and the digital systems through formal experiments. The iterative circle of usability studies aims to help the designers understand the mental model the users construct when they work with a specific system. This approach is limited to adjusting a few parameters of the system each time and rules out much of the underlying complexity in people's experiences using it. In addition, it does not allow the users to provide empirical information on how they perceive it and its prescribed properties and how they conceptualize its use. Therefore, usability testing improves usability but does not define a strategy for designing the optimal system from the inception of the project. As (McCullough, 2004) states, 'usability metrics remain more an inspection and less an aid to conception'.

By equating human mind to an information processing unit, objective cognition disregards the physical, aesthetic, emotional, cultural and social aspects which influence human experience. Since the 80s, there has been a resurgence of interest in placing cognition in the context of a body acting in the world which brought the model of objective cognition under debate. Bodily actions challenged the conventional linear view of perception-cognition-action and brought to the foreground a dynamic perspective of those three aspects in which they are interwoven, influence each other and are influenced by the body and the environment. This

³The theory of meaning is an enormous and complex topic. Here I touch upon notions relevant only to HCI design

philosophical thesis is known as *Experientialism* or *Embodied cognition*.

Embodied cognition escapes the Cartesian dualism. It does not approach cognition as a discrete step between perception and action but considers a dynamic model where perception, cognition and action are concurrent and codependent. At the center of the model is the body. The definition of perception subsumes that of action which is shaped by bodily interaction with the world. Cognition is concurrently in all three.

Mind is not some mysterious abstract entity that we bring to bear on our experience. Rather, mind is part of the very structure and fabric of our interactions with our world (Lakoff and Johnson, 1999, p.266)

The philosopher Mark Johnson and the linguist George Lakoff have elaborated in this approach to cognition in (Lakoff and Johnson, 1980) and (Lakoff and Johnson, 1999). Drawing on the philosophy of Immanuel Kant, they argue that the construction of meaning is essentially a result of relating mental concepts to bodily experiences. Elaborating on a concept more fundamental than mental models, one that has its roots in the synergy between mental and bodily activity, Johnson (1987) defined *image schemata*. An image schema is 'a recurring, dynamic pattern of perceptual interactions and motor programs that gives coherence and structure to our experience' (Johnson, 1987, p.14). Image schemata derive from our sensorial and bodily experience of the life-world and, instead of a set of base rules, they use abstract propositional structures and particular mental images to structure mental organizing activity and construct meaning (Johnson, 1987, p.29). Dependent on concepts of motion, sensory and spatial relations, image schemata are hypothesized to ground aspects of the mind in aspects of the body, and thus, seen as expressions of the notion of embodiment (Lakoff and Johnson, 1980) and Johnson (1987)).

One example of an image schema is the NEAR-FAR schema which derives from the experience of reaching. The image schema can be instantiated for various purposes such as interface design. One example of this instantiation is the *zoom* function implemented in many application software. Image schemata are a type of conceptual metaphor which transfers the experiential structure of sensory-motor experience to abstract domains.

Metaphor in linguistics is a literary expression which uses the original meaning of one word to describe a situation or an element which belongs to a different domain than the one in which the word is defined. Lakoff and Johnson (1980) have defined conceptual or cognitive metaphors as the mapping between two conceptual domains where one element of the first domain can be understood in terms of an element of the other. Bringing an example from image schemata, we relate the CONTAINER image schema as a metaphor of the proprioceptive sense we have of our body and of our skin as a boundary between the inner body and the outer world. What is interesting in their approach, is that metaphor becomes something more than simple mapping; it acquires a bodily dimension.

The significant differentiation from objective cognition is that in the embodied approach symbols already have a meaning, found in bodily experiences, and they do not conform to mathematical-based rules to transform them from forms to meaning and action⁴. In embodied cognition, meaning exists in the world. Although supporters of embodied cognition deny the theory of mental models, they do not rule out symbols. In Lakoff and Johnson (1980)'s linguistic and philosophical analysis, image schemata substitute the algorithmic-based rules that cognitive psychology used to pass from symbols to meaning construction with the functioning of imagination. Image schemata are 'nonfinitary meaningful symbols of the sort excluded by the strict mathematical characterization of algorithmic manipulation'. (Lakoff, 1988, p.120).

From the total 250 schemata which have been recognized by cognitive linguists, some have been tested for use as guideline to HCI design (e.g. (Hurtienne and Blessing, 2007), (Maglio and Matlock, 1999), (Raubal et al., 1997)). All analyses were followed by relevant design recommendations. For example, Hurtienne et al. (2008) have tested twelve primary metaphors that predict relations between spatial gestures and abstract interactive content. Their results provide a promising step toward inclusive design guidelines for gesture interaction with abstract content on mobile multi-touch devices.

Embodied cognition shares similar grounds with the philosophical area of phenomenology, developed in the 20th century (Heidegger, 1978), (Merleau-Ponty, 1962), (Husserl, 2001) and (Schutz, 1967)). Phenomenology seeks to understand and define in depth the meaning of embodiment having as a central stance the notion that humans experience the world as embodied agents in it. According to phenomenologists, human understanding of the world is a natural embedded skill and does not follow any formalistic process or rules. Husserl (2001) considered that everyday life was based in embodied experience and not abstract reasoning. Schutz (1967) explored phenomenology in the social world. Heidegger (1978) was concerned with the nature of *being* and argued that we live and act as agents embodied in the world while Merleau-Ponty (1962) recognized the critical role of the body in the meaningful activity within the world. To phenomenologists, the cognitive processes worked at higher levels of abstraction than those encountered in objective cognition. Symbols were defined within the context of bodily experience situated in the environment and mental representations were '*sublimations* of bodily experience, possessed of content already, and not given content or form by an autonomous mind' (Anderson, 2003, p.104).

Lakoff and Johnson (1999) have received extensive critique for being indifferent to the philosophical perspective and to 'the large amount of related work in philosophy, artificial intelligence, and cognitive science ⁵' (Anderson, 2003, p.105). Many aspects of their theory

⁴For a more detailed research see the Symbol Grounding Problem Vogt (2002))

⁵Svan (2007) gave as a possible explanation for Lakoff and Johnson (1980)'s disregard of the philosophical work on embodiment. Both scholars are both brought up in the Anglo-American philosophical tradition with very

have been reviewed from the phenomenological point of view.

Lakoff and Johnson's theory of conceptual metaphor has received critique by Haser (2005) who claimed that despite their reference to the bodily experiential grounding of meaning, they discuss it in the context of cognitive linguistics in which it is considered to have a mental rather than bodily nature. The critique by Haser (2005) was based around the fact that although Lakoff and Johnson (1980) grounded cognition in embodiment, they did not define image schemata in that level of bodily experience as phenomenology does. Along the lines of Haser's critique, philosopher Andy Clark points out that Lakoff and Johnson (1980) and later theorists of embodied cognition took the existence of mental representations for granted, only substituting their metaphorical mapping through algorithmic-based rules with mapping through embodied image schemata (Clark, 1999). He named this approach *simple embodiment* and suggested that there is another model, that of *radical embodiment* (also: (Van Gelder, 1995), (Varela et al., 1991), (Thelen and Smith, 1994), (Turvey and Carello, 1998), (Kelso, 1995)) 'in which attention to bodily and environmental features is meant to transform both the subject matter and the theoretical framework of cognitive science' (Clark, 1999, p.345). In radically embodied cognition, cognition is present in the cycle of activity that runs from the brain to the body and the environment and back and does not necessarily include the internal representational objects. Clark (1999) supported the argument with the example of a calculator which is used as an extension of the brain's capacity to perform mathematical functions and concluded that 'the distinction between the simple and radical forms is, however, not absolute, and many (perhaps most) good research programs end up containing elements of both.' (Clark, 1999, p.348).

Discussing the difference, as well as whether there is one, is a matter of philosophical discourse. This thesis considers the notion of embodiment as a property of our experiential interaction with the environment we act in. It also views cognition as something that subsumes both perception and bodily action which resonates with both the cognitive linguists' and phenomenologists' approach. Taking this research perspective, my practical studies on designing a digital workspace for puppet stop-motion animators were grounded on the users' embodied experience. As Coyne (1995) writes,

By beginning with the bodily activity of drawing rather than the general mechanism of binary logic, a different kind of computer may be produced. The point is that once we accept the grounding of the computer in bodily metaphors, we are in a position to explore new aspects of those metaphors, or new interpretations of the metaphors. Where this may lead in terms of computer systems design is unknown at this stage (Coyne, 1995, p.269)

little influence from 20th century Continental philosophy which demonstrates a considerable body of work on embodiment

1.2.2 Enaction

The phenomenological roots and the action-centered nature which characterize embodied cognition highlight the important role of action in directing perception and uncovering the meaning which exists in the environment. Sensory and motor engagement and sensory-motor coordination are the main channels through which we constantly perceive the life-world. Touching is the way our body sees. Seeing is the way our eyes touch (Merleau-Ponty, 1962). We move closer to listen to a whisper. As Larssen et al. (2007) expressed it, 'sensing and motor skills are in constant dialogue, performing in concert. The organization of our movement patterns depends upon our habits of perception'.

Varela et al. (1991) and Noë (2004) have, amongst many, discussed action in perception, or *enaction*, on philosophical grounds and Gibson (1979) has addressed it in psychology. Enaction supports the view that knowledge comes from the coupling of perception and action during our interaction with the world orchestrated by our senses. Enactive knowledge is direct, in the sense that it is natural and intuitive, based on the perceptual array of motor acts. It is constructed through lived experience and through the mutual influence between ourselves and the environment. In skilled practice, physical action is the predominant channel through which the knowledge is acquired so the knowledge is inherently embodied before it becomes part of the skills. Therefore, the concept of enaction offers an interesting lens through which to investigate the skilled practitioner's process of knowledge acquisition and metamorphosis in the virtual environment.

Physical action is mediated in a virtual environment via digital user interfaces, hardware devices with a software component, the application software, which are used for handling the digital information. The design and development of a digital user interface through the lens of embodied cognition has been an integral part of my practical work. In the following section, I will introduce digital user interfaces and I will make a review of interface mechanisms which have been designed for creative skilled practices starting from two-dimensional input devices and moving on to digital technologies which support gestural control and multi-sensory action.

1.3 Interfacing with virtual environments

As with the physical environments, virtual environments can be experienced through three main routes: navigation, object selection and object manipulation. These actions can be performed by using digital interfaces. The word navigation usually points towards the sense of way-finding and indeed much of research in navigation is pointed towards how people manage to find their destination in a virtual environment. Working with information spaces, a super-set which apart from virtual environments also denotes digital application software such as word processors, online sites on the World Wide Web or the contents on an optical drive,

(Benyon and Höök, 1997) has suggested two complimentary definitions for the term navigation: the sense of *exploration* and *object identification*. Exploration focuses on goal-free navigation. According to Benyon and Höök (1997), when the users navigate an information space, they are not necessarily trying to find their way. They may equally be interested in exploring the nature of the environment and the objects in it and how the environment relates to other environments. Exploration may mean that on many occasions users will not want to return to this particular environment they explore. Finally, object identification is concerned with retrieving information about objects the users encounter and discovering how they are related to other objects in the environment. Navigation can be first person navigation or through the control of an avatar, a humanoid graphical representation of a body that is meant to be the representation of the user's body in the virtual environment. Selecting an object concerns the possible techniques of accessing an object in a virtual environment. Object manipulation refers to the task of specifying its properties such as changing its position and orientation, colour or scale. Selection and manipulation often share the same techniques, but selection can be explored as a task on its own.

1.3.1 Skillful actions are not for WIMPs

The conventional way of interfacing with a virtual environment is through the mouse and keyboard devices. The software part that completes the interface includes graphical representations of the devices and of the several low-level operations run by the digital application. These representations are known as Graphical User Interface (GUI) and they are the main on-screen mediator of the software's functionalities to the user. GUIs provide visual interaction through graphical icons such as menus, sliders and buttons. GUIs use the Direct Manipulation style for user-computer interaction, a term introduced by Shneiderman (1982) in the context of screen-based digital applications that could be accessed with the mouse device. Direct Manipulation refers to an interaction style that attempts to establish a transparent communication between user and computer with the following fundamental rules:

1. continuous visibility of the object of interest
2. rapid, incremental, reversible, physical actions on the object
3. immediately visible results

An example of Direct Manipulation is the way that users can access elements on the computer desktop with devices which provide two dimensional input, such as the mouse device, through their visual representation which moves in the two dimensions of the screen (most commonly an arrow). This interface is known as Window/Icon/Menu/Pointer (WIMP) and is considered to be a subset of GUIs. The WIMP interface, employing the mouse and,

to a lesser extent, pen tablets, is widely used to manipulate and animate characters in digital character animation software.

While the WIMP has been designed to facilitate work processes which are two dimensional, such as writing in a word processor or digital sketching, it arguably fails to communicate the richness and complexity of human gestures which are necessary for three dimensional actions (Scali et al., 2003). Consequently, it cannot accommodate skillful actions. In the context of animation, the virtual workspace for digital character animation is accessed extensively through the WIMP interface which fails to transfer the embodied skills of puppet stop-motion animators and makes them unable to work in the virtual environment.

This incompetence of the WIMP interface is firstly due to a mismatch between the Degrees of Freedom required for the task in a virtual environment and those afforded by the two-dimensional input devices (Gauldie et al., 2004). In Mechanics, Degrees of Freedom (DoF) are sets of independent transformations that designate the translation and orientation of a body or system. Makers are extremely dexterous with manipulating objects in free three dimensional space. Three dimensional spatial gesture requires at least 6DoF, three for rotation and three for translation while the mouse, for example, allows only two (translation in a two dimensional plane). The consequences of the mismatch of the DoF is the increase in the number of steps that are necessary to complete an action which makes it more complex (Gauldie et al., 2004).

In digital character animation, the rig and any other parts of the character, like its clothes, are, in most cases, manipulated with the WIMP interface through the mouse. The mouse device restricts the three dimensional gestural knowledge of the puppet stop-motion animators to two dimensional gesture space and adds cognitive load to the animating task. Badler et al. (1986) showed that positioning a virtual model requires the definition of separate parameters for orientation and position in each of the three axes which must be input separately with the mouse. This mapping asymmetry proves to be disruptive for the cognitive process of handling an object in physical 3-D space and hinders the unencumbered continuity of the maker's creative process, what Csikszentmihalyi (1990) has termed as *flow*. In craftsmanship, the upper body and particularly the hands are most often the conductors of the craftsman's embodied knowledge. Wilson (1998) and Goldin-Meadow (2003) have both attested the synergy between hands and brain to trigger imaginative thought. Goldin-Meadow (2003) explained that the hands are the externalization of the thought process while their gestures reflect the practitioner's interpretative methods. When this synergy is lost, the creative process comes to an end.

Another reason for the inability of the WIMP interface to support skillful action, is its emphasis on iconic and symbolic structures in the form of the visual elements of the interface. The role of the visual elements is to materialize the abstract digital information so that the user understands how to handle it. Working with and through symbolic or iconic structures

depends extensively on the sense of vision and the rest of the senses are neglected. The mouse and similar devices provide cutaneous feedback on the fingers but this sense derives from their property of being physical objects and is not related to their control actions in the virtual environment.

In addition to the predominance of visual cues over other senses, there are numerous algorithmic processes which have made the graphical part of the interface quite dense. In the context of digital character animation, most of the functions that are accessed through GUI elements are not used by the puppet stop-motion animators who find the complexity of GUIs and the time required to learn how to use them deterring for working in the digital workspace.

Finally, digital animation software use the architecture of prescriptive modeling which discourages the animators from exploring and experimenting with the motion of the characters through bodily expression. In prescriptive modeling, users specify parameters through menus, sliders and buttons which inform algorithmic process that give shape to the virtual models. An example in digital character animation, is the parametrization of the model's rig and the positioning of the model by manually inputting numerical data (coordinates in virtual space) instead of moving its different parts.

Overbeeke C.J. et al. (2001) and Shillito et al. (2003) have attested the disadvantages of prescriptive modeling in the context of product design and applied arts respectively. They state that in the germinal phase of design the designer searches for forms, while computer-assisted modeling applications expect the definition of forms. Jorgensen (2005) has emphasized the static nature of prescriptive modeling in contrast to the physical and intuitive relationship with form that the traditional maker experiences concluding that it fails to support the explorative stage of the design process in which the generation of ideas and creativity have a central role.

The aforementioned limitations that the current interfaces for digital animation present for the puppet stop-motion animators, show that a digital workspace capable of transferring their embodied skills needs to resonate with the gestural and multi-sensorial nature of skillful action. Conversely, the abstract nature of the virtual environments needs to become clear in more concrete ways than through visual feedback in order to be understood.

Gibson (1979) has argued that information from a variety of feedback channels is crucial to our understanding of physical space. Similarly, Waterworth (1996) suggested that in the context of Virtual Reality design, the bodily and the abstract in the human participant is under researched while it has immense potential in allowing Virtual Reality systems to be designed with the express purpose of supporting cognition and creativity through virtual spatial action and experience. Shortly before Waterworth (1996), Hinckley et al. (1994a) observed that physical three dimensional space is difficult to understand and, quoting Ivan Sutherland, suggested that people do not innately understand three dimensional reality but rather they experience it through two-handed interaction, multi-sensory feedback, and simulating physical constraints.

Hinckley et al. (1994a) made an extensive overview of the available interfaces that enable these features. The interfaces which they presented employed 3-D input devices for understanding and conveying three-dimensional spatial user gestures. In order to emphasize the spatial gestural input, they called these interfaces *spatial input interfaces*.

1.3.2 Spatial Input Interfaces

Examples of spatial input interfaces include camera-based systems and sensor-based devices which both record velocity, acceleration and orientation of the body and its individual parts in different ways. Example applications of the first include Motion Capture technology and MicrosoftTM's Kinect device (Oikonomidis et al., 2011), while examples of sensor-based interfaces are data gloves, the NintendoTM Wii Remote (Schlömer et al., 2008), magnetic trackers and tangible interfaces where physical objects are mounted with sensors (Ishii and Ullmer, 1997).

A variety of research projects using spatial input interfaces have been realized in the context of digital character animation. One of the earliest projects to use gestural input for animating digital characters was *Monkey 2* produced by Esposito et al. (1995). *Monkey 2* was a tangible input device comprised of individual pieces that could be combined to form a skeleton (Figure 1.3 left image). The product, which is now discontinued, was used to perform instrumented puppetry. The skeleton's joints were mounted with sensors which recorded the movement of each part and mapped in the data real-time to a virtual model. This first example of a tangible interface for skeleton animation was not a particularly efficient tool as it allowed for limited range of motion and lacked the flexibility to express a variety of forms.

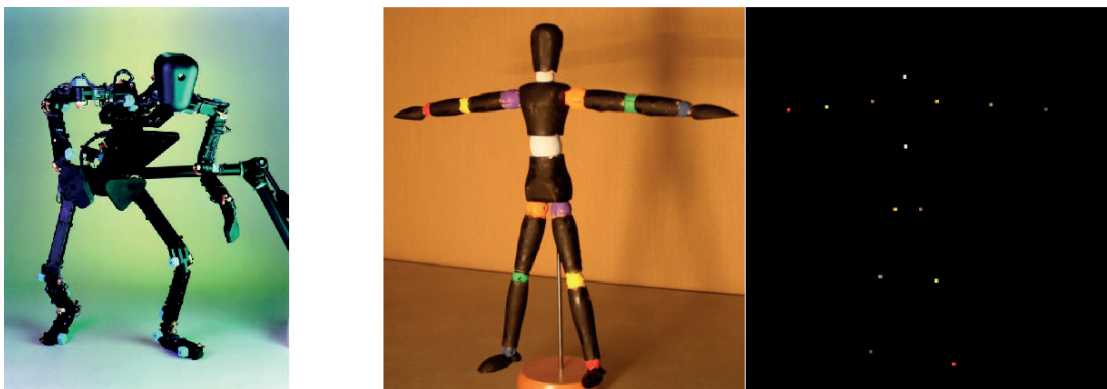


Figure 1.3: Left: The *Monkey 2* interface, (Esposito et al., 1995), Right: The artist's doll with painted joints and the data from the stereo camera, (Gunawardane et al., 2007)

Working also with a physical puppet, Gunawardane et al. (2007) proposed a camera-based interface. They painted the joints of a physical rigged artist's doll in distinct colours to be

detected by a stereo camera (Figure 1.3 right image). The stereo correspondence from the captured images was used to determine the three positional coordinates for each of the joints and adjust the corresponding joints on a virtual generic skeleton. Each pose was passed on to the software as a keyframe and they then applied algorithmic functions to smooth motion between key frames. The authors did not conduct any user studies with animators to provide insights and generate discussion on the technical and use-related challenges of the approach. They stated that their aim was to provide an easy way for non-animators to generate high quality animations.

Oore et al. (2002) presented an interface for low-level control of a digital character where the input device consisted of two motion trackers embedded in two bamboo rods. The users had one rod on each hand and by moving the rods they controlled the characteristics of motion. The joints of the figure were split into several layers. Each layer had its final motion created and recorded separately. In the end the final animation was produced by playing back the different recordings together. The interface was also used for editing previously animated motion paths of the character in real time. Their research lies at the crossroad between performance animation, which essentially is digitally mediated puppetry, and physics-based animation which is concerned with advancing computer processes to produce real-time animation of objects according to laws of physics. Thus, their results contributed to these two fields but they provided no further evidence on whether and how their proposed interface advances the skilled technique of stop-motion into the digital workspace. They investigated the efficiency of the proposed interface in comparison to 'traditional animation techniques' (Oore et al., 2002, p.137), however they did not make any comparison studies nor specified these techniques. Finally, their expressed aim is that the proposed interface will 'allow trained animators to create nearly instant animations'. However, their tests were executed with three non-animators and one fairly experienced user who 'had prior experience with other complex continuous interfaces' (Oore et al., 2002, p.133) but was not an animator.

Another project in the context of performance animation was that of Bar-Lev et al. (2005) who used a 5 DoFs data glove-style device to define and operate virtual marionettes. Similar to Oore et al. (2002), their research was concerned with advancing physics-based calculations in order to get real-time physically correct responses from the marionette to the user's actions. The input devices, one for each marionette, transduced and transmitted the stretch of several strings attached to the user's fingers.

Tangible Handimation, a research project by Svensson et al. (2008), was the first to be done with the puppet stop-motion animators in mind. Svensson et al. (2008) employed three NintendoTM Wii Remotes and the Senseboard⁶ hand-worn units to control parts of a digital character. The goal of the project was to explore more expressive interaction and make use

⁶<http://senseboardinc.com/senseboard-inc/home>, accessed 12 July 2011

of the tacit skills that digital animators have that does not easily map to current computer interfaces. The project used the metaphor of a sequencer where the data tracks of real-time movement were recorded and replayed. Svensson et al. (2008) ran tests and one workshop session with animators providing some guidelines related to the sequencer functionality to record movement. With regards to the Wii Remotes, the authors did not provide much information about the mapping mechanism between the animators' gesture and the resulted motion of the digital character. However, they presented some interesting insights deriving from the animators' engagement with the Wii Remote including an observation they made regarding the control of the character which resembled the one used in the aforementioned examples. The animators suggested to have the Wii Remote inside physical puppets and manipulate them in order to trigger the corresponding motion of the virtual character. They also envisaged the interface as a way to create a bridge between computer animation and traditional puppeteers.

Three NintendoTM Wii Remotes were also employed in the study conducted by Shiratori and Hodgins (2008) which used them for locomotion of a dynamically simulated articulated character through the motion of the user's arms, wrists, or legs. Rather than focusing on character animation per se, the study explored the different designs for an interface that uses the Wii Remotes to control the motion of a character and tested the circumstances under which the interfaces outperformed a traditional joystick. The study used patterns of motion for the character like walking and running which are pre-animated and are triggered depending on the gesture the user will perform. Their design aimed to make users feel a connection between their actions and those of the character. For example, the gait transitions were designed based on frequency and phase of motion of the Wii Remotes. When the Wii Remotes were moving in phase, the character jumped. When the Wii Remotes motions were out-of-phase, the character either walked or run depending on whether the frequency was low or high (Shiratori and Hodgins, 2008, p.123). Their quantitative experiments involved competitive tasks and were run with fifteen university students associated with the project, some of whom were computer science students. The study did not consider the working methods of puppet stop-motion animators nor did it address digital character animators.

Although not directly considering the aspects of the puppet stop-motion animation process, the aforementioned projects illustrate the intuitiveness and abilities of spatial input interfaces over the conventional WIMP interface. Spatial gestural control is certainly significant in transferring the expressiveness of gestures and bringing a higher level of embodiment to the animating experience than WIMP interfaces do. However, enactive exploration of a virtual environment requires the physical aspect of our encounter with real world environments. The participation of the sense of touch is essential in enforcing the coupling between perception and action. A virtual environment can be navigated by pointing, but in order to

simulate the exploration of physical spaces, the interface should operate 'by extending the user's perceptual-motor capabilities into these virtual environments, in some sense. Without this sensory feedback, users are impaired in acting within the virtual environment' (Visell, 2009). Before presenting a category of interfaces which are capable of enabling, creating and maintain the action-perception loop, I would like to present one sensory modality which plays a significant role in skillful action, the haptic sense.

1.3.3 The haptic sense

Humans are capable of using a range of senses. One very important, yet under-researched one, is the sense of touch. Touch is part of a larger complex of senses which interrelates mental and bodily processes, the haptic sense. Haptic exploration is a fundamental experience that assists people in perceiving and making sense of the physical world around them. The word *haptic* means to *touch*, however, haptic perception does not pertain solely to the sense of touch.

The human haptic sensory system consists of three individual perceptual systems. These are the cutaneous, the kinaesthetic and the proprioceptive. The cutaneous system is related to the skin sensations upon touching a material, such as pressure, temperature or pain (McGee, 2003). The kinaesthetic system refers to the feeling of motion as performed by the orchestrated movements of muscles, joints, tendons and soft tissue. In his taxonomy⁷ for gesture, Cadoz (1994) introduced the haptic sense through its kinaesthetic constituent. He suggested that gesture can be generally divided into three major groups based on its different functions, one involving communication, the second involving manipulation and prehension and the third involving haptic exploration. These are:

- *semiotic*: when gesture communicates meaningful information and results from shared cultural experience
- *ergodic*: when gesture is associated with the notion of work and the capacity of humans to manipulate the physical world, create artefacts
- *epistemic*: when gesture allows humans to learn from the environment through tactile experience or haptic exploration

According to Cadoz (1994), haptic exploration is a fundamental experience that assists people in perceiving and making sense of the physical environment around them. Proprioception is described as the understanding humans have for the sensory information on the internal status of the body at every state. Both the kinaesthetic and proprioceptive systems are associated with the perception of forces while the cutaneous system with tactile perception.

⁷Mulder (2009) and Kwon (2008) have given a detail account of other gesture classifications.

Considering the domination of GUIs, visual cues are widely researched and available in the majority of digital media. Auditory modalities have been well studied and are usually designed into application software as an extra feedback channel. Interaction with virtual environments through the haptic modality, on the other hand, has been by comparison so far poorly supported. The WIMP as well as many spatial input interfaces address primarily the visual sense, and only to some extent hearing and touch. The mouse as a physical object activates the cutaneous sense when touched. This is one passive level of tactility. Some of the spatial input interfaces, for example the Wii Remote, produce vibrotactile feedback to the user as a sensorial response from the virtual environment. This mediation of touch provides more advanced haptic response in comparison to the mouse but it is still a very abstract response and cannot be attributed to more specific things, such as tracing the surface of a virtual object and feeling it at the same time. Fine-grained haptic exploration is essential to skillful operations. In his book *Abstracting Craft: the practiced digital hand*, McCullough (1998) invited the reader to question the lack of the touch sense in skillfully handling objects positioned in virtual environments:

Too little has been said about sophisticated computer input, as opposed to stimulating output. Vision is largely passive, but constructed realities need not be passively received. [...] On the grounds that computer designs need to do more with what people already know and expect about handling their physical environment, there is no reason to downplay the physical. If we are to bridge the physical and the virtual worlds, then dematerialisation is not the answer. (McCullough, 1998, p.129)

Similarly, Jorissen et al. (2006) denoted that a tangible experience of the abstract three dimensional space provides advantages to its perception. Treadaway (2009a) (and in Treadaway (2009c)) attested that the lack of haptic sensitivity in the interfaces that are used by artists in computer-assisted creative practice frequently inhibits the expression of emotion and frustrates the user.

In craft, the haptic sensory modality is used more than the visual and the auditory and is one of the major conductors of creativity. Prytherch and Jerrard (2003) have carried out in-depth discussions with creative practitioners (artists / designers / makers) to find that much of the significant perceptual information is dealt with at a pre-conscious level via the haptic senses whereas the vision performs a role as monitor of process. Barrett (2007) explained how the continuity of artistic experience with normal cognitive processes is situated at 'the impulse to handle materials and to think and feel through their handling' (Barrett, 2007, p.116). In her investigation about the fundamental aspects of creative processes, Treadaway (2009b) argued that creative processes are heavily reliant on the artist's / designer's / maker's memories of physical experience and explains how hand use and materiality both trigger remembered physical experience and stimulate the imagination.

1.3.4 Enactive interfaces

The growing interest in enabling the haptic sense in virtual environments led to the development of technological innovations which have the ability to maintain the enactive relationship between action and perception. These technologies employ sensors and actuators to provide force feedback to users while in many cases they trigger the proprioceptive and kinaesthetic perception by operating in three dimensional space like spatial input interfaces do. Interfaces which use these technologies are able to augment the user's existing sensory abilities in a virtual environment and give the impression of physical presence. Central to their role, is the dynamic constitutive relationship between sensory input and motor output which they enable and maintain throughout the activity of the user in the virtual environment. This relationship reflects back to the enactive construction of knowledge about the environment, giving those interfaces the term *enactive interfaces*. I consider the definition of enactive interfaces given by Froese et al. (2011) as the most complete one because it addresses the ability of enactive interfaces to create new kinds of embodiment and enable novel ways of experiencing the virtual environment.

Using the enactive framework for thinking about perception, action and the design of interface technology we can now concisely define an enactive interface (EI) as follows: an enactive interface is a technological interface that is designed for the purpose of augmented sense-making. (Froese et al., 2011, p.4)

Enactive interfaces provide interface designers with a suitable framework to address how digital interfaces can mediate and augment our embodied interaction with the physical world. Thus, I argue that they are the most suitable interfaces through which to study the transfer of embodied skills.

Haptic technologies are the most advanced and commonly used technologies for developing enactive interfaces. They assist their users in perceiving and making sense of the environment by employing what perceptual psychologist J.J. Gibson termed as *the sense of active touch* (Gibson, 1962). Active touch occurs when people move their fingers and hands to explore properties of an object (Larssen et al., 2007). Apart from tactility, active touch includes the kinaesthetic and proprioceptive senses which work alongside touch to form the haptic perception. Kinaesthetic aspects of human computer interactions have been explored in the practical work of Svan (2007), Schiphorst et al. (2002) and Moen (2006) to name but a few. Boeck et al. (2006), Levisohn (2007), Mine et al. (1997) and Grant and Magee (1998) have investigated the proprioceptive sense in human computer interactions.

Haptic technology was established out of the field of tele-operations as an attempt to reduce the complexity and expense of tele-operation systems caused by the need for highly precise operations without the ability of physical gestural control, such as tele-surgery and tele-manipulation of radio active materials (Salisbury and Srinivasan, 1997). The second large

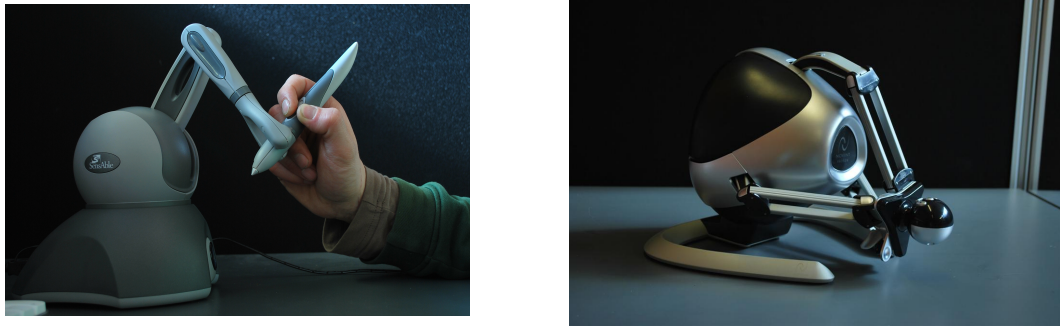


Figure 1.4: Haptic devices with different degrees of freedom and manipulandum

area of haptic research concerned the provision of useful information of the virtual worlds to visually impaired and blind people as well as the construction of virtual learning environments for them. Since the 00s, haptic technology has inspired numerous research projects on the transfer of skillful practices in digital workspaces with applications in the fashion and textile industry, applied arts and craft.

Haptic interfaces are categorized into cutaneous-based and kinaesthetic-based. The first category includes motor sensors, tactor arrays, vibro-tactile devices and touch displays which produce vibrotactile feedback to simulate the sensation of touching and tracing a surface. The other category includes haptic devices and exoskeletons which produce force-feedback. Haptic devices allow the user to feel the surface of 3-D virtual models by mechanical exertion of forces and vibrations which are sensed by the user's kinaesthetic system. They are dynamically reconfigurable since parameters like the weight of an object, the stiffness of its surface and the material it is made of can be easily adjusted.

Haptic devices can generally be organized into two categories, active and passive (Stanney, 2002). Passive haptic devices, such as the mouse, keyboard or trackball provide tactual feedback because of their shape or texture and it is not controlled by the computer they are connected to. On the contrary, active haptic devices, such as force-feedback devices and exoskeleton armatures, are able to apply computer-controlled reactive forces through sensors and actuators to simulate the sensation of touching virtual objects (Srinivasan and Basdogan, 1997). Users of active haptic devices are in constant exchange of haptic sensory information that facilitate their understanding of the phenomena which take place in the virtual environment as a result of their actions. The haptic technology used in this research are force-feedback haptic devices and they were selected because of their ability to enable the synergy between the kinaesthetic, proprioceptive and touch senses. They consist of a base and an extension with a type of grip in their end (Figure 1.4). Grunwald (2008) named the grip through which the haptic signal is transmitted to the haptic device's user as *manipulandum* (Grunwald, 2008, p.365).

The region of space in which a manipulandum can move is the haptic device's workspace. The haptic device provides the coordinates of the manipulandum in 3-D space and data about its orientation where this is possible as haptic devices come in a range of different DoFs and some models do not allow rotation on the manipulandum.

The device mediates the sense of touch by generating forces, computed via coding, and exerting them to the user or generate forces which are opposite to the ones the user applies. The forces are produced by motor mechanisms located inside the base of the device. This process is called *haptic rendering*. The intensity, direction and other properties of the forces are programmable. During haptic rendering, the forces are updated every 1/1000th of a second to ensure that the haptic sense is maintained at realistic levels⁸. The representation of the device in the virtual environment is a virtual object capable of moving in the $2^{1/2}$ - D space in all three directions. The representation can be any kind of virtual model. The user moves the manipulandum in the virtual environment and when it comes in contact with a three dimensional virtual surface, the device's extension provides force-feedback to the user's hand through internal mechanical actuators. The forces are exerted locally at the base of the manipulandum the user holds while the result is experienced on the virtual environment on screen. Haptic devices operate through the control metaphor of a virtual probe to simulate the way our hands work as part effector and part probe. The device's representation acts as the visual extension of the device in the virtual environment. Polanyi (1966) has explained people's capability of probing with the concept of distal and proximal phenomena. He suggests that embodied skills rely on our focus on phenomena which happen in the space around us (distal) while our sensory experience takes place close to our body (proximal).

Several research and commercial projects have employed force feedback haptic devices as digital interfaces for skilled work in virtual environments. A project that has inspired my research is the *Tacitus* project, led by applied artist and designer Ann-Marie Shillito. *Tacitus* investigated haptic interaction for computer-aided design in the applied arts, particularly jewelery, where haptic technology can be used for the conceptual phase of a experimenting with different designs where the form of the artifact is being explored (Shillito et al., 2001). As Shillito et al. (2001) suggested, the aim of the project was 'not to imitate the working practices and environment of the craftsman, but to create a generic virtual environment that can be applied to a variety of 3D creative disciplines, in which the applied artist feels comfortable and uninhibited by the novel synthetic environment and yet can bring their experience and knowledge to extend their levels of creativity more fluidly using a new digital medium'. In Shillito et al. (2003), the authors described the development a haptic interface which exploits spatial input and stereovision and worked closely with jewelery makers and product designers for evaluating the interface. Their work produced significant insights for the design of the

⁸Ruspini (1997) has made a detailed analysis of all haptic rendering algorithms

interface (Shillito et al. (2003), (Wall et al., 2002), Gauldie et al. (2004)) some of which I will discuss in detail in later chapters. The practical work and research during the *Tacitus* project culminated in the development of a commercial application for haptically mediated 3-D modeling, *Cloud 9*. *Cloud 9* used a 3 DoF haptic device for working in a virtual environment in which jewelers and product designers can work on their models before printing them in 3-D. Figure 1.5 shows an example of the work flow with jeweler Farah Bandoorkwala⁹.



Figure 1.5: Bandoorkwala working with the haptic device, a screenshot of the application with the designed digital artifact and a 3-D printed bracelet. Images courtesy of Anarkik3D

The Fashion Design Studio in London College of Fashion, under the direction of textile designer Philp Delamore, has been developing haptic interfaces for virtual textile creation through collaborative work and knowledge transfer projects. The interfaces are used by the students as well as by professionals.

In the commercial domain, Sensable's FreeFormTM modelling application used a haptic device to simulate the sculpting principles for digital sculpting. The virtual 3D models were *made of* virtual clay which can be directly sculpted using a 6 DoF haptic device. The ClayTools plugin by the same company was used to import the digitally sculpted artifacts to the commercial 3-D modelling package AutodeskTM Maya for further editing. In the Maya

⁹Images of her work can be seen in <http://farahb.com/>, accessed 20 December 2011

virtual environment the models could be touched and manipulated with the haptic device through the plugin. Due to the fact that the Maya workspace is conventionally accessed with the WIMP interface, the haptic device emulated the mouse operations for selecting the graphical tools. This is a case where the hardware device was employed in an existing digital workspace which was designed with a different interface and requirements in mind. There has not been any specific study on the experience of using ClayTools.

A few projects have employed force feedback haptic devices to design interfaces for digital character animation. Most of them use the haptic device for controlling the motion path of the character rather than directly manipulating the character itself. Garroway (2005) introduced a haptic interface for editing NURBS¹⁰ curves of an animation path. The system was presented at a major conference where the audience showed impressive speed and skills in editing the curve. Two animations were presented. In the first, the audience were asked to explore the trajectory of a bouncing ball using a haptic device and then were showed how they could edit the curve using the device. The second animation was that of a man, fully rigged with kinematics executing a walk cycle. The device was set to be connected with the trajectory of the man's hand as he walked and the user was given the control to move the hand with respect to the man's body. The results show that haptic interaction with lines can be easily understood and used. Although no studies with animators were conducted, the results show that haptic interaction led to quick and unencumbered navigation and manipulation in the virtual environment. This project falls more under the category of motion editing or motion adaption than digital character animation¹¹.

In the same category, Bierz et al. (2005) presented a haptic interface for interacting with characters whose behaviour is driven by artificial intelligence. By exerting force to the character through a haptic device, represented in the virtual environment with five spheres corresponding to five fingers, the character's planned motion stops and is recalculated based on the exerted force (Figure 1.6). Their reasoning for using a haptic device was that it relates to the natural human way of acting on another person. The researchers did not rule out the possibility of using the keyboard, a joystick or a 3-D mouse in order to realize this interaction but maintain that 'for untrained persons the handling of these devices and the corresponding navigation tasks are often very difficult' (Bierz et al., 2005, p.444).

¹⁰NURBS stands for Non-Uniform Rational B-Spline. NURBS are mathematical models which are used to create graphical curves in computer graphics. Apart from modeling purposes, these curves can be used to dictate the path of an object so that the animators do not have to animate the object in each position but declare the beginning and end of the curve as well as its shape

¹¹Donaldt and Henle (2000) investigated techniques for editing motion where a family of animated particles defined a vector field which could be altered with a haptic device. This project did not concern motion of characters.



Figure 1.6: Sequence of screenshots showing the character walking along a planned path and its interaction with the haptic fingers, which are represented by five spheres, (Bierz et al., 2005)



Figure 1.7: Haptic puppetry, (Kim et al., 2006)

The only example outside motion editing is the work carried out by Kim et al. (2006) which simulated marionette motion by using two haptic devices, each one controlling one string (Figure 1.7). Their approach strongly resembled that of a puppeteer and followed the metaphor of digital puppetry used by spatial input interfaces such as Monkey 2 and the interface built by Oore et al. (2002). They used two haptic devices which manipulated two sets of strings to model the behavior of real-world marionette bar controls. The interface provided to the puppeteer responsive forces as a result of the string motions. The interface is directed towards animators or puppeteers with a secondary aim to be used in interactive games. Kim et al. (2006) stated that the puppeteers have a better sense of control over the marionette and that they can create sophisticated motions in a short amount of time, however, they have not validated that claim by testing, for example, the interface with puppeteers or animators.

Despite their valuable contribution to unwrapping the potential of haptically-augmented workspaces for animating digital characters, the majority of the aforementioned projects were driven by the technology and its capabilities and not by the broader implications that enactive interfaces present for the design of those spaces. With the exception of the work by Shillito et al. (2001) in applied arts, the projects in digital character animation approached the haptic sense as a property of the device that made manipulation of the characters more easily understood by any user, skilled or not, and shortened the time needed to animate them. My research has a different starting point. It is set to explore the transfer of embodied animation skills in a haptically-mediated virtual environment and, consequently, focuses on the cognitive experience of the skilled animators evoked by haptic control. Therefore, I have framed my research methodology through the lenses of embodied cognition and enaction.

One reason for this, which I justified in the previous section, is that by enabling multi-dimensional and multi-sensory bodily action, these complementary approaches provide an appropriate basis to study skillful creative engagement. Their significant role in my exploration is further supported by the approach I have taken on my practical work on designing the interface which resonates with the changing role of the interface since enactive interfaces came into wide use in the research domain. In the context of HCI, the development of enactive interfaces has shifted the attention of interface design from a linear process which focused on the engineering aspects of the applied technology to a dynamic one in which the focus is on the experience the interface evokes to its user. This has enabled an extended discussion on the refashioning of the role of the interface from being a means of communication disconnected from the relationship between user and environment to being a conductor of the users' actions embedded in the environment.

Revisiting the role of the interface

Enaction 'gives primacy to a notion of embodiment that places the body of the perceiving, acting person at the center, embedding them within a much broader biological, psychological and cultural context where the interaction with any computational device is no more privileged than the interaction with any other artifact or tool' (Gillespie and O'Modhain, 2011, p.482). Enactive interfaces denote a return to the naturalness of actions upon the environment and the responses coming from it. This change has had a significant impact on the definition of what an interface is. If we consider the dynamic relationship between the user and the virtual environment in the embodied cognition approach, the conventional role of the interface is an independent means of communication and external to this synergy. In its new role, the interface can be regarded as a transparent participator in the synergy and its facilitator, mediating the user's actions in the environment. The philosopher John Stewart has circumscribed this new role of the interface:

Our point of view is that computers are basically technical devices, and should be treated in the same way as other technical devices. Certainly, they are devices of a special sort, and the 'worlds' that are brought forth when a human being uses them are a special sort of 'world'; but the interaction that occurs (that is mediated by the machine) is between the human being and this 'world'; it is not an interaction between the human being and the machine. Thus, there is something deeply wrong in the very phrase 'Human-Computer Interface'. (Stewart et al., 2004) in (Gillespie and O'Modhain, 2011, p.483)

In the context of HCI, many interaction models have followed the refashioned role of the interface and contributed relevant design and development approaches. Beaudouin-Lafon (2000) proposed the concept of Instrumental Interaction, which introduced the notion of instruments to mediate interaction, inspired by our everyday experience of using tools, instruments and devices to operate on the physical world instead of with our bare hands. Jacob et al. (2008) unified the new, post-WIMP interfacing styles in a methodological framework for designing and developing computer systems called Reality-Based Interaction. They observed that those styles draw strength from how people experience the world using their pre-existing knowledge of it and are empowered by reality-based themes such as 'users' understanding of naive physics, their own bodies, the surrounding environment, and other people' (Jacob et al., 2008, p.201). Experiencing media and digital application as part of the physical environment is central to the research on Organic Interfaces (Schwesig, 2008). The practical work conducted by (Schwesig, 2008) illustrated the ability of the interface to suspend our disbelief making us 'forget that we are operating a machine to manipulate virtual, digital data' (Schwesig, 2008, p.67). Their work is focused extensively on using analog input mounted with sensors to measure subtle changes in physical gesture, for example bending of objects. Having the graphical interface responding to such gestures gives a physical dimension to the abstract digital information and makes their integration more natural for the user, hence the term *organic* interfaces. Models

of interaction with a virtual environment, such as the ones just described, remain an active field of research which grows in parallel with emerging technologies.

Viewing the interface as a mediator of action between the physical and digital world has embraced my approach for exploring the mediation of the puppet stop-motion animator's skillful action from the physical to the virtual environment. Conversely, using contextually-conditioned skillful actions to explore the ways enactive interfaces can accommodate embodied activity in virtual environments contributes a different perspective to their navigation and insights to the design of the interfaces. In my practical work, I have investigated both processes as I considered them closely interrelated, evolving in parallel and affecting each other. In relation to this, Khatchatourov et al. (2009) have usefully observed that the enactive approach can resolve the epistemological ambiguity between the use of interfaces in cognitive studies and the necessity of such studies for the design of interfaces. They start with the remark that under the enactivist framework, the senses are the instantiation of the physiological and cognitive relation between ourselves and the environment and that this relation and the knowledge about this relation are both constructed. Therefore, Khatchatourov et al. (2009) concluded, if we consider that the mechanisms of sensing (interfaces) can affect the senses and affect also the knowledge about the senses at each instance (since they are both constructed), 'an epistemological coherence of the complementarity between [cognitive] studies and the technological development of the interfaces can be guaranteed' (Khatchatourov et al., 2009, p.35).

Similarly in HCI, the challenge that is presented to the community of HCI designers is to identify, articulate and understand how people interact through the new interfaces for the specific tasks the interfaces are designed to support. This field of research and that of the development of new interaction models compliment each other as Khatchatourov et al. (2009) remarked. In the final section of the SIGGRAPH 2011 course publication on *3D Spatial Interaction: Applications for Art, Design, and Science*, Laviola J and Keefe (2011) made a statement that foregrounds the importance of research on enaction and cognition in contemporary interface design:

'As interfaces move increasingly in the direction of mixing 2D and 3D inputs, working in tandem with 3D displays, and mixing tangible and freehand modes of action, perceptual and cognitive issues are sure to become increasingly important factors to consider in interface design' (Laviola J and Keefe, 2011, p.64)

In addition to placing the importance on the enactive approach to cognition, using this approach to develop a suitable virtual environment in which skilled practitioners can work creatively, requires a methodical framework for the design of this environment. The projects that I have so far presented, which use haptic devices, focus heavily on the technology they employ. The knowledge about how the interface is designed, developed and used is fragmented

and incoherent. Therefore, they miss the opportunity to contribute to the appreciation of how a body-driven haptically-mediated experience is designed. This observation does not address only haptically-mediated interfaces for animation but also extends to the broader field of haptic interface design.

In 2009, Visell (2009) reviewed numerous examples of enactive interfaces and highlighted that their most important features were those that enable cross-modal perception. He noted that it is necessary to understand better the design considerations relevant to these features in order to aid the exploration of the design of enactive interfaces. As recently as 2011, in the field of haptic interface design, Gillespie and O'Modhrain (2011) suggested that there is a need for a new understanding of how to design haptic interfaces under the embodied cognition framework. In the same year, Froese et al. (2011) discussed this need and presented practical work through their project, *Enactive Torch*, a haptic interface for navigating an imaginary environment (a simple maze) without the help of vision. Their project is the first practical study to be framed by the enactive approach to cognition and to consider the haptic interface as an implicit mediator of new kinds of augmented experiences. Their results contribute to studies of perception in cognitive science.

Addressing the call by Gillespie and O'Modhrain (2011), my research is set to explore a methodology for designing haptic virtual environments which accommodate the embodied and multi-sensory skills of puppet stop-motion animators through the lenses of embodied cognition and enaction.

1.4 Conclusions

As workspaces are becoming rapidly digitalized a growing number of traditional skilled practices become computer-assisted and many of them are carried out entirely in digital workspaces. Digital workspaces employ tools and media which are fundamentally different than the ones used in physical settings. Skillful actions are an amalgam of body-driven, multi sensory activities which inform the skilled practitioner's perceptual experience. Existing digital workspaces for the animation of digital characters cannot facilitate the coupled dynamics between embodied skillful action and perception as their design fails to take into consideration embodied activity.

There is a need for understanding and endorsing the multi leveled experience of skilled animators prior and throughout the design of a digital workspace that aims to facilitate their actions. Therefore, I have framed my research perspective through the embodied approach to cognition in which action and perception subsume the process of meaning-making. By triggering perception through action and enabling the haptic sense, haptic interfaces have the potential for transferring successfully the embodied skills of puppet stop-motion animators in

a haptically-augmented workspace for animation. In the following chapters, I will describe my practical studies which employ haptic technology to create a haptic workspace.

In parallel to my investigations of how these new technologies contribute to digitally mediated skilled activity, I have emphasized another important point. Despite the valuable explorations that examine the digital mediation of creative, skilled practices, there is not a coherent methodological framework to support the process and transcribe valuable insights making them available to future HCI designers and researchers. Therefore, I started an investigation on existing design methodologies in HCI with the intention to select individual elements that serve my research aim. The next chapter outlines this investigation and describes the main elements that comprised my design approach to the practical work that I carried out.

Chapter 2

Design methodology

In the previous chapter, I referred to the absence of a specific methodological framework in HCI for designing digital workspaces that successfully transfer the embodied knowledge of skilled practitioners and allow them to work unencumbered.

In this chapter, I will discuss my investigation of existing HCI design methodologies and present the elements that I chose to comprise my methodology for studying the potential of haptic interfaces to transfer the tacit embodied skills of puppet stop-motion animators into a digital workspace.

While designing under the embodied cognition framework, I have acknowledged the importance of the user's experience which incorporates all experiential aspects of using an interface. I have then expanded the process of accumulating experiential information towards my own practice and understood the process as a dialogue between two participants both of whose experiences were equally catalytic to the design decisions and outcomes. In order to do that, I approached design itself as an experience, following the Experiential Design framework which sees the experience of the designer as equally important to the one of the user.

Under this framework, I have engaged in collaborative design with the puppet stop-motion animators with whom I co-designed and developed a haptic workspace as a way of directly and practically intervening in their traditional work methodology.

Influenced by the experiential approach, I have developed an understanding of design, in which all processes happen in a parallel rather than sequential form. In the light of this holistic appreciation, I propose that multiple streams of reflection is an essential design tool for addressing both experiences and for identifying, understanding and analyzing the different processes which occur simultaneously throughout the design activity.

2.1 The importance of the user's experience

Enaction foregrounds the close relationship between knowledge and action, and through action we relate to the world in order to experience it. Therefore, I consider the experience that the users have of using and appropriating an enactive interface that aims to transfer their skills, as central to the interface's design process.

The user's experience has been approached in HCI in three different ways which can be traced across three major intellectual waves that shaped the field, identified by Harrison et al. (2007) as 'the three paradigms of HCI'.

2.1.1 The (H) in HCI

The first paradigm identified by Harrison et al. (2007) is a pragmatic view of the interaction between user and machine which focuses on task execution. Under this view, the user's experience has little influence in the design and development of digital systems. Instead, the importance is only on ergonomic and human factors that make the use of the systems easy to operate.

The second paradigm shifted the focus of design on the user's cognitive abilities and placed psychology and cognitive science in the center of HCI research. This paradigm was developed around the premise that the human mind is analogous to a computer processor. This premise is similar to that of the objective cognition framework, which is predominately used for user studies in this paradigm. Under this particular perspective, research includes formal studies of user behaviour, such as cognitive analysis of tasks, in order to maximize the efficiency of the prototyped system. Characteristically, the users are considered to be, and often referred to as, subjects.

Since 2000 onwards, HCI has extended the boundaries of user studies and moved from considering the human mind as analogous to a computer processor to recognizing the importance of the social, emotional and sensorial aspects of people's lives. These aspects greatly influence how people make sense of and use products, services and technological systems that are available to them. The consideration of those additional factors that influence human experience has additionally been enabled by the development of mobile, gestural and haptic technologies and ubiquitous computing. These technologies offer people the ability to connect, express themselves in various ways and explore a plethora of applications outside the work-specific setting and within the physical environment. With the shift of focus towards the social, emotional and sensorial aspects of user experience and the technological advances that support them, HCI design is strongly informed by the embodied cognition approach.

Dourish (2004) drew on the philosophical area of phenomenology to describe the design and analysis of interaction between people and the environment using the central notion of

embodiment. He defined embodiment as 'the property of our engagement with the world that allows us to make it meaningful' (Dourish, 2004, p.126). In his theory of embodied interaction, people are seen as embodied actors within the world, who make sense of the phenomena that unfold around them by directly interacting with them. Consequently, Dourish (2004) views digital technology as part of our being-in-the-world and emphasizes that it should be designed based on how we understand, appropriate it and act through it as embodied agents.

In accordance to Dourish (2001), Wright et al. (2006) suggest that human experience is constituted by continuous engagement with the world through acts of meaning making at many levels. User experience in the third paradigm is about experiencing the world by participating in it with all the senses, the tool that assists us to construct meaning. Enaction, on the other hand, is about meaning-making by acting in the world through our senses. Therefore, I propose that viewing the user experience under the third paradigm provides a fruitful basis for investigating the mediation of embodied skills through haptic interfaces.

With the advent of the concept of embodied cognition and the rapid changes in technologies that people use in everyday life, the cases where research methodologies from the first two paradigms are followed have gradually decreased. However, the engineering, user behaviour and experiential approaches of the three different paradigms can work complementary and it is useful to view them as co-existing rather than think that one substitutes the another.

2.1.2 Co-designing with the user

Collaboration between the designer and the prospective users is a fruitful method for developing and testing ideas which benefits both participants. The collaboration between designers and users was established in the second HCI paradigm, however, the knowledge that was produced during this collaboration was one directional, from the user to the designer. The aim of the collaboration was to understand the users' behaviour when using a system and the methods to achieve this was to provide them with a set of predefined tasks and evaluate their response with metrics such as efficiency and efficacy of the tested system and user satisfaction.

In the third paradigm, the knowledge exchange that takes place throughout the collaboration is considered central to the design process and one that provides a fruitful ground for exploration, ideation and development which is oriented towards the user's needs and requirements. The designer is able to identify and understand the different aspects of the user's experience while embedding herself in the users' context. The users, who are the experts in the context to be addressed, are given the opportunity and the tools to shape ideas and provide suggestions and reflections on the design through the development process. This design philosophy is known as *co-design*.

In my research, I established collaborations with different teams of stop-motion animators which guided the iterative development of a prototype haptically-augmented virtual workspace. The majority of them were third or fourth year students, while I have required additional input by faculty professors and technicians in the Animation Department at Edinburgh College of Art. They were all specialized in animating physical objects and both human and non-human puppets. All the discussions and design activities that will be described in the following chapters took place in-situ at their own studios in Edinburgh College of Art. Later collaborations included one professional stop-motion animator and one professional digital animator.

Placing the user in the center of the design process is referred to in the HCI literature as *User-Centered* design. The term was first coined in the second HCI paradigm to denote the involvement of the users in the design process. I contrast this with the User-Driven design framework in which my research is positioned. In User-Centered design where users are merely consulted with regards to their needs and are asked to evaluate a set of predefined targets and task requirements (Norman and Draper, 1986). In User-Driven design, design is led by the users' responses throughout the process and users actively participate in the conception and design of the end result. It uses users' feedback and experiences as a source of inspiration, rather than requirements when setting the agenda and goals for design (Holmquist, 2004). Alan Cooper has extensively stressed the difference in the two approaches in his book *The Inmates are Running the Asylum* (Cooper, 1999).

2.1.3 Intervention and Prototyping

A design intervention is a design-led set of actions which disrupts the normality of a specific context. Its aim is to reveal information about the context which is otherwise difficult to elicit using conventional methods, e.g. interviews. Coyne (2006) writes about the value of direct intervention as a research tool:

A major difference between design-led research and that exercised within the social sciences and anthropology is that design-led research discovers what can be learned from direct intervention by the researcher. Coyne (2006)¹

Design interventions can often be used metaphorically as probes, extensions which are used for thorough physical exploration. An example of probing through design is the work by Gaver et al. (2004a) who introduced *cultural probes*, non-technological kits which are given to the target group for a period of time. As a similar technological design concept, Hutchinson et al. (2003) who have introduced *technology probes*, a method that involves installing simple technologies in the real context of the target group of users in order to gather intelligence about how they are used in-situ. Technological interventions are tangible embodiments of concepts in the form of digital systems or tools. Hutchinson et al. (2003) emphasize that

¹accessed 21st September 2011

this method is open-ended, which means that it is applied with the aim to produce results which are shaped by the way the users will use the probes. Cultural probes differ from technology probes in their purpose: the first aim to inspire the future designs, the latter have the additional role of gathering data about how users appropriate them. They both have low functionalities, they record users' actions and are deployed early in the design process. However, both are not meant to be changed based on user feedback.

In co-design situations, such as the one followed in this research, initial design interventions are developed further in order to be refined with respect to the needs and requirements of the prospective users. In this case, each stage of the iterative development produces an updated prototype version of the initial intervention.

The value of prototyping has been acknowledged to a great extent in design as the tangible representation of ideas for improvement or change. The use of prototypes by the prospective users turns them into platforms that assist the evolution of a design idea. Iterative prototyping foregrounds the relationship between user and technology 'which is not fixed but instead involves a continuous and dynamic re-attribution of the system's purpose(s) through the interaction related to the past, present and future' (Thieme et al., 2011, p.2). It also assists the designers in practically exploring and better understanding the use and appropriation of the prototypes by the users in order to form ideas of potential designs.

In my practical work I have used a large-scale technical prototype system, the haptic workspace, to intervene in the traditional stop-motion practice and to connect my research and design activities. The prototype was developed over a series of design key studies in collaboration with the animators. The studies were conducted as a series of reconfigurations of the prototype with the aim to investigate how gestural and haptic modalities transfer the multidimensional embodied skills of puppet stop-motion animators into a haptic workspace.

The design process was realized in three stages. It began with a detailed analysis of the physical workspace and the work methodology of the stop-motion animators. After designing the first prototype of the haptic workspace, the process continued with a series of iterative software and hardware configurations that aimed at refining it. Each one of these attempts was based on a practical study of the stop-motion creative process. Most reconfigurations were not necessarily radical refinements but were set as alternative designs, serving the exploration of various aspects of the stop-motion practice.

The process of the collaborative iterative development of the haptic workspace foregrounded the animators' needs and requirements for working in this environment and highlighted issues and challenges related to the design of the enactive interface. At each design stage, issues and challenges were identified, understood and discussed so that solutions could be proposed and be integrated in the development of the haptic workspace where appropriate.

The overall role of the haptic workspace prototype was not that of a probe since it could be changed based on the animators' feedback and it was itself a product of the research (whereas technological probes are not meant to be themselves direct products of the subject under research). However, the prototype acquired a probe-style character within each individual design study as it acted as a means to understand aspects of the traditional practice and produce considerations regarding their refashioning in the digital realm.

2.2 Design as experience

I have so far discussed the importance of considering the experience of the user as it unfolds during the design process and argued for the value of a collaborative design process with the users and the direct intervention in their practice, elements which I have followed in my practical studies.

In addition to deciding on a design methodology, I also sought to investigate it and evaluate its potential as a general strategy for designing enactive interfaces for skilled practitioners. For this reason, critical observation of my own practice was necessary for providing insights into my proposed design methodology. In addition, my participation in the dialogue with the animators, which the co-design process establishes as one in which we both enter as equal participants, led me to consider my own experience in equal terms to that of the animators.

In this section I will discuss the importance of the designer's experience as equally valuable to that of the user during the design activity. In order to make this claim, I will take a step back and instead of centering the collaboration between the user and the designer only around the user's experience, I will position their relationship within the broader context of the co-design experience.

2.2.1 Design approaches in HCI

Design can be considered as a methodological approach for developing solutions to problems or for conducting creative explorations with the aim to frame a specific concept and develop it further. Across the three paradigms of HCI, design was regarded in different ways². In the first two paradigms, the dominant model towards design and evaluation is built on a scientific and a rationalist philosophical foundation. It considers a problem and aims at synthesizing engineering solutions to overcome it. Wright et al. (2006) have named this perspective as the *design-as-engineering* approach. The iterative cycle for the solution of the problem consists

²For the following review, I have used the distinction by Wright et al. (2006) to portray the place of design within HCI throughout the three paradigms recognized by Harrison et al. (2007). Forlizzi et al. (2008) have also made a detailed review of the history of HCI with respect to design approaches, and the corresponding social and technical factors that have resulted in the different design methods, methodologies, and criteria that the HCI community uses today.

of its definition, synthesis of a solution by the engineer, testing of the solution by the end-users and return to the synthesis step to adjust the settings and repeat the process. There is always a design perspective in the implementation of the solutions, however, as (Wright et al., 2006) emphasize, characteristic of the engineering approach is the tendency to control the interaction of the users through design. In the iterative process towards problem solving that is followed in the first two paradigms, the evaluation phase is distinct from the design phase. Users are consulted with respect to their expectations of what the resulting output should be like, but do not actively participate in the design. Evaluation methods are formal, mainly task-based and are targeted at measuring the usability of a design outcome, product or interface, with quantifiable metrics such as efficiency, efficacy and user satisfaction (Preece et al., 2002).

In contrast to the design-as-engineering approach, in the third paradigm of HCI, design is seen as a situated and constructive activity which evolves around the experience of the user and thus is focused of meaning making rather than problem solving. The notion of *situated action* was originally introduced in cultural anthropology by Suchman (1987) who explained how human action is strongly linked with the world within which it unfolds being 'an emergent property of moment by moment interaction' Suchman (1987) between people and people and the environment. The foregrounding of the emotional and sensorial phenomena which occur during experiencing, in addition to the pragmatic ones, focused the HCI research on designed explorations of values and goals for the user experience such as design for emotion (Boehner et al., 2007), design for affect (Norman, 2004), ludic design ((Gaver et al., 2004b), (Blythe et al., 2004)) and design for creative engagement ((Bilda et al., 2008)). Wright et al. (2006) have named the design approach which these different design goals share as *design-as-craft* and contrasted it with the design-as-engineering approach. In addition, they proposed a design methodology that is based on dialogue and empathy among the participants so that the multi-dimensional aspects of experience are foregrounded and used as the design driving force.

Wright et al. (2006) provided a broader understanding of experience highlighting its dialogical nature, and positioned the designer's experience alongside that of the user's. The design-as-craft perspective places particular emphasis on the process of making sense of a situation, 'where designers interpret the effects of their designs on the situation at hand and the effects of the situation at hand on their designs' (Wright et al., 2006, p.7).

The design-as-craft perspective emphasizes the exchange of the background knowledge of all collaborators in a design process considering the knowledge as bi-directional. It also acknowledges the transformations that each of the collaborators' knowledge and experience undergoes. In order to fully explore the potential of the haptic interface to transfer the tacit embodied knowledge of skilled practitioners into a digital workspace, I considered important

to carry this exchange into the design process. Therefore, I approached design itself as an experience.

2.2.2 Experiential Design

Experiential Design acknowledges design as a process of producing knowledge through experiencing. Thus, it considers the design process itself as experience and especially in collaborative design situations it foregrounds the synergy between user and designer and examines how both their experiences interact and converge. Woo Heung Ryong (2007) regarded experiential design as 'a transformational process between concept and experience, with a holistic view of design phenomena'. In experiential design, the designers' existing design knowledge and the users' existing knowledge of the context are brought together and dynamically interact, creating new experiences which, in turn, create new knowledge. The circle continues 'in a process of reproduction and regeneration' (Friedman, 2000) in Woo Heung Ryong (2007) leading each time to design innovation.

Wright et al. (2006), Woo Heung Ryong (2007) and Nieminen (2011) have emphasized the importance of considering the designer's experience and the knowledge that she brings into the design process. Wright et al. (2006) recognizes that,

How an individual makes sense of a situation, interaction, episode or artefact is as much about what the individual brings to the experience as it is about what the designer puts there (Wright and McCarthy, 2005, p.11)

Wright et al. (2006) also emphasized the dialogic relation between designer and user. Although they do not contrast explicitly dialogic with dialectic, I would like to emphasize the difference of the two and the importance of dialogic discourse for experiential design. A dialectic discourse brings multiple perspectives into a discursive process that aims to produce an outcome which will represent the perspective that has prevailed over others during the process. A dialogic discourse brings again multiple perspectives into dialogue but its aim is to extend them, inform and be informed by them and keep them in a co-existing relationship where the appropriate approach will be primed over others according to the given point of discussion.

In order to identify and integrate in the circular design process the continuously produced knowledge, as a result of the several processes of design, the designer should adopt a holistic understanding of the design phenomena that occur in parallel, for example her own and the users' experience, contextual approach, intuition or social interaction. Experiential Design and the design-as-craft perspective, as proposed by Wright et al. (2006), are founded on a holistic appreciation of design. Woo Heung Ryong (2007) recognizes that:

We need to deal with collaborative and cognitive approaches to design knowledge, and take note of cognitive interaction using a holistic view of design phenomena. [...] Knowledge and experience have a close relationship and dynamic interaction, and a holistic

approach carries these convictions into design research and practice(Woo Heung Ryong, 2007, p.2)

Similarly, Nieminen (2011) refers to the designer's experience as 'a holistic understanding and a state of mind towards the users, their contexts of use, and their competencies during the design process' (Nieminen, 2011, p.245).

The idea of a holistic understanding of design is still at an initial stage and there are multiple questions to be addressed such as the recommended methodologies for invoking designer's experience, and what are the relevant research topics and practical future uses for designer's experience. It is not the main concern of this thesis to address these and other questions. The holistic approach to design that I have adopted enriched my perspective towards the collaborations that I established, and led me to propose the process of multi-streamed continuous reflection as a valuable tool for capturing, understanding, analyzing and articulating the parallel processes that occur during the co-design activity.

Throughout my collaborations in this research project, I used multiple streams of reflection as a method for enabling the gathering of different ideas and perspectives, validating the process at each stage and facilitating the collaboration between us. The following section discusses the power of reflection as a design tool, exemplifying approaches that have applied reflective models to HCI design and have inspired my own design practice.

2.3 Streams of reflection

In this section I will discuss the notion of reflection as a tool within the design process. I will then describe the sequential ways in which reflection is often applied and debate about the necessity in the Experiential Design framework to move from linear to dynamic reflective design models. Finally, I describe in detail the methods which I have used as tools for eliciting insights based on multi-dimensional and multi-leveled streams of reflection.

2.3.1 Theories of Reflection

The notion of *reflection* has been originally discussed in the context of psychology since the beginning of the 21st century. A retrospective analysis of it reveals three different perspectives associated with three different eras. Dewey (1933) proposed reflection as 'a continuous and creative meaning-making process that draws on past experiences to stimulate rigorous thinking'. In contrast to perceptual inquiry which requires imminent actions adjustable according to each situation, Dewey's reflective inquiry involves a more disciplined approach that meticulously formulates actions. Reflection for Dewey is a particular way of thinking that is driven by imagination, believing and stream of consciousness. He also implied that a motivated individual must have an open-minded approach in what she experiences and must also be

curious and interrogative about perplexing phenomena in those experiences to trigger reflection. Dewey identified five different phases, or aspects of reflective thought when a person faces a perplexing or difficult experience³:

- the occurrence of the experience
- the clarification and definition of the problem(s) that arises out of the experience
- the suggestion of a possible solution to the problem(s)
- the use of the suggested solution to form a hypothesis
- the test of the selected hypothesis by means of action and experiment

Dewey also makes a special case for the importance of judgment as a subordinate process of reflective thinking. He further suggests *analysis* and *synthesis* as the two functions of judgment.

As analysis is emphasis, so synthesis is placing; the one causes the emphasized fact or property to stand out as significant; the other puts what is selected in its context, its connection with what is signified. (Dewey, 1933, p.129)

Reflection has a central stance in psychology, where Lev Vygotsky has examined in his writings reflection from a socio-cultural perspective. Vygotsky (1978) considered reflection as 'a process that happens at the inner psychological level of learners during the stage of proximal development' (Vygotsky, 1978). According to his theory, reflection is driven by activities situated in the social and material environment in which the learners participate. Vygotsky (1978) considered the importance of language as a tool through which meaningful activities are transformed into knowledge.

Another scholar whose research on reflection links to the field of design research is Donald Schön. Schön was an advocate of the reflective approach in all aspects of professional practice and highlighted the significance of the pervasiveness of learning in a changing society ((Schön, 1987) and (Schön, 1995)).

Central to his theory of reflection was the notion of 'knowing-in-action', the implicit knowledge which is acquired by carrying out one's practice and which is difficult to teach. He introduces two notions, *reflection-on-action* and *reflection-in-action* to facilitate the transfer of this type of knowledge. The first describes professionals' reflective dialogue within a given situation of uncertainty, instability and uniqueness, after they have carried out their actions, while the other refers to their reflective dialogue while work is being undertaken. These two identified types of reflection reveal the continuous conversation of the practitioner with herself in an uncertain situation. The dialogue aims at the practitioner's better understanding and change of the situation. Schön identified four distinct phases in this dialogue:

³the wording is mine

- the perception of a specific problem in the phenomena confronting the practitioner
- the definition and framing of the problem based on the components of each situation
- the reviewing of the framing of the problem
- the re-framing of the problem on the basis of tacit norms and the practitioner's prior understandings and knowledge.

Schön's described phases connect his theory directly to the designers' practice since design can be used as a methodological approach to problem solving as continuous framing and re-framing of the problem is a process that designers often follow in order to propose and develop a solution. He used the term *design moves* to describe how designers frame a design situation through experimentation. Ylirisku et al. (2009) expanded the notion of design moves suggesting that when they are placed into the use context, and in the midst of potential users, 'they introduce novel entities that stem from the new relations and structures that emerge.' (Ylirisku et al., 2009, p.1132). Reflection-in-action suggests a unity between theory and practice, the abstract space and the building space. This continuous interplay is one of the reasons Schön's theory has been embraced by HCI and Software Engineering (e.g. (Law, 2004), (Palacpac et al., 2004), (Sengers et al., 2005), (Foong and Kera, 2008)).

The aforementioned theories on reflection offer important knowledge on how reflection can be practiced, the purposes that it serves and the benefits it brings to one's design perspective. Notwithstanding their valuable insights, the models do not discuss reflection as part of the experiential phenomena but treat it as a cognitive process under the objective cognition approach. For example, the reflective inquiry proposed by Dewey (1933) follows a sequential path in order to gather information moving from analysis of a given problem to the synthesis of a solution. Following discrete steps results to the understanding of reflection as a purely cognitive process and makes the model similar to the design-as-engineering approach that was discussed in section 2.2.1. In a similar way, Schön (1987)'s model follows a sequential model of problem naming, setting and framing. This linearity in the steps comprising the reflective process detaches it from the experiential realm. Moreover, in the case of Schön's model, which has brought reflection in the practice domain and was embraced by the HCI community, reflection within the practice follows a sequential path.

Schön (1987) considers reflection towards only one direction, from the practitioner to the practice. The experiential approach advocates for the designer's self-reflection but also considers reflection of the users towards the practice and its outcomes as equally important. Another point of divergence of Schön's model from the experiential approach, is that it does not suggest continuous conscious reflection on the practice. Instead, reflection-in-action is triggered only during unexpected break downs during the process. In contrast, constant and conscious reflection on the side of the designer is essential for engaging in experiential design.

Thus, Schön's model does not provide adequate information for the design situation which takes into consideration both the designer's and user's experience. Instead, multi-directional streams of reflection are a more appropriate model for the experiential approach.

2.3.2 From sequential to dynamic reflective processes

In search of more dynamic reflective processes, we discover a few design practitioners and scholars in HCI who have brought to the surface and used the multiple streams of reflection which take place during the design process. Their work pertains to the Experiential Design framework.

Schön's reflection-in-action is one of the several practices involving reflection that were reviewed by Boehner et al. (2004) and Sengers et al. (2005) in order to propose an HCI design model in which reflection is acknowledged as a core principle and as an outcome of technology design. Their proposal is grounded in critical theory, which advocates that instead of accepting unarguably dogmatic advocacies we should understand the world through individual reasoning. Reflective thinking is an essential tool for critical theory. Building on a growing body of approaches and practices in HCI in which reflection is present but not central, Sengers et al. (2005) constructed a reflective design model which states that technology design practices should support both designers and users in ongoing critical reflection about:

- technology and its relationship to human life
- unconscious assumptions in HCI that may result in negative impacts on our quality of life

Critical reflection by both participants on these broad areas of HCI links the reflective design model to the Experiential Design framework. Sengers et al. (2005) have recognized that 'reflection is not a purely cognitive activity, but is folded into all our ways of seeing and experiencing the world' (Sengers et al., 2005, p.50). Another connecting point is what Sengers et al. (2005) acknowledge as the importance of the designer's critical thinking about their attitudes and practices particularly in socially responsible design. The authors have exemplified their approach with two case studies and conclude them by proposing six principles of reflective design, which have been extremely inspirational to my design methodology. These are:

1. Designers should use reflection to uncover and alter the limitations of design practice
2. Designers should use reflection to re-understand their own role in the technology design process
3. Designers should support users in reflecting on their lives
4. Technology should support skepticism about and reinterpretation of its own working

5. Reflection is not a separate activity from action but is folded into it as an integral part of experience
6. Dialogic engagement between designers and users through technology can enhance reflection

Hummels et al. (2009) have provided an additional perspective to reflective design practice which includes design for the society. They stress the need for flexibility in the design for societal change and argue that current design practices closely related to societal change should not follow structured paths. Hummels et al. (2009) proposed *Reflective Transformative Design* as a design process that is characterized by openness and flexibility.

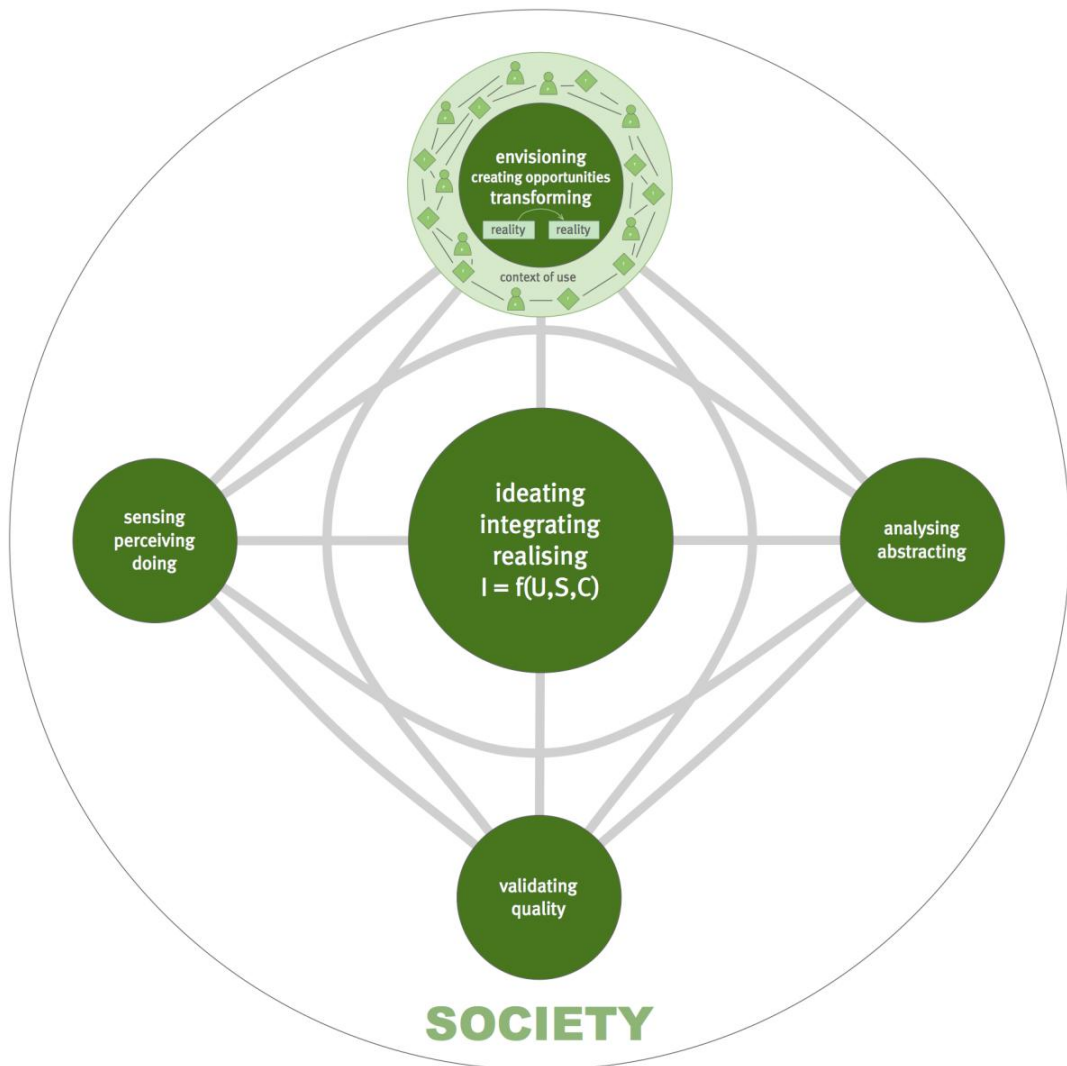


Figure 2.1: The Reflective Transformative Design model, (Hummels et al., 2009)

The designer may move between any of the five activities (Figure 2.1):

- ideating, integrating, realizing

- sensing, perceiving, doing
- analysing, abstracting
- envisioning, creating, transforming
- validating, quality

This proposed model considers knowledge construction as a continuous process of information gathering and identification of design challenges so that at no moment is a design decision considered the right or the final one. Like in science where there is never a confirmation of the truth but only confirmation of suspicion or hypothesis the authors suggest:

We feel that it is more appropriate to consider design decisions as conditional. That is, a designer makes decisions to the best of his/her experience and knowledge. These decisions are not necessarily correct decisions, though it is possible that further insight into the design challenge invalidates a decision, forcing the designer to rethink certain solutions and come up with more appropriate solutions (Hummels et al., 2009, p.208)

Their view can be well positioned in the holistic approach to design, which advocates that the design process never comes to a definite end and that each design decision and outcome is subject to further examination in different circumstances and under different conditions. In this infinite process, new evidence can either lent support to some hypotheses or refute them.

Tomico et al. (2009) identified the non sequential design processes in the model by Hummels et al. (2009) and proposed tools for successful user involvement within those processes centered at invoking user reflection. In their *Co-Reflective* framework, design is viewed as a highly dynamic process driven by dialectical enquiry rather than the structured model of hypothesis-deduction. Like Hummels et al. (2009), they highlighted the different streams of reflection that dialectical enquiry creates and bring them to the center of design. A co-reflective process is seen as a face-to-face conversation between the users and the designers that allows more direct and trustworthy exchange of information and knowledge. The aim of the Co-Reflective model is to converge the user's point of view with the designer's vision, since 'the user is the expert in the context to be addressed, while the designer is the expert on how to implement it into a product or service' (Tomico et al., 2009, p.2696). Motivating users to be more descriptive than prescriptive, provides the designers with a deeper understanding of their needs, motivational aspects and associated behaviours.

Tomico et al. (2009), as well as Hummels et al. (2009), emphasize the need for a holistic appreciation of the design process which is important when applying reflection within the Experiential Design framework. However, they do not specifically acknowledge nor discuss in detail the part of the reflective process where reflection is consciously carried out by the

designers on their design practice. In comparison, the work by Sengers et al. (2005) has been more specific and descriptive about designer's reflection.

My method of using technological intervention in conjunction with multi-streamed reflective processes is related to the Critical Technical Practice method proposed by Agre (1997). Agre (1997) suggested technological intervention as a basis for provoking critical reflection within the field of Artificial Intelligence. He suggested a constructive and flexible approach to design and evaluation of technical Artificial Intelligence practice that is shaped through deep and rigorous understanding of the general difficulties in design practice. For this, he suggested that technical complications cause the researchers to distance themselves from substantive beliefs and rigid approaches towards their practice and leads them to foreground phenomena that carefully planned design actions could marginalize. This was my aim for the practical studies.

The reflective models by Tomico et al. (2009), Hummels et al. (2009) and Sengers et al. (2005) have been extremely useful to shaping my approach to reflective thinking during the design and research processes. I have extensively used multiple streams of reflection as a tool for eliciting user responses including reflection on my own methodology.

2.3.3 Multi-streamed reflection and dialogic discourse during the design studies

Reflection was considered of high importance in the progress of the design process and practical explorations for the development of the haptic workspace. Figure 2.2 shows the streams of reflection at each stage of the experiential co-design and development processes.

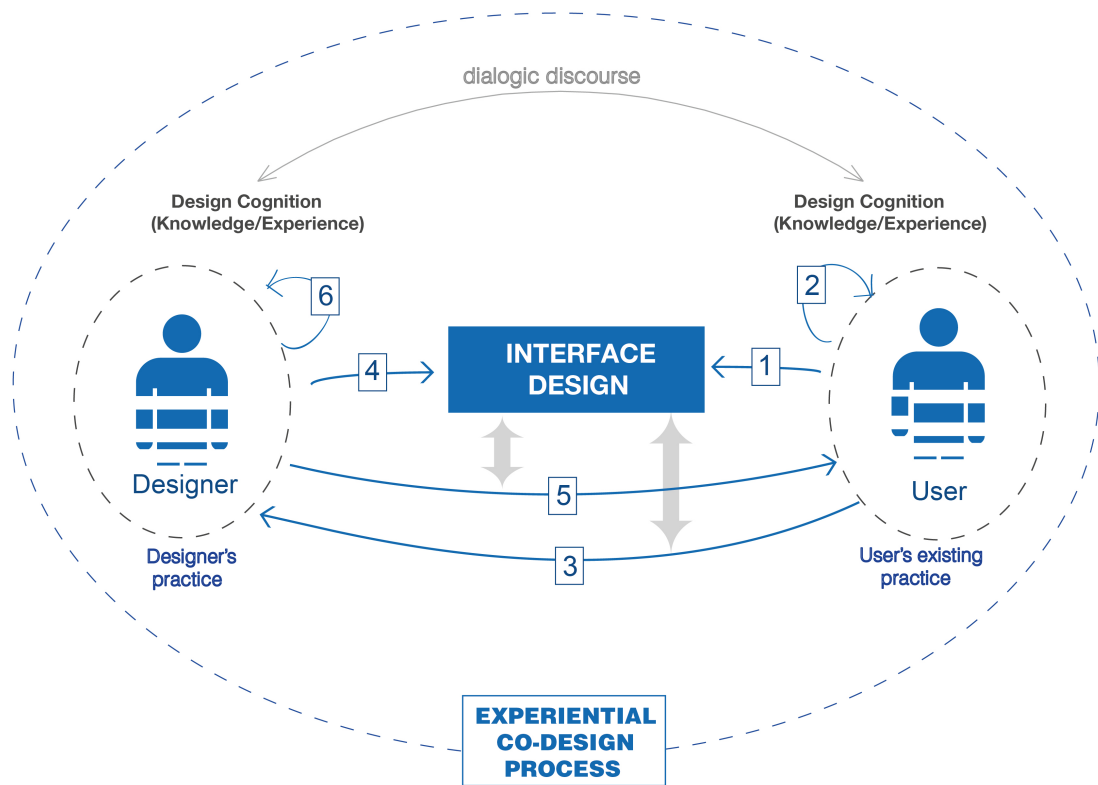


Figure 2.2: Multiple streams of reflection

The animators reflected on their experience working in the haptically-augmented workspace and assessed their interaction with it at every stage of its development (Stream 1 in Figure 2.2). While using the haptic workspace to perform a range of studies, I triggered their reflection on the effect it had on their practice and how they envisaged its use in the stop-motion niche (Stream 2 in Figure 2.2). I did so by asking questions at appropriate moments and carrying out informal discussions after each session.

In order to enable their reflection towards my practice, both design and research-wise (Stream 3 in Figure 2.2), I asked them to interview me. Being in the position of the interviewer offered them a direct way of asking crucial questions about the design, the haptic workspace itself and the aims and objectives of the overall research. As a result, it did not just trigger their reflection but also encouraged them to ask challenging questions for both my research and their practice.

Another way for encouraging their reflection towards my practice was to address our joint design conduct and informally discuss with them research questions that I had in mind. My aim in doing so was to inform my research by gathering an amalgam of different perspectives and views. In this way, their responses shaped my conduct as a researcher, as well as designer.

Their individual reflective process was dependent on their background which was very helpful for the dialogic discourse that we followed. All animators that I collaborated with had different backgrounds and carried different approaches on how to adapt to the imposed changes into their usual practice. While most of them were experienced mainly in puppet stop-motion animation, some of them had a background in fine art, others in photography, drawing and one was previously a software developer. The majority of the animators recognized the increasing infiltration of digital media in their work and maintained an open approach to their experience with the new workspace contributing insights with the current and future puppet stop-motion practice in mind. Other animators experienced difficulty in detaching themselves from the physicality they experience in the traditional workspace. There were, in a sense, different kinds of engagement with the developed workspace all of which were taken into consideration in the dialogic approach to our collaboration.

I critically reflected on the way they were experiencing the prototypes at each stage, filtering my thinking through my knowledge as a designer and combining the results with their reflective thinking in order to design the proceeding prototype (Stream 4 in Figure 2.2). In parallel, I analyzed my findings through the lens of HCI design. The initial contextual enquiry and the information the animators provided about aspects of their practice at each design stage helped me to reflect on the design of the interface in relation to their practice (Stream 5 in Figure 2.2). Self-reflection led me to constantly evaluate the methods themselves that I used to invoke reflection from the animators during the studies (Stream 6 in Figure 2.2).

The insights produced by the different streams of reflection in one study formed points for investigation for the next study. Schön suggests that observing and re-arranging the materials of a design situation over-time is critical to opening up new solution spaces and envisaging emanant possibilities (Schön, 1984).

2.4 Conclusions

After making the observation in the first chapter that there is a lack of a coherent design methodology for researching the transfer of embodied skills of craft practitioners from the physical into a haptic workspace, I proposed a design methodology that:

- Considers the totality of the user experience as it unfolds during the design process
- Follows the Experiential Design framework which sees design as an experience and

therefore, in addition to user experience, considers the designer's experience of equal importance

- Highlights the holistic nature of a design situation which prompts the designer to consider both design-related and use-related phenomena that occur simultaneously during the design process
- Uses multiple streams of reflection as a method for capturing, understanding and analyzing these different phenomena

I have designed a prototype haptic workspace in collaboration with the group of practitioners I wished to design for, as I considered that a co-design process facilitates the holistic approach to design. Under the Experiential Design framework, the nature of such collaborations is not defined by the designer but is a result of a dialogical relationship between the designer and the users. I propose both direct technological intervention and reflection as methods for enabling this synergy.

The use of technological intervention in the traditional practice serves as the catalyst for revealing aspects of the practice and motivating the users to contribute with insights on their experience with the prototype and ideas on its further development. In addition, it offers the designers the opportunity to practically identify and understand issues surrounding the design of the interface.

Following the experiential design approach, continuous and conscious reflection on my experience throughout the design process has been a powerful tool for validating design decisions and evaluating their results. Drawing on the work by Sengers et al. (2005), Hummels et al. (2009) and Tomico et al. (2009), I propose that applying a dynamic rather than a sequential model of reflection makes designers better aware of the multiple processes of design as they are shaped throughout the design activity. This assists the broader consideration of design processes and provides designers with a creative tool for innovation.

Under the holistic appreciation, the design process is iterative and never ending. It rather reaches many milestones that are defined by the research goals set at each stage. Although a series of design studies was completed for the purposes of my research, this thesis transcribes them and makes them available to future designers and researchers with the aspiration that they will comprise input for further design discourse in this and broader fields.

In the next chapters I will present and discuss the design studies which were carried out following the methodology described in this chapter. At the end of each study I will discuss the insights, reflections, intuitive responses and contextual discussions taken by me and the animators in order to finally draw on conclusions.

Chapter 3

Design Studies

3.1 Introduction

The previous chapters have laid the context of the thesis and have presented the methodology behind my design-led research. This chapter will describe the practical work that I carried out in the form of a series of design studies which drove the development of the haptic workspace. My practical work is strongly based on the quote by Kurt Lewin, 'If you want to truly understand something, try to change it'. Each design study used a prototype design of the haptic workspace as an intervention in the puppet stop-motion animators' work flow.

The aim of each design study was to reflect upon and explore in depth the transfer of different aspects of the puppet stop-motion animators' embodied skills into the haptic workspace. These explorations were carried out from the perspective of embodied cognition and were the result of a fruitful collaboration between myself and a group of puppet stop-motion animators, both students and professionals. The objective of each study was to design a prototype of the haptic workspace in order to investigate a specific aspect. As a result, the haptic workspace was constantly re-configured for each study and at each stage it embodied the design insights, the empirical observations and the outcomes of the multiple streams of reflection that occurred during the experiential co-design process.

I began the studies from a user-centered design perspective, giving the puppet stop-motion animators a prototype of the haptic workspace that was designed based on my understanding of their needs and expectations as formed after our initial discussions. This offered me a first insight into the functional and non-functional parts of my design and helped me to identify fundamental aspects of the practice and address them in the later studies.

Throughout the descriptions of each study, I discuss the issues and opportunities that were brought to the foreground with respect to haptic interface design. In parallel, I draw on the outcomes of the multiple streams of critical reflection, which inspired the formation of the studies that followed. Self-reflection led me to involve digital animators in the process,

a decision which yielded prolific results. I also conducted a study with 2-D animators which can be found in Appendix A. As the studies progressed, multi-streamed reflection assisted in revealing the interdependence of all elements under investigation and the outcomes of each study became interconnected and integrated in the proceeding haptic workspace prototype. This process informed my investigation on the transfer of the puppet stop-motion animators' physical embodied skills into a haptic workspace.

In the following sections, I will try to keep a fine balance between describing the technical development of the haptic workspace, articulating each stream of reflection, and discussing the insights that derived from the reflective processes.

3.2 Initial Encounters

The design studies took place between November 2009 and December 2010 at the animation studio at Edinburgh College of Art. I collaborated with three puppet stop-motion animators from the Animation Department of Edinburgh College of Art. Two of them were fourth year students and the third was working as an animation assistant at the Animation Department in Edinburgh College of Art. Further collaborators included an experienced animation technician and the Head of the Animation Department, a very experienced and renowned stop-motion animator.

At the beginning of the research, I sought to gain a first insight into the technique of puppet stop-motion, what it involves in terms of physical practice and what are the valuable elements for the puppet stop-motion animators. During November 2009, I carried out discussions with the group and also spent a period observing them in their workspace at the department's studios. In the following two sections, I will describe the discussions and studio observations alongside some reflections on these initial encounters.

3.2.1 Contextual Discussion

A ubiquitous quality the puppet stop-motion animators acknowledged in their practice was physical touch, the sense of materials and textures that comprise the puppets and the experience of it through the hands. One animator initiated discussion around the differences between digital and physical animation techniques by commenting on the absence of the physical relationship puppet stop-motion animators have with their hands in digital tools.

People respond very well to texture and actual materials, being able to recognize an object. I think with the digital you can replicate that look but it is never quite the same. It has got these imperfections in it which make it appealing. It has got this charm and magic. In the computer you start with something unnatural and you try to make it look natural

Another animator emphasized the fluidity, flexibility and intuitive control of one's own hands which he has not encountered in a digital workspace.

It is just the unfamiliarity. Some of us have fears of the complexity and the slightly non-intuitive ways of computers. We all have ideas, it is how we translate the ideas via the computer, the interface into something that we intend. It seems more immediate if you start working with your hands, if you can feel how heavy something is or how flexible it may be. That communicates very quickly through your fingers and your hands and you are so consciously making all sorts of adjustments and assessments of things actually working with them. The difficulty I am sure I will find is getting over that initial sort of hurdle where all of those intuitive sensory things are, as far as I know, not so immediate. You are suddenly pressing buttons or you are working on a keyboard, you move the mouse around. The feedback you get back from this is very modernized, it all feels the same unless you do something very important or you do something with no importance at all

The abstractness of the digital workspace, which is reflected in the ways of animating in it, was juxtaposed by many animators with the concrete structures of the physical world. One animator referred particularly to the action-response loop which is triggered by body motion and described the construction of the same loop through digital means as abstract and one existing only in the mind. This comment ties strongly with the embodied cognition approach.

It amazes me how subtly you can move something and it will have an effect. I suppose you can do that in a computer but it is more abstract way of thinking, of doing it with the mouse. There are certain advantages in computer animation as well but you are getting quite frustrated

Another animator added to this comment:

People who work in traditional ways particularly with puppets, they feel they have a relationship with the material world which they are comfortable with. They live in the real world, they observe what happens in the real world, they interface with things in the real world and so on so it feels as a natural thing to do. You have to create the real world

I intervened at this point to say that digital animators also take inspiration from being in and observing the real world to which he responded that, whilst this is true, the way the transition between the traditional and the digital workspace is designed now, is a barrier 'that one [a puppet stop-motion animator] has to overcome in order to work in the digital'.

One point that was regularly raised during the discussion was the need for continuous and complete control over the motion of the articulated character. The animators referred to this in comparison to the numerous automated functions for motion production which exist in digital animation software. By having control over the character's motion, the animators have the freedom to exaggerate movements or slightly twist the model in a way that will render its motion believable. For this reason, algorithmic processes that calculate automatically the position of an articulated character's parts were not of interest to them.

At one interesting point during the discussion around the differences between digital software and manual practice, the group unanimously emphasized that it is not so much the tools that they use to animate the puppets that underpins the essential quality of a successful puppet stop-motion animator, but the ability to tell a good story. The development of the narrative is the driving force behind an animated movie. As long as the movie is one that will fascinate the audiences, the tools used to produce it are of little importance. In addition, they strongly advocated that narrative is created by the expression of ideas and purposes through movement which is the same whether it is made in digital or physical ways. Given these notable comments, I enquired about the challenges that digital tools for animation present nowadays.

The discussion turned towards the characteristic elements of the puppet stop-motion animators' skills. They identified acting and timing as two important elements that all stop-motion animators are trained in. They described themselves as actors who, instead of acting themselves, they instill their acting in the motion of their models. They possess skills in representing the position and posture of the character at each frame, having, at the same time, constant control of how motion unfolds over time.

The design and creation of the armature, the internal skeleton structure that I mentioned in Chapter 1 is of particular importance as it determines how the character will move. The making of the armature involves defining the exact hierarchy of the joints based on how the animator has envisaged the motion patterns of the character. This means that the armature is built after the story has been roughly planned.

Returning to the digital tools for character animation, I made an overview of the advanced digital interfaces that can enrich the interaction between people and computers. Having some experience with digital interfaces mainly in the form of digital software for post-production and software that record, store and playback the camera snapshots, the animators listed some of the advantages that digital technology offers to their practice. The most significant one they identified was the ability to make alterations easily and rapidly. Functions such as *undo* or the possibility of going back in the time line to edit a specific frame, delete it or replace it with another one, eases the control of the frame sequence. It also saves a considerable amount of time for tasks that are considered to be tedious. These are, for example, the tasks involved in changing an undesired frame: the animator has to reset all objects in the physical setting as they were positioned before the take of the specific frame and repeat the process of creating the character's posture and other elements for this frame and for the ones which came after this.

During the discussion, I exposed the animators to the haptic device I was going to employ in the studies through a minimal example. They used the device to manipulate a virtual cube in a physics simulated virtual environment. This was done to make them familiar with the

general functionality of the device and allow them to explore the kinaesthetic, proprioceptive and touch sense it provided. The cube was placed in a virtual room with four walls. Interaction involved grabbing the cube with the haptic device and moving it in the virtual space. The weight of the cube could be felt when grabbed and its surface could be traced using the haptic device. The animators were surprised and fascinated with the simulated sense of touch and the feeling of the cube's weight while they were moving it around the virtual environment with the haptic device. They commented that they 'could see how this could work for stop-motion animation'.

3.2.2 Studio Observation

Alongside the discussion, I spent a period observing the animators in their studio. Each animator was working on a different aspect of the animation making process, which was very useful to my research since I was able to gain insights into the different stages of animation production. Two of them were animating the puppets and the third was working on post production¹.

One of the first things I observed was related to the digital camera they use to capture the image of the scene. One of the two animators working with the puppet had taken the puppet's head off and had placed close to its position the digital camera, zoomed in considerably, in order to approximate the view of the puppet and animate it (Figure 3.1). I kept this idea of positioning the viewpoint to use it later in the designs.

Another observation was made in relation to the workspace. The animators use digital software to capture the image with the digital camera (the camera capture button is connected to the computer and can be pressed from there) and manipulate the frame sequence. The software is installed in a computer close to the workspace, which makes them work interchangeably between the computer display and the scene, capturing and evaluating the frames on the computer and correcting details in the scene. This means that they work creatively in the physical space and technically on the computer. This distinction produces a seamless workspace in which the animators can be detached from the flow of the animating process and the story progression (Figure 3.2).

While observing one animator animating a puppet, I commented on the dislocating space that was formed when, during her work, she continuously changed from making small adjustments to the camera on the scene to operating mouse and keyboard on the computer desk. She brought out a remote keypad with which she could operate the camera from the distance and explained:

Technically, I could press [the camera button] over here which is, when you are

¹For complimentary material to the following descriptions please watch the videos in folder Chapter3/Observations of the DVD



Figure 3.1: The camera close to the puppet's head



Figure 3.2: The puppet stop-motion animator's workspace

walking forwards and backwards, an advantage to have it when you are animating. But I just find it easier to do it on the computer. It has all the controls and you can click between frames and playback

Her answer indicates that she would prefer to work in a more seamless workspace focusing on the scene instead of having to move constantly away from it. She could capture with the remote the frame and view it on the computer screen without moving from the physical setting. However, the small details as well as the progression of the motion over the frames which requires playback are still essential processes and can only be done on the computer.

One of the animators made an interesting observation about the function of playing back the frames. He mentioned that prior to animating, a usual task is to set the frames per second (FPS), the number of frames which will be displayed in the period of one second. The two most commonly used FPS rates for animation are 12 and 24 FPS. These speeds have been considered to be optimum for the eye's perception of smooth movement. Related to the FPS is also the method of shooting frames. *Single frame* shooting of frames means that each frame displays a different character pose while *double frame* shooting means that the pose does not change for two consecutive frames. Shooting on double frames produces the effect of slow motion. The manner of shooting frames depends on the animator's aspirations. Shaw (2008) notes that single frame produces a fluid movement for the 24 FPS rate, appropriate for hand gesture or flag waving (Shaw, 2008, p.22). This discussion sparked some ideas about implementing this in the haptic workspace with the ability to switch between single and double shots and choose different FPS. The aim would be to observe how the animators will make use of it and whether it would add to their existing knowledge of timing in relation to movement.

The animator working on post production explained the process that takes place after the puppets' design and capturing of motion has been completed. The captured frames are exported as a movie file. The backgrounds and visual effects are added in commercial software applications such as AdobeTM After Effects.

Finally, he emphasized the important contribution of sound to the final aesthetic result. Sound in animated movies is composed in collaboration with sound designers. This is a regular process in the animation film industry and in large productions this process is reversed. It is a common practice to have the script first read by an actor and then proceed to the animation of the characters based on the accentuation, flavour and mannerism of the recorded speech.

3.3 Intervention 1 : Workspace intervention

Having noted down and reflected upon the observations presented in the previous section, I set up a first prototype of the haptic workspace following my vision of how it would be and asked the animators to explore it. This first prototype, which I called a *workspace intervention*,

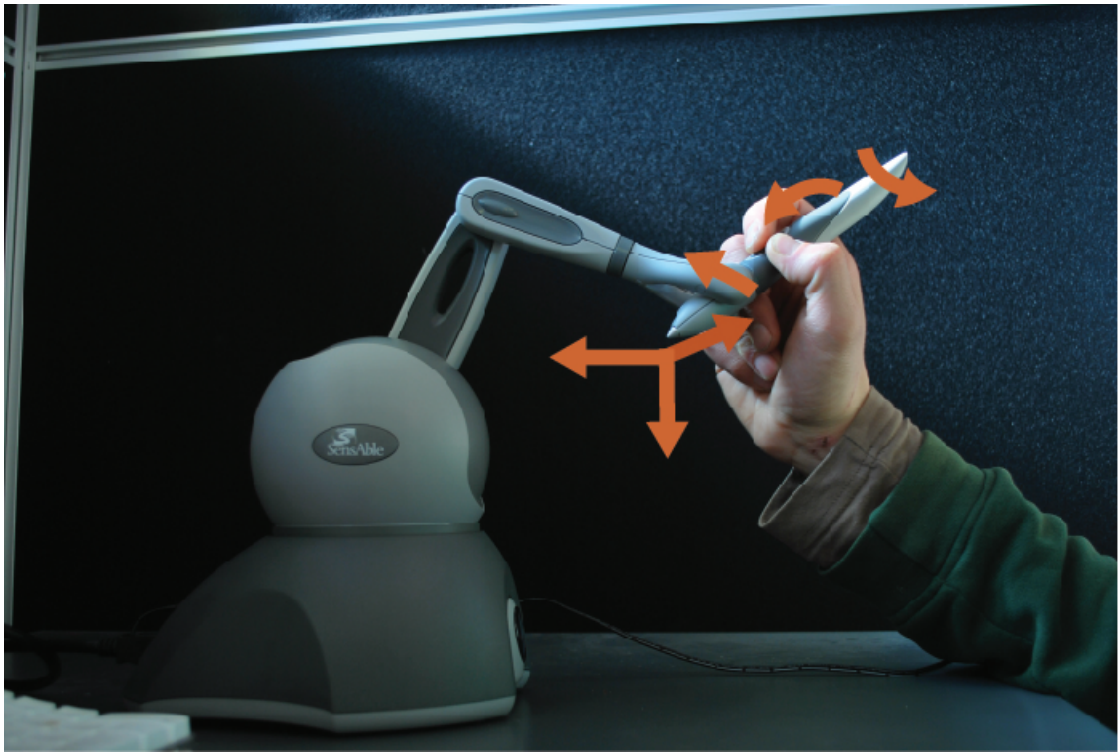


Figure 3.3: The Omni haptic device

provided a basis for the co-design process. I aimed to use this first prototype as a means to identify qualitatively issues related to use early in the development process. In this way, I would have a clear understanding of both the functional and the non-functional aspects of the designed prototype but also a first impression of the animators' requirements. Their responses assisted me in isolating elements that the proceeding design studies could investigate.

The importance of enabling the haptic sense was reflected in the choice of using a haptic device as the main gestural enactive interface for accessing the virtual environment. I employed a stylus-based haptic device, the SensableTM Omni, a haptic device with a robotic arm as an extension at the end of which sits a stylus-like manipulandum.

The device has six Degrees of Freedom (DoF) as it can move and rotate in three directions (Figure 3.3). The Omni device operates with point interaction which means that its user senses objects in the virtual environment through a single point contact. I designed the representation of the device in the virtual environment to be a solid sphere. The sphere is a common model to use as it is successfully perceived as a representational element of the single point contact with the virtual environment. The point that controls the device's representation in the virtual environment is the tip of the pen. The motion of the models which represent the stylus on screen, like the sphere, provide the sense of depth. The models are scaled up when the stylus is moved towards the user and scaled down when it moves away from her. When the sphere collides with virtual geometry, motors placed in the base of the haptic device create

force feedback which is felt at the pen's tip and consequently in the hand that operates it. The force feedback simulates frictional forces such as those created when one traces the outline of a surface with one's fingers. The simulated tactile sense depends on the material properties that have been set. For example, moving the sphere on a smooth surface produces low frictional force making the sphere's motion easy whereas in a bumpy surface there is generally more difficulty in motion. Haptic information for the virtual characters' surface was not implemented in this prototype and the sphere penetrated the model's geometry. Finally, on the stylus there are two buttons. During the studies, each one was assigned various tasks but their main utility was to grab virtual objects.

In order to improve the animators' kinaesthetic sense, I scaled the motion of the haptic device. The coordinates of the stylus tip were mapped to the motion of the virtual sphere and scaled so that the limits of the tip's range of motion in the two dimensional plane vertical to the animator's optical axis were equal to the boundaries of the computer display. This meant that if the animator moved the stylus at the end right point in physical space, the sphere would move to the right edge of the computer display. This spatial coordination between the motion range of the stylus, sensed physically within its maximum points, and the motion of its representation, sensed visually within the physical borders of the display, was done to improve the animators' kinaesthetic sense while they used the device.

Drawing on the fact that currently puppet stop-motion animators work in two different spaces, the scene and the computer screen, I aimed at merging them in the haptic workspace and design the enactive interface appropriately so that the physical aspect is represented in the new workspace. The haptic workspace was a screen-based virtual environment. As it happens with $2^{1/2}$ - D virtual spaces, the information about the position and orientation of all objects in a screen was stored in 3-D coordinates in the computer and was then projected into the 2-D screen using a mathematical transformation called perspective projection. As a direct analogue of puppet stop-motion animation, it was decided to present pre-modeled articulated characters which could be directly manipulated enactively using the haptic device (Figure 3.4).

The characters had a *skeleton* attached to them, an invisible hierarchical chain of bones and joints, which played the role of the armature. The skeleton was given dynamic properties through kinematics algorithms. There was the choice of two algorithmic processes, Forward Kinematics (FK) and its inverse, Inverse Kinematics (IK). Both algorithms are used to indicate the motion of the virtual character when it is being manipulated and the FK offers more control than the IK. The FK algorithm accepts rotation of joints as input and produces translation of the bones that follow the joint including extremities like hands. For example, if the elbow is rotated in any direction, the forearm, wrist joint and hand will move accordingly. In contrast to FK, IK takes translation of the extremities as input and outputs joint angles to

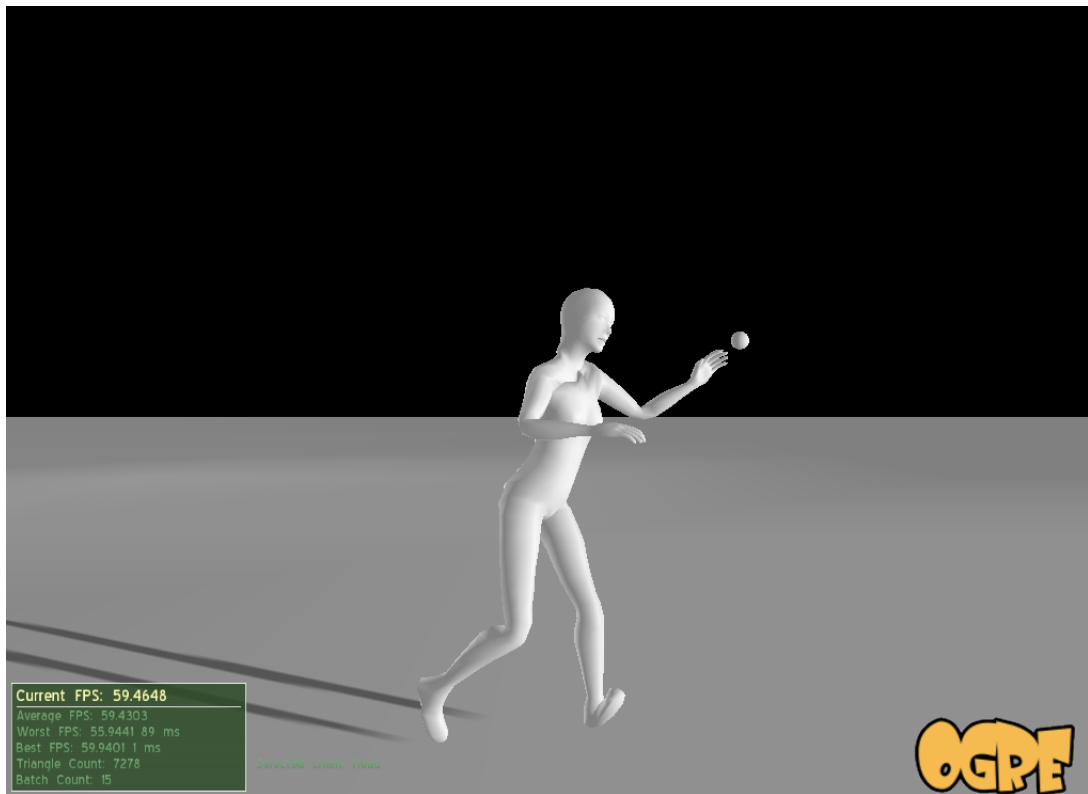


Figure 3.4: The character in the virtual environment

specify the position of the corresponding bones. Figure 3.5 shows a sample motion using IK. The animator has grabbed and moved the hand. Throughout the studies, depending on the algorithm used at each time, the animators could grab with the stylus and rotate a joint or move an end-bone. In the introduction of each study, I refer to the algorithm which was used and the reasons behind its use.

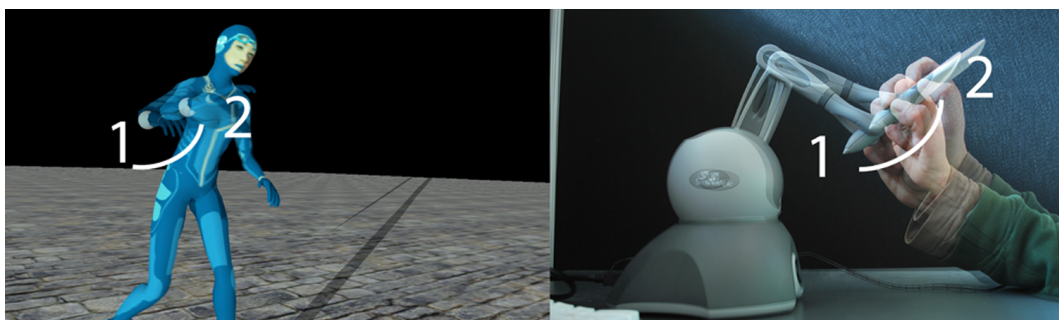


Figure 3.5: Depiction of IK algorithm grabbing the character from the forearm

For this first prototype, I used the IK algorithm as I thought it to be closer than the FK to the way the animators manipulate the puppets. The animators could simply drag an end-bone, such as the hand, and the rest of the skeleton would follow automatically. I implemented one

of the optimal IK solvers that exist in the literature. The skeleton was divided into five bone chains, two starting from the hips and ending at the left and right toes respectively, two chains for each one of the arms and one chain which started from the hips and ended at the head. Each chain had one *parent joint*, the joint to which the first bone of the chain was connected (e.g. the shoulder for the shoulder-elbow-wrist chain). All chains were linked to one joint, called the *root joint*, which in this case was the hips. Each chain could be selected for manipulation by pressing numeric keys on the keyboard. Once it was selected, the animator could grab it by placing the sphere, the device's representation, close to the end bone of the chain and pressing the first button on the stylus. This locked the sphere inside the bone. By keeping the button pressed and moving the stylus, the animator could move the bone.

At no point were physics applied in the virtual environment so the implementation of the kinematics algorithms did not take mass and forces into consideration. However, the forces reactive to those performed on the characters with the haptic device were calculated in order to be sensed in an enactive way while the animators manipulated the characters. When the animator grabbed and moved a bone or the whole character, a reactive force and the corresponding torque were felt at the animator's hand. Their magnitude depended on the force the animator exerted. Torque was calculated for all three rotational axes of the stylus. The reactive force was computed using Hooke's Law $F = -kx$, where k is the stiffness of the selected object and x is the distance between the center of the object and the sphere's position.

All character models which were used throughout the studies were created by me in the AutodeskTM Maya digital modeling application software except for two which were used under the Creative Commons license. The characters were then exported in a format that could be read by the software part of the haptic interface. In all studies the articulated characters had rigid bodies. The virtual geometry of rigid bodies is computed to be solid and cannot be deformed by applying forces on it.

I provided the animators with a list of different characters and background items. I modeled and imported six different characters and three different backgrounds which were accessed through two drop-down menus. The characters were not necessarily humanoids. Some of them were pets and insects while other kinds of characters included a robot, an artist's doll and an ogre.

The backgrounds were a grass field, a cave and a marble-textured surface. Apart from being able to choose from a variety of characters and background geometry, the animators could change the background sky colour which allowed them to create different styles of ambiance. Figures 3.6 and 3.7 show two different backgrounds, models and sky colours.

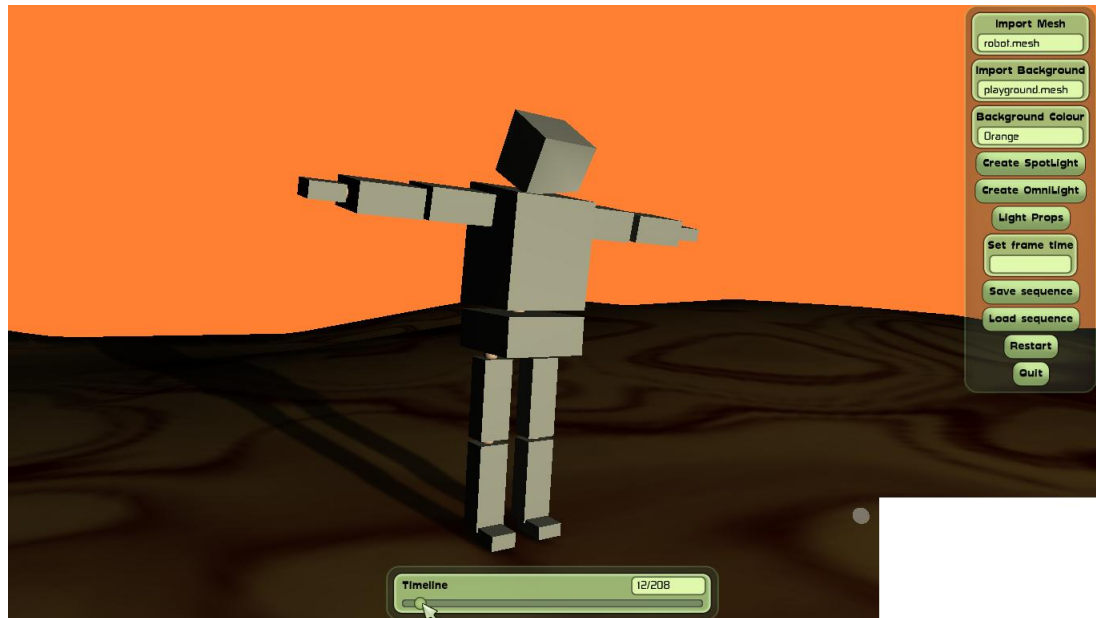


Figure 3.6: Robot on a marble-textured surface, orange sky colour



Figure 3.7: Ogre on a rocky cave surface, purple sky colour. The model is used under the Creative Commons License

The ability to make alterations on the timeline easily and also to import quickly new models led me to develop a GUI interface with the intention to make it as simple and as effective as possible. The GUI was accessed with the mouse and provided the basic tools for setting up the scene, making adjustments and running the application ². I developed, as part of the software, an animation making tool which used keyboard buttons for storing a pose, advance and retrace the stored poses and playing them back in sequence. Each stored pose was counted as one frame and the action of storing moved the pointer of the visual slider one unit forward.



Figure 3.8: Timeline at the bottom of the screen. The model is used under the Creative Commons License

The time line, a visual representation of the stored frames, was a slider placed on the bottom of the display (Figure 3.8). By moving the pointer of the slider the animators could navigate the captured frames. In each frame, the characters and objects in the virtual environment took the corresponding poses defined by the animators at the time of capture. Two buttons were used for saving and loading the sequence of images. I provided the animators with the choice to select different FPS for their animations through a drop-down list which provided the options of 8, 12, 24 and 25 FPS. This function took all the frames and disseminated them per second accordingly so that the animation was played back in different speeds. Finally, one button restarted the application by deleting all models, backgrounds and lights as well as any camera transformations and one button was used to quit the application. This initial GUI was reshaped during the design studies and involved functions which were essential to the puppet stop-motion animators and were deemed as useful to have visually

²An example of the GUI is presented in the video entitled 'GUI' in folder 'Chapter3' of the DVD

represented or impossible to design in in any other way, for example the menu list of the virtual characters.

The final element of the haptic workspace, the camera that looks at the virtual scene and plays the role of the animators' viewpoint, could be translated in all directions with the corresponding keyboard arrow buttons. Another two keyboard buttons were used for moving it upwards and downwards but none for rotating it.

The prototype was presented to the animators and they had the opportunity to explore it with no time restrictions and without a specific brief.

3.3.1 Responses

The animators were particularly impressed by the feel of force-feedback that the device recreated by applying reactive forces when a bone was moving. The device was also regarded as delicate and precise enough to perform subtle actions that deform the character, e.g for facial animation. They commented that it enhanced the interaction with the characters in the virtual environment. They found they missed the tactile sense when the sphere traced the surface of the model.



Figure 3.9: One of the animators working with the first prototype

One animator recalled the feeling of touching the cube during the first meeting I had with them and said:

I think that it [surface touch] will be, you know, in terms of control, quite useful to have something like that because when you are actually grabbing a certain part of the body it is kind of a main help

The ability to touch the character's body was not programmed in this first prototype since it was not the main focus of the study. It will be implemented in Section 3.6.

The animators had difficulty in understanding where the sphere was in relation to the character's bone structure when they wanted to approach and move a bone. To overcome this issue, they suggested that visual cues would greatly help their understanding of the character's dimensions. For example, they thought of visual indications to mark the selected bone such as highlighting the bone or placing a rectangular prism around it. Another useful visual cue for them was the angle that the joint is rotated at, displayed in real time over the joint. They drew on professional digital animation applications that use these functionalities:

Something else that might be useful is for the model to have some kind of visual markers on it. I know in Maya they have these circles on the limbs which are divided up so that you can see how far the angle of the limb has gone and in which direction

In terms of manipulating the virtual character, kinematic controllers are extensively used by digital animators but puppet stop-motion animators have no experience of using them. Thus, designing them in the workspace in a way that supports enaction was one of the key design points. I thought that the IK algorithm would provide more control in the way the skeleton was manipulated. The animators suggested otherwise. They had difficulties in manipulating the different chains as IK computed motion that was unwanted. One animator commented:

My main comment is on the subtlety of the way you control the puppet because as soon as you press down on it, it moves quite quickly and in animation you need refined movement

Furthermore, it was not clear to them how they could bend parts of the character. This was not easily done with precision with the IK algorithm. One characteristic example they gave summarizes the issue:

You might as well select the knee as well as the whole leg. You might want to create for example a walk cycle or an uncompleted movement (at this point he stands up and performs the motion)

They also indicated that although the IK is closer to how they would move the different parts of a physical puppet, it does not isolate movement of each part:

For example when I move the hand it would be good to be able to control it so that the body does not move as well. It is better to control first the hand and then the body

Isolating motion of each part is what gives complete control over the manipulation. When moving parts of the physical puppet's armature in the physical workspace, one hand moves the bone while the other hand holds the joint so that no other part than the one(s) selected is moved. An algorithm that gives such level of control is FK.

A question they asked was whether there can be the opportunity to move around lights. This, they emphasized, would be very useful since, in their work, it is quite a difficult task to move the lights around. For this reason it is common practice to decide the lightning well in advance without leaving much space for experimentation. Most of the time, they said, the lights remain fixed and if any special lightning is needed, it is usually done in post-production by adding special effects. The post-production process is done exclusively in digital software.

Finally, they brought up the need for a larger number of viewpoints so that the part of interest can be seen from different angles in order to gain a better view of its position in relation to the other parts and adjust its motion. Of particular interest was also the use of multiple angles to determine the sphere's position in relation to the character. One animator said:

I suppose the only thing that helps me identify where the sphere in relation to the puppet is the viewpoint. So I suppose you can have two of these so that you can have a view from another angle

He essentially suggested having two different renderings of the virtual environment from different angles placed side by side on the display, a rather linear way of identifying position which is often used in digital animation software.

3.3.2 Reflections and Insights

The animators' suggestion for visual cues indicates a close and complimentary connection between visual and haptic perception. One inconsistency between the haptic and the visual rendering that was revealed enforced this insight. The reactive force that was applied at the animator's hand produced the feeling that it should cause the sphere to move with the corresponding difficulty, thus, slowing down its motion. However, this was not reflected visually. I had not taken into account the reactive forces in the visual rendering of the sphere and as a result the sphere was moving visually a greater distance than the one that was felt kinaesthetically. This was one of the first things observed by the animators and it was a first indication that the coupling between visual and kinaesthetic cues is important to the perception of the virtual environment.

The need for visual cues derived initially from their difficulty to understand where the sphere was in relation to the character's bone structure which indicated an issue with the perception of the virtual environment. I considered space perception fundamental to the ani-

mating experience in the haptic workspace. Therefore, I began the design studies investigating space perception and navigation (see Section 3.4)

Drawing on the synergy between the gestures performed and the kinematics of the character, the motion of the end-effector bone was very rapid with regards to how the animators moved the sphere. This caused inconsistencies between the gesture they performed and its result. The animators often asked how they could twist parts of the character indicating that this was not an easy task to do with the IK solver as it was implemented. Twisting implies rotation of the joints and this is something that the IK algorithm did not compute with precision and also did not compute without affecting the position of nearby parts to the one that was being moved. This led me to experiment with the kinematics algorithms in the next studies, testing the FK algorithm first.

With regards to using the FK algorithm, its design must be in accordance with the direct manipulation in three dimensions that the haptic device provides. Since the mapping between the animators' gestures and the motion of the sphere is mimetic, meaning that the gesture is mapped exactly as performed to the motion of the sphere, the way that animators work physically is closer to IK. However, my implementation proved to have several design faults. The use of FK results in a different manipulation metaphor and proved a design challenge. I explore this further in Section 3.5. This and the study on space perception and navigation (see Section 3.4) inform each other.

One observation in relation to the kinematics and the perception of the virtual space was about the physical structure of the haptic device and the gestures it afforded. I observed that one of the animators was holding the stylus like a mechanical lever. This led me to re-negotiate the potential designs of the device's physical attributes for interaction in the virtual environment. Different haptic devices have specific properties that afford specific uses. Gibson (1979) introduced the concept of *affordance* to define the potential for action and use offered by the physical environment to an agent acting within the environment. The concept of affordance was appropriated in HCI by one of Gibson's students, Don Norman. Norman (2002) defined affordances as 'the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used³. Different

³Norman and others who have developed their own theories based on Gibsonian thought have been criticized for having misinterpreted Gibson's original approach to perception (e.g.(O'Neill, 2008)). Svan (2007) refers to Norman's explanation in an online mailing list:

J.J. Gibson invented the term affordances, although he does not use them for the same purpose I do. I got the idea from him, both in his published writings and in many hours of debates with him. We disagreed fundamentally about the nature of the mind, but those were very fruitful, insightful disagreements. I am very much indebted to Gibson. Note that in *The Design of everyday Things*, the word *affordance* should really be replaced (if only in your mind) with the phrase *perceived affordance*. Make that change and I am consistent with Gibson

affordances on the device present different opportunities for the design of the relationship between the animator's gesture, the navigation of the virtual space and the output motion of the virtual character. Therefore, I began an investigation of how the animators enactively experience navigation, selection and manipulation using two haptic devices with different ergonomic designs and different DoF input.

Lighting is a part of the animation process which seems to benefit most from digital tools. The digital software used for digital character animation offer a range of possibilities for setting up and animating lights. Of course, these lights are virtual and the light that they emit, its colour and behaviour, such as its reflective properties, as well as its interaction with other virtual surfaces, such as virtual textures, is determined by functions within the software. Lighting in virtual environments is graphical rendering and its development follows advances in CG. The animators brought to my attention the fact that in the digital animation industry there are specialized professionals who work explicitly with the lighting conditions of the scenes and they are able to work expertly in the relevant digital software. The importance of lighting in puppet stop-motion indicated a fruitful field for exploring further the opportunities and challenges of manipulating virtual lights. The study on lights can be found in Section 3.7.

The animators' reflection of the intervention in terms of their working methods was positive. They were very keen on providing all sorts of feedback and also discussing the prospect of working with similar interfaces in the future. A key point in this and a vital part of the collaboration was the fact that they were not particularly defensive of their practice. They were quite critical towards the functionality issues they found during this first encounter, but they were also capable of reflecting on the haptic workspace with the prospect of working on it in the future. They acknowledged the fact that the haptic workspace provided much richer interaction than conventional WIMP interfaces and that, once it were a smooth tool to work with, they 'would not see any reason for not using such a tool for stop-motion animation'.

Reflecting on the difficulties the animators encountered with the first prototype, the most distinct outcome of the study was the identification of their perception of the virtual environment. As perception is fundamental to their experience of the virtual space, I resolved that it was necessary to investigate this first. In Section 1.3, I mentioned that virtual environments can be experienced through navigation, object selection and object manipulation. These aspects are explored in all the design studies but the first two studies focus particularly on them. For the first study of the two, on space perception and navigation (see Section 3.4), I improved the IK algorithm making it more accurate but did not implement the FK. I did this in the second study (see Section 3.5), which is designed to investigate object selection and manipulation, exploring kinematics in-depth.

3.4 Intervention 2 : Space perception and navigation

This study aimed at triggering reflection on the navigation of the animators in the virtual environment in order to reveal issues and design challenges. In order to explore navigation of the virtual environment, this study has focused on the animators' perception of the virtual environment as a 2-D projection of a 3-D space on the computer screen. When a 3-D environment is projected onto a 2-D display, a pseudo 3-D space is created. Since vision is so dominant in the design of virtual environments, the object that exists in the pseudo 3-D space must illustrate the sense of depth for the viewer.

In order to provide this sense of depth, I modeled and imported a 3-D model of a cave into the virtual scene (shown in Figures 3.10 and 3.11). I created two different virtual models for this study with skeletons of different complexity. The first one represented an arm modeled with three cylinders connected between them with spherical joints (Figure 3.10). The second model was a mannequin, created based on the off-the-shelf artist dolls to assist basic human character sketching which can be found in art stores (Figure 3.11).



Figure 3.10: The robotic arm

In this study I sought to cross check the need for visual aids for space perception, such as markers or bone highlighting, when haptic cues are available. Because vision is the



Figure 3.11: The model of an artist's doll

predominant sense in the experience of virtual environments, I questioned the need to allow vision to become a necessity in the design of an enactive interface. The visual cues which were suggested as an aid for space perception during the first intervention study were not implemented. This was a conscious design decision as I aimed to enable the animators to focus only on the haptic sense for exploring the virtual environment. I kept this part of the research open to further input.

3.4.1 Navigation metaphors

Navigation metaphors in 2-D digital applications, such as Internet browsers, are developed under the desktop metaphor and 'are often restricted to scroll bars or the well known hand-cursor that grabs the canvas to move it around' (De Boeck J. et al., 2005, p.262). A virtual 3-D space requires 6DoF spatial gesture for its navigation. In general, a virtual environment can be viewed from a first person viewpoint or from a third person view through an avatar, a 3-D character representing the user. I did not take into account navigation metaphors that involve an avatar since my aim was direct interaction with the characters in the haptic workspace. Instead, I have used the metaphor of a first person viewpoint which I named the *animator's eyes*. The animators look at the scene from a first person perspective and

control the viewpoint by moving the virtual camera with the 3-D mouse. Various theoretical and practical studies have informed research on navigating the camera viewpoint in a virtual environment. Mackinlay et al. (1990) identified four types of viewpoint motion for virtual environments:

- General movement. Exploratory movement, such as walking through a simulation of an architectural design.
- Targeted movement. Movement with respect to a specific target, such as moving in to examine a detail of an engineering model.
- Specified coordinate movement. Movement to a precise position and orientation, such as to a specific viewing position relative to a molecule or a CAD solid model.
- Specified trajectory movement. Movement along a position and orientation trajectory, such as a cinematographic camera movement.

The animator's eyes metaphor that I implemented, is based on the first type of motion, the general movement. This type includes the *flying-vehicle* and *eyeball-in-hand* metaphors as introduced by Ware and Osborne (1990), which both allow the user to directly move the viewpoint through the virtual environment. The *scene-in-hand* metaphor, also proposed by Ware and Osborne (1990), translates and rotates the whole virtual environment instead of the viewpoint. Ware and Osborne (1990) carried out a qualitative evaluation which showed that this metaphor is not particularly intuitive for navigating large and complex scenes but can be useful for discrete object manipulation. Design-wise, this technique presents various limitations and conflicts with the haptic rendering. Haptic rendering runs in parallel with the graphics rendering. Updating both renderings, requires a lot of processing power which, especially in slow processors, can make the system unusable.

Turner et al. (1991), whose research is in physically-based animation, proposed an interactive camera navigation based on physical modeling of the virtual camera according to Newtonian laws. The dynamic behaviour of the virtual camera is generated using phenomena encountered in the physical world like frictional forces, inertia, damping factors and spring constants. This presupposes that the virtual environment is physics-based.

There are also indirect ways of moving the viewpoint. In the taxonomy of the different navigation metaphors in virtual environments that De Boeck J. et al. (2005) provided, they described as indirect Camera Control Metaphor the teleportation metaphor where the camera instantly brings the user to a specific place in the virtual environment. Citing Bowman and Hodges (1997), De Boeck J. et al. (2005) suggested that indirect metaphors have generally been deemed disorienting for the users. The results presented by Bowman and Hodges (1997) have explanatory potential for way-finding navigation tasks. However, for object manipulation,

indirect metaphors play an integral role in facilitating manipulation of the object of interest within its local context (I discuss object manipulation metaphors in Section 3.5 and 3.7). Issues with the control of the viewpoint motion include the control of velocity and acceleration as well as constraining motion to a specific path. These issues will be extensively discussed further in this and the following design studies in relation to the device that was used for camera navigation.

The design of the control metaphor of the viewpoint's motion is a challenging task that needs to be addressed in the specific context that we seek to design in. Two things are connected to it, the properties and affordances of the input device that controls the camera and the context for which the control metaphor is designed. The affordances of the input devices are combined with the actions that the users perform in the virtual environment. In addition, the structure of the virtual environment is catalytic to the way the viewpoint will be controlled. For example, Ware and Osborne (1990) conducted qualitative evaluation of each of the three metaphors, flying-vehicle, eyeball-in-hand and scene-in-hand, in three different virtual environments, a cube, a maze and a space with three objects resembling road signs placed on a regular grid. The task was to navigate the viewpoint in each environment using the three different metaphors. The results showed that each metaphor caused different cognitive responses in the users depending on the virtual environment's structure. This suggests that 'when designing interactions around a spatial metaphor, considerable attention should be tied to cognitive conflicts which may result' (Ware and Osborne, 1990, p.181). In the context of digital systems, cognitive conflicts are discrepancies between the users' understanding of what the results of their digitally-mediated actions should be and the actual results produced by the digital system. This conclusion pertains to the embodied cognition approach and in this study I sought to reflect on whether the navigation metaphor that I designed engaged the animators transparently or caused cognitive conflicts.



Figure 3.12: ConnexionTM's Space Navigator

For the camera navigation, I added the ConnexionTM's Space Navigator 3-D mouse as an enhanced mouse interface that provided 6DoF control (Figure 3.12). With the Space Navigator the animator is able to zoom, pan up and down, pan left and right, tilt, spin and roll the

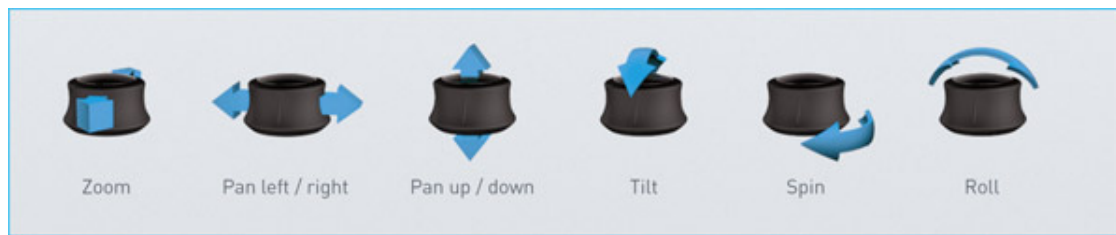


Figure 3.13: Motion of the Space Navigator 3-D mouse

camera (Figure 3.13). The camera could be moved in all six directions with both the 3-D mouse and the keyboard but rotation around three axes (spin, tilt, roll) was possible only with the 3-D mouse. All these settings comprised the navigation metaphor for the virtual camera.

The assignment of the camera control to the other hand than the one operating the haptic device was a result of observing the animators working during the initial encounters with them. Bi-manual⁴ actions are extremely significant in their work since the two hands work in synergy to reconfigure the position and orientation of the objects of the workspace, occasionally with the help of additional tools. The assignment of the camera control in his particular study followed the kinematic chain dictum, proposed by Guiard (1987). Guiard (1987) observed that most of the tasks we carry out with our hands are asymmetrical, meaning that each hand carries out a different part of the same task, and he proposed a theoretical framework to study this asymmetry. His kinematic chain model suggests that bi-manual activities are subject to the following three principles and I present them here using the *dominant* and *non-dominant* hand terminology. The dominant hand is the hand which is, or feels, more efficient in performing fine motor tasks.

- The non-dominant hand sets the spatial reference framework for the actions of the dominant hand.
- Motion follows a path from the non-dominant to the dominant hand.
- The two hands carry out different actions. The dominant hand's movement is quicker and more precise (micrometric) than that of the non-dominant hand's which are coarser (macrometric)

Asymmetrical actions are encountered not only in puppet stop-motion but also in traditional animation techniques. For instance, in hand-drawing animations the animator uses one hand to hold the paper while the other hand moves the pen. In addition, in digital character animation the mouse is the main controller that manipulates the virtual model while the non-dominant hand uses the keyboard in combination with the mouse for tasks such as opening selection menus. Furthermore, bi-manual interaction has been proven to assist orientation

⁴Using or requiring the use of both hands

in a virtual environment. In their survey of design issues in 3-D spatial input, Pausch (1994) conducted informal user observations of a virtual reality interface and noted that users of two-handed interaction are less likely to become disoriented versus users who interact with only one hand.

I assigned the camera to the non-dominant hand because I sought to design camera motion to act as a reference framework for the action of manipulating the character with the haptic device. Figure 3.14 shows the setup of the haptic workspace.

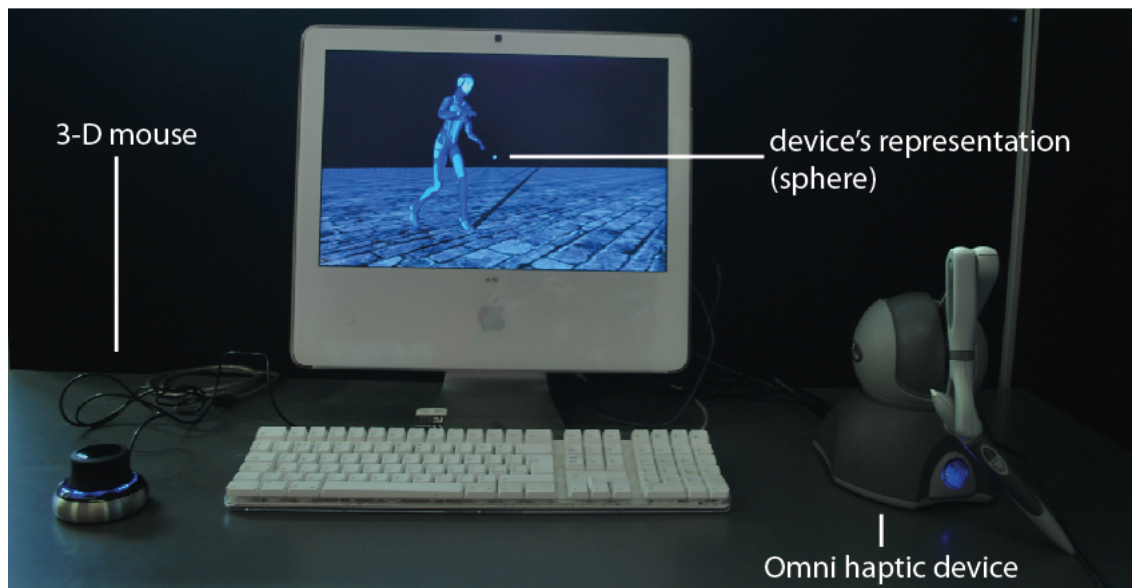


Figure 3.14: First prototype of the haptic workspace

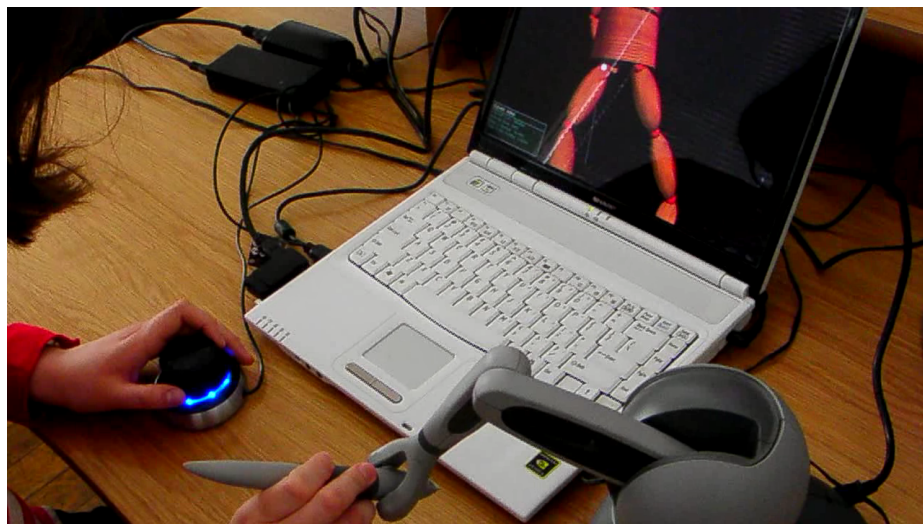


Figure 3.15: One of the animators working in the haptic workspace using the Omni haptic device

3.4.2 Reflections and Insights

In order to carry out the study, I organized a one day design session during which I presented the prototype to the animators explaining my aim to explore the navigation of the virtual environment. As in all the following studies, there were no time limitations and they were encouraged to explore the virtual environment at their own leisure.

Scale

To start with their reflection on the haptic workspace, several interconnected issues concerning the notion of scale proved to be disruptive to the navigation of the virtual environment. The first and most important observation from which the rest of these issues derived, was that the manipulandum's visual representation, the sphere, was not attached to the camera's viewpoint. Consequently, the viewpoint moved independently from the sphere. According to this configuration, if the camera would turn 180° and look towards the opposite direction, the sphere would not be visible because it would be behind the camera (Figure 3.16).

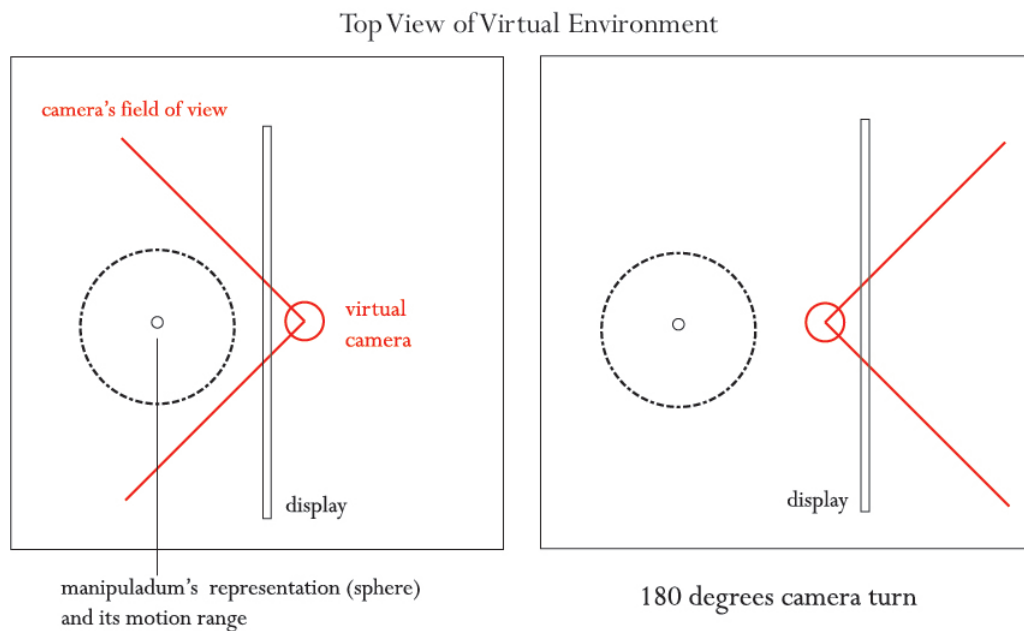


Figure 3.16: The sphere disappears from the virtual camera view when the camera turns 180°

One of the animators asked a question which was valuable in spotting another inconsistency related to the independence between the camera and the sphere. As the default position of the camera looks at the characters' front, he enquired whether he could go around the character with the camera. When he did so, the camera was positioned behind the character and looked at it. The camera's orientation was now the opposite in relation to the initial one. The sphere was visible because, apart from turning the camera by 180° , he also moved it beyond the virtual character. When he grabbed the character with the sphere to move it

along the axis parallel to the display, the sphere, and consequently the character, moved in the opposite direction than the dictated motion by the manipulandum. This was caused because the direction of motion of the sphere was calculated based on the camera's initial orientation and, in this case, the camera's orientation in relation to the sphere's, which remained the same, was reversed (Figure 3.17). The issue was relevant for all axes depending on which axis of the camera's orientation was changed. This issue was not noticed during the workspace intervention because the animators would only translate the camera with the keyboard and they changed the viewpoint's orientation for the first time when they operated the 3-D mouse.

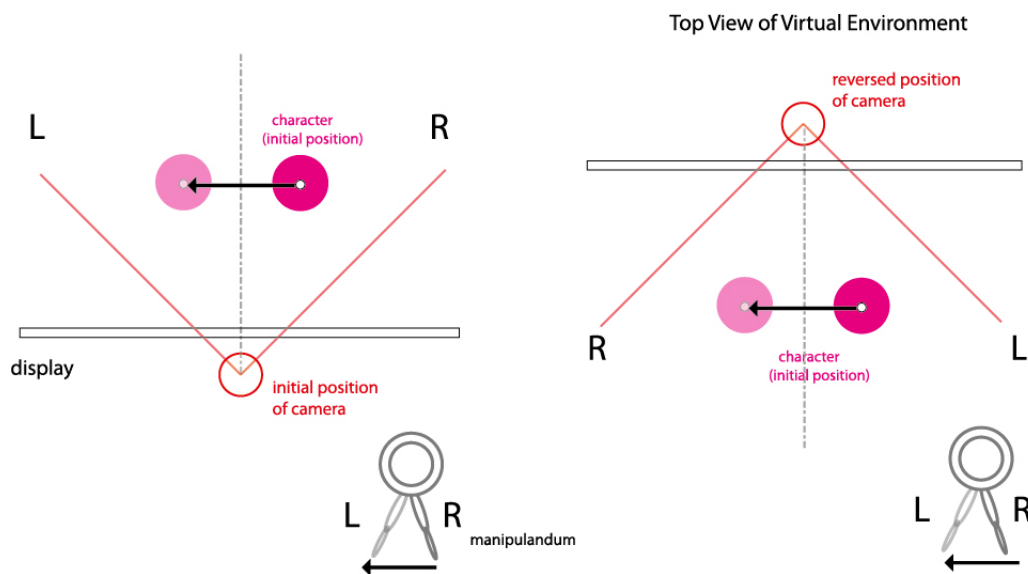


Figure 3.17: Orientation when the camera is reversed

This was a major embodiment issue as it pointed to the importance of aligning egocentric representation with bodily action in the virtual environment. Egocentric representation considers a first person frame of reference and calculates all transformations⁵ in the virtual environment relative to the user's position and orientation. From an interface design perspective, this issue indicated that it is important to ensure the correctness of all transformations in relation to the physical gestures in the design of direct manipulation in virtual environments. The significance of coordinating the transformations between the sphere and the camera led me to connect them so that the sphere, and its area of motion, is at all times in front of the camera.

I placed the sphere at a small distance from the camera and corresponded the sphere's initial position on the optical axis of the animator to be the middle point in the device's physical workspace (the one that has equal distances from the maximum range limits in all

⁵In computer graphics, translations and rotations together are called transformations

three axes. This is regarded as the point (0,0,0) for the manipulandum). I ensured that the sphere followed the camera's transformations (Figures 3.18 and 3.19).

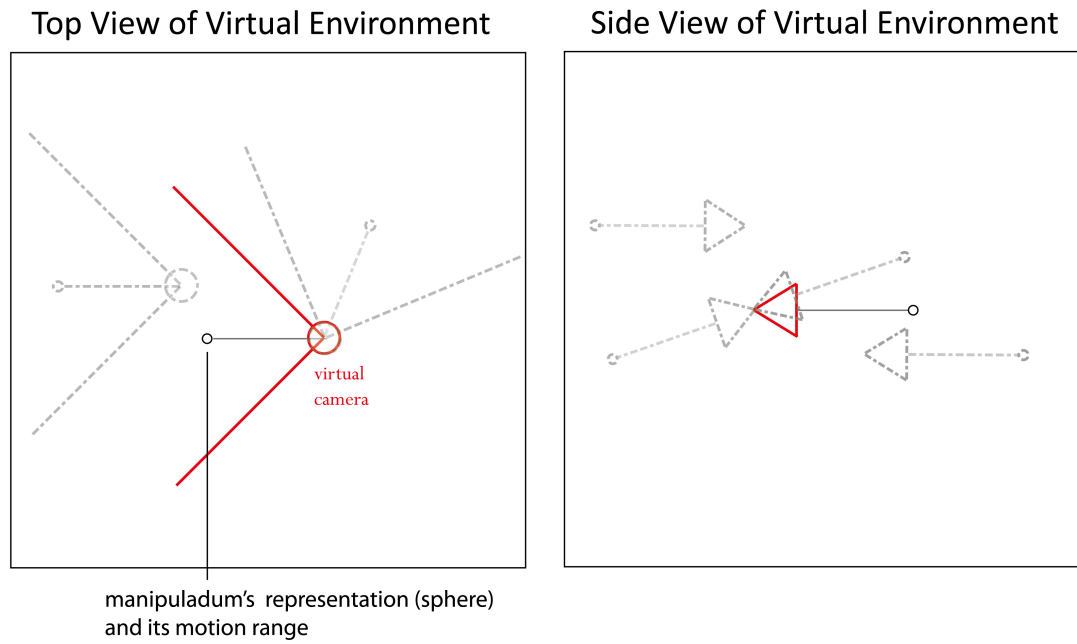


Figure 3.18: Sphere following the camera in all directions

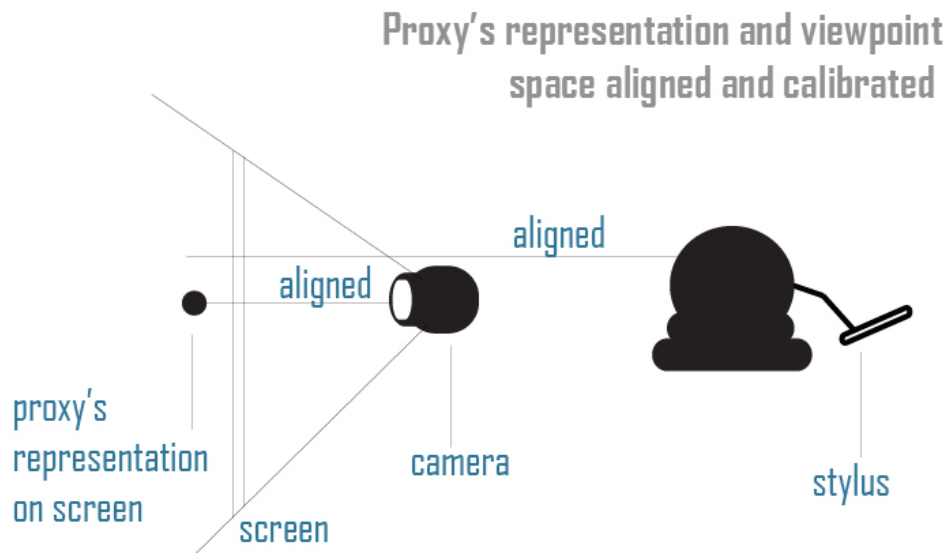


Figure 3.19: Sphere following the camera in all directions - side view

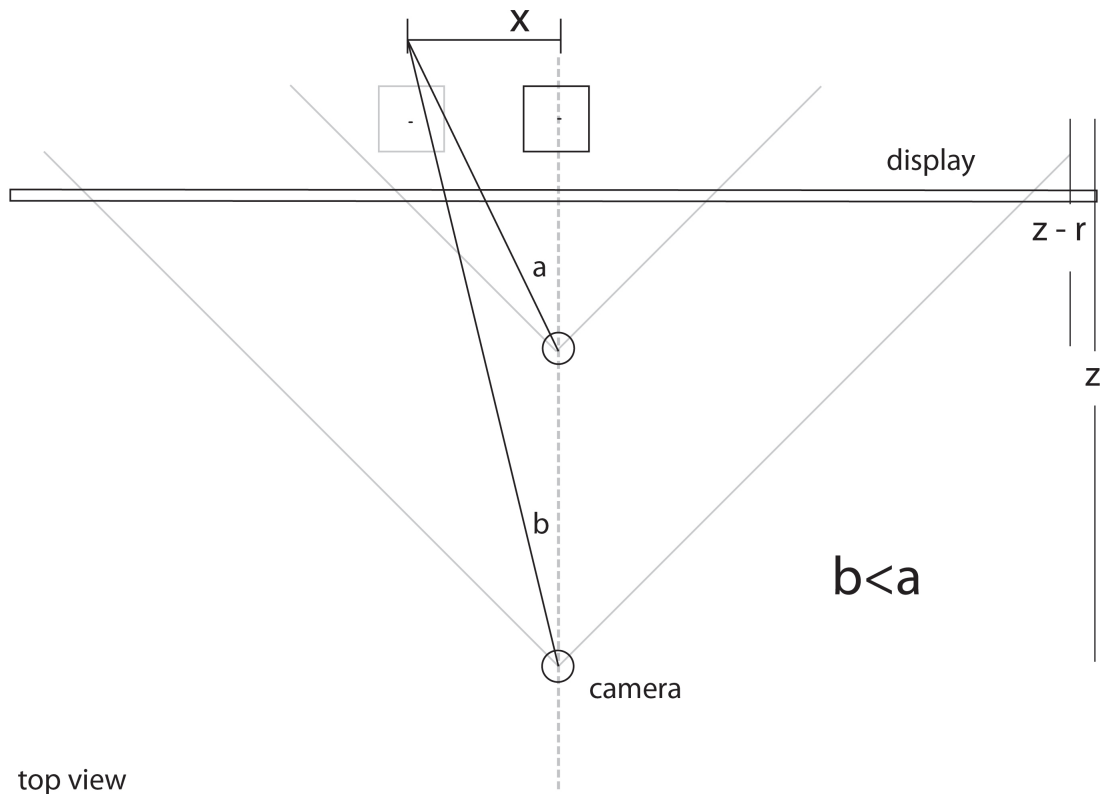


Figure 3.20: Scale of motion depended on range of view

In addition, I redesigned the mathematics behind the sphere's motion, taking into account its dependence on the orientation of the virtual camera. Consequently, all transformations of the sphere were in accordance to the transformations directed by the manipulandum irrespectively of the camera's position and orientation.

The second issue related to scale, before I connected the sphere and the camera, was about the displacement of the character or the parts of the character's skeleton. As I mentioned in the workspace intervention, the motion of the manipulandum was mapped to the motion of its representation in a way that the animator could perceive the mapping correctly kinaesthetically. I found that the way the scaling was done, affected the navigation negatively. The displacement that the animators made with the manipulandum, as well as the reactive force that was generated when they did so, was the same whether the camera was away from the object or when it was close to it. The scaling depended on the camera's initial position. This meant that the mapping between the physical and virtual environments was scaled in absolute terms but not relatively within the virtual environment. Figure 3.20 portrays the issue.

If the camera is located in an initial place a distance z from an object and the manipulandum is moved by x units in the right direction in the physical world, the sphere and, in

turn, the object will move x units right in the virtual environment. If the camera moves r units closer to the object (its distance now is $z-r$) and the manipulandum is moved by x units again, the object will appear to have moved more than x . Due to the fact that the camera is closer to the object, angle a is larger than angle b so the object's displacement on the parallel axis of the display will look larger. This made manipulation difficult when the viewpoint was close to the character especially since the animators often used this position to make subtle changes. When I connected the camera and the sphere, this issue appeared when the camera changed its distance from the sphere but within the sphere's range of motion, as otherwise the sphere and the camera would move together (Figure 3.21). However, it was less distinguishable in this case due to the small distance between the camera and the sphere (e.g. distance z in Figure 3.21).

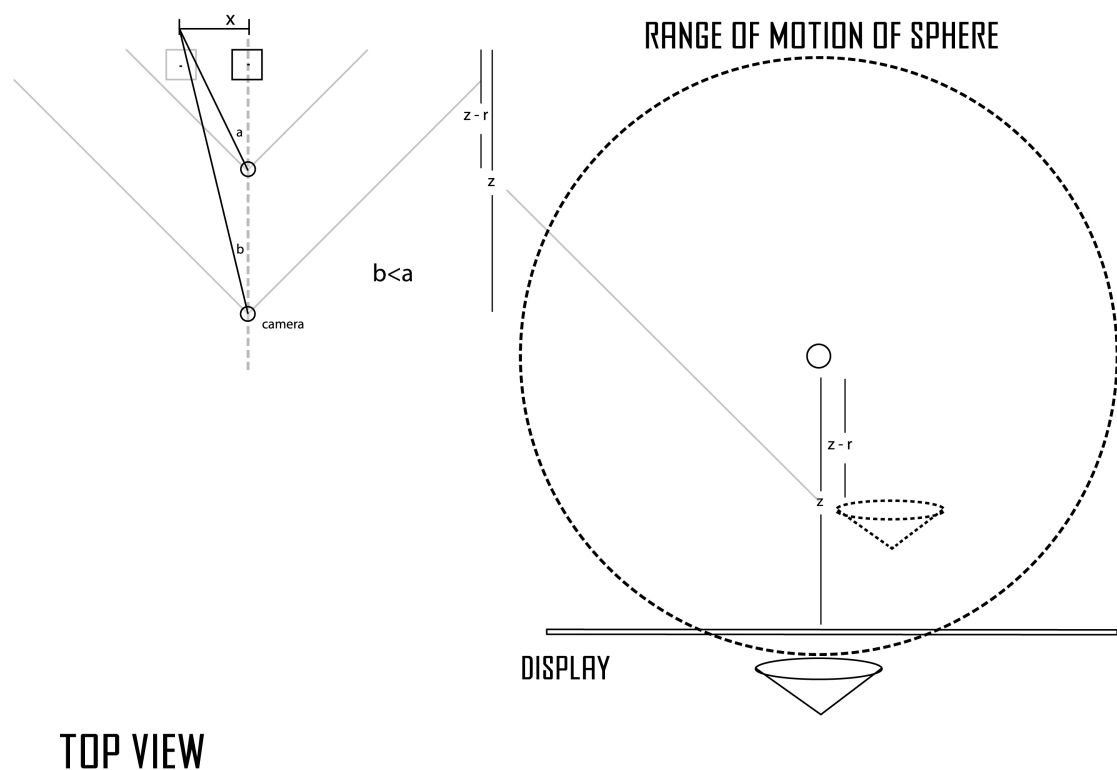


Figure 3.21: The scale of motion issue within the sphere's motion

To overcome this issue, I created a function that applied a multiplying factor to any displacement based on the difference in position between the camera position and the sphere, taking as initial maximum distance the default distance between the camera and the sphere when the application is first launched. The calculation of the reactive forces followed this multiplication in order to align the visual and the haptic perception.

Having corrected these issues, I returned to the animators for another one day session a

few days later. Observing how they used the interface and from their reflections, I realized that calculating scale in the relative space was not an adequate design solution. The relative scaling of the sphere's motion solved the issue of the different visual representation of the various displacements but also revealed new ones. The first was the level of visibility of the model in the viewpoint.

Puppet stop-motion animators often work close to the model to adjust small details but at any point during their work they are able to step back and see the whole model. In the haptic workspace, whenever they needed to work on the details in a part of the character they had to zoom in with the camera close to the model. Zooming in and out happened by changing the camera position in the virtual environment so that its frustum displayed geometry that was within its field of view, the value of which was fixed. This motion is similar to the way the eyes work as we tend to move closer to an object to see it better. The difference with the virtual camera is that the eyes have a wider field of view so that if we are adequately close to an object of the size of an artist doll we can still view the whole doll and its details. On the contrary, zooming in with the virtual camera brought the animators close to the part they wanted to focus on, but at the same time hid from their viewpoint the parts of the character that surrounded it. The inability to change easily between a close view of the part of interest and the whole figure at the same time proved to be quite disruptive to them.

One reason that caused this issue was the relatively constrained motion of the sphere. The sphere's transformations were now coordinated with those of the camera and for this I had positioned the sphere at a certain distance from the camera. Due to the fact that the motion range of the sphere on the 2-D plane parallel to the display was scaled to match the motion range of the manipulandum in its physical space, and the scaling had to be the same for the three axes, the sphere could move a lot away from and towards the camera. Thus, when the camera was positioned ideally for the animators so that the whole character was visible within the viewpoint and its details were adequately visible for them to work on, they could not reach the character with the sphere.

To remedy this, they suggested smaller models which could be fully visible within the viewpoint or at least visible to a high percentage when the camera was very close. Both reflecting on this decision, we discussed that it would take a lot of experimentation between modeling them and importing them to the haptic workspace so that the scale issue would not be disruptive. We concluded that it was not an ideal solution at least for the moment where there is not a modeling option in the haptic workspace. However, we agreed that it is an interesting idea to pursue in the case where 3-D modeling is implemented. At this point of the discussion, the animators reflected on the broader use of the haptic workspace for stop-motion animation, and some of them supported the view that the opportunity to make and rig the models in the haptic workspace would be extremely beneficial.

Another approach that we discussed was to create a dynamic field of view which becomes wider if the camera is closer to the character. Ware and Osborne (1990) pointed out that the action of placing a viewpoint in a virtual 3D environment' must introduce, apart from the inherent 6DoF, an additional degree of freedom to provide a field of view scale factor function equivalent to the zoom of a camera' (Ware and Osborne, 1990, p.175). However, this can disrupt the dimensions of the projected virtual environment severely and, consequently, affect the scaling of the manipulandum's motion with implications for the manipulation of objects.

The solution that I proposed, which was deemed by all as the most suitable one, was to introduce a customizing function which would allow the animators to scale the models after they are imported according to their needs. I proposed this as I thought that it would provide an excellent way of understanding and manipulating the dimensions of the character in relation to scale in an enactive way.

Range of motion

An additional issue that I observed, related to scale, was that the animators did not use the full range of motion of the haptic device. They would very often move the camera to get closer to the character instead of moving the sphere towards it. This meant that they kept the manipulandum of the device roughly in one spot in the device's workspace. In addition, they moved it on the 2-D imaginary plane parallel to the screen instead of exploiting the range of its motion in the third axis, from themselves towards the screen. When I first reflected on this, it led me to think that they encountered some difficulty in conceiving depth as a degree of freedom of their own actions and use it effectively for achieving certain movements. According to the design, they could perceived depth through the visual illusion of increment and decrease of the sphere radius.

I demonstrated to them how they could use the range of motion to navigate the space in its depth. They were discerning to my demonstration and after this they were using the motion of the stylus in all three dimensions but only for the action of moving the whole character. When they manipulated the character's skeleton, they switched back to not exploiting the full range of the manipulandum's motion. This revealed to me that the difficulty in conceiving depth appeared when they performed the particular action of skeleton manipulation and was somehow related to it. A closer observation showed the connection between this difficulty and the issue of scale with regards to the character not being visible as a whole in the viewpoint when the camera was close to it.

The fact that the character could not be visible as a whole in a way that made it easily manipulable, led the animators to work more often close to it. As a consequence, they used camera navigation most of the time and worked with small motions of the manipulandum

which seemed more useful to them. Because of the small movement, the manipulandum was not used in its full range. Moreover, when they worked doing small displacements, the change of the sphere's radius was imperceptible and did not encourage them to think about depth.

I compared the video recording with that of the workspace intervention and realized that during that session they were utilizing the whole range of the manipulandum's motion. However, in that design, the sphere was not co-located with the camera. In that design, the center of the sphere's range of motion was co-located with the character and the range of motion in all directions was larger than in this design. Therefore, the character could be manipulated and be fully visible at the same time. In that setting, the animators had no difficulty in perceiving and conceiving depth.

Speculating further on this issue, I interpreted it in terms of the kinematic chain theory of Guiard (1987). I assumed that moving in depth with the camera, in other words zooming in and out, is one of the motions that the 3-D mouse affords. Consequently, and in cognitive terms, it might be easier for its user to prefer this interface for the action of moving along the depth dimension, which is a task that can be regarded as referential to the main task of object manipulation, animating a character in this case.

If this holds true, it is possible that the two dimensionality of the virtual environment stands out and breaks the illusion of the three dimensionality that is constructed by the perspective projection and the motion of the device's representation in the depth dimension. Consequently, in terms of embodiment this disrupts the perception of acting in 3-D space. This reflection enforced the choice of doing a separate study on object manipulation and I kept this hypothesis aside to investigate it further in that study. I will discuss it in Section 3.5.2 where additional information attests my assumption.

Agency in camera motion

Overall, the animators did not consider the 3-D mouse to be an adequate interface for navigation. It was regarded as a rather static device, more like an extended joystick. Most of the time its functionality did not support smooth navigation because it required very small gestures and, most importantly, it required a series of discrete gestures to ensure that the viewpoint moved in the way they desired, e.g. in a straight line. Very often they would turn to use the keyboard arrows as they provided far more precise motion in a seamless gesture.

The keyboard outperformed the 3-D mouse in terms of precision and provided better control over the speed and acceleration of the viewpoint. A slight press of the button made the camera move in the direction towards which it is oriented without diverging from its path. This observation indicates that for subtle motion, a degree of agency is necessary to provide both stability and ease of access. Precision and stability are offered by the keyboard but in the case of the 3-D mouse, which extends to all gestural controllers, continuous data received from

acceleration and spatial coordinates makes this implementation less direct. In the physical world, the bio-mechanical constraints of the hands and the arms prevent translations from being independent of rotations, so rotations are always followed by inadvertent translations, and vice versa. One way to enable agency is to constrain the camera motion to a specific path. This means that some of the data sent should be filtered out so that it does not interfere with the motion along a straight path. The sending/receiving data function must, of course, be enabled again after the desired position has been reached. Although we did not test this in practice, we extensively discussed the possibility of reducing the dimensionality of movement based on the needs of the specific task. This is an issue that should be considered in future designs.

With regards to the kinds of motion the camera can perform in the virtual environment, the animators suggested placing the camera in orbit around the character. This idea evolved after one of the animators asked if she could go to the other side of the character with the 3-D mouse. My initial understanding was that she could do that by zooming in towards the character, passing the character's position and then spinning the camera by 180° to face its back. It was not until further discussion that I realized that what she meant was to spin the camera from its current position having the character as the center and navigate to its other side rapidly. The animators agreed that an orbiting camera was a useful navigation metaphor to be carried forward in the next designs. As well, it will inherently have a level of agency as it will follow a constraint path, that of circular motion around the character.

Navigating through time

Although not directly related to navigation in the virtual environment, I considered the animators' reflections on the animation making tools, such as capture, store, move forward and backwards frames, called for simplicity *animation maker*, and timeline relevant as they concerned the navigation of the fourth dimension, time.

With regards to the animation maker, the animators welcomed the fact that they could add a frame anywhere in the timeline or swap one frame with another 'because in real stop-motion you would not be able to do that'. They learned quickly which keyboard buttons they had to use to navigate but suggested that a visual timeline is a better option to have 'some sort of small graphical representation of the frames'. I suggested a slider as the simplest GUI element that can assist in timeline navigation to which they agreed. They suggested that a slider could accommodate some additional utilities they thought the current controller was missing.

In particular, they suggested the possibility of moving directly to the beginning or the end of the animated sequence, and being able to pass over a large number of frames at once instead of having to go through each single frame before reaching the desired one. They also commented on the benefit of including a thumbnail of the captured image above the place of

the corresponding frame in the timeline. This gives them the ability to understand where they are in the timeline using vision and visual memory of the previously animated frames.

The fluidity of the animation maker was given more weight from the moment it existed in the same location as the scene. The puppet stop-motion workspace consists of the scene where the puppets are located and the computer screen where the animators view the captured frames. The haptic workspace co-locates these two places in one uniform 3-D space.

As well as reflecting on their suggestion to have a visible timeline, I thought that in the next step other functions might also need a simple GUI. For example, I regarded as particularly important the fact that they should be able to select between a variety of virtual models and backgrounds instead of having one or two options pre-imported. In addition, the studies on lights would probably need on-screen elements to adjust their properties. Therefore, towards the end of the session, I discussed with them the possibility of adding a simple GUI which would include the following:

- A timeline displaying the frames
- A menu of virtual models
- A menu of virtual scenes (backgrounds)
- Any functions related to lights

They agreed that these would be helpful additions but they warned that the interface should have as few buttons as possible to reduce complexity.

Since the workspace intervention, I was concerned with the increasing number of functions I had assigned to the keyboard. So far, they used keyboard buttons for the animation maker functions, for selecting the kinematic chains and for the camera control if they chose to. (Hinckley et al., 1994a, p.218) have observed that:

keyboards are especially problematic because they can get in the user's way. We have noted that users frequently rest their hands on the desktop while manipulating spatial interface tools

However, I did not observe any excessive cognitive load on the animators' work who used the keyboard with the same hand they operated the 3-D mouse. When I asked them whether it was disruptive for them to change between devices, their reply was negative.

Finally, they suggested that upon implementing the slider, visual correspondence for the transition between two frames would be really helpful for their better understanding of the motion progression over time within the virtual environment. They referred to a similar process which is common in the frame recording digital software they use which is called *onion skinning*. Onion skinning is a process in which the current pose of the puppet, as



Figure 3.22: Example of the onion skinning technique

appears through the camera's lenses, is superimposed with the last captured pose. The last pose is faintly visible underneath the current image to give a hint of how motion will progress in the next frame (Figure 3.22). This allows the animators to make any necessary changes according to how they want motion to progress.

My proposed implementation, which they welcomed, was to show the progression of the motion from the previous to the current pose once the new pose is captured. It is important to note that this implementation, as well as the process of capturing a frame, exploits and foregrounds the two dimensionality of the haptic workspace since a frame is the two dimensional image of the 3-D virtual world. My argument for this way of applying onion skinning in the haptic workspace connected the space with the navigation of time and both facilitated the understanding of how the character's motion unfolds. Consequently, it linked action, perception and cognition simultaneously. In addition, it did not require the animators to move between two different places like they move in their normal practice from the scene to the computer screen.

Following this in depth study on navigation, I moved on to investigate object selection and manipulation in the virtual environment as was indicated during the workspace intervention study.

3.5 Intervention 3 : Crafting motion

The third intervention was set up to enable further reflection upon the synergy between the animators' physical gestures and the characters' motion. In the workspace intervention, I realized that the device's ergonomic properties and the level of gestural freedom they allowed were central to the way this synergy is created. In order to explore this in depth, in this study I employed another haptic device with a different ergonomic design for a comparison.

The second haptic device was a NovintTM Falcon (Figure 3.23). Falcon is the cheapest device currently available on the market (1/10th of the Omni's price) and is mainly used for playing haptically-enabled video games. NovintTM has produced drivers that allows around 100 video games to be haptically-augmented using the Falcon, in the majority of which the device is used for generating vibrotactile feedback, for example. when firing a weapon⁶.

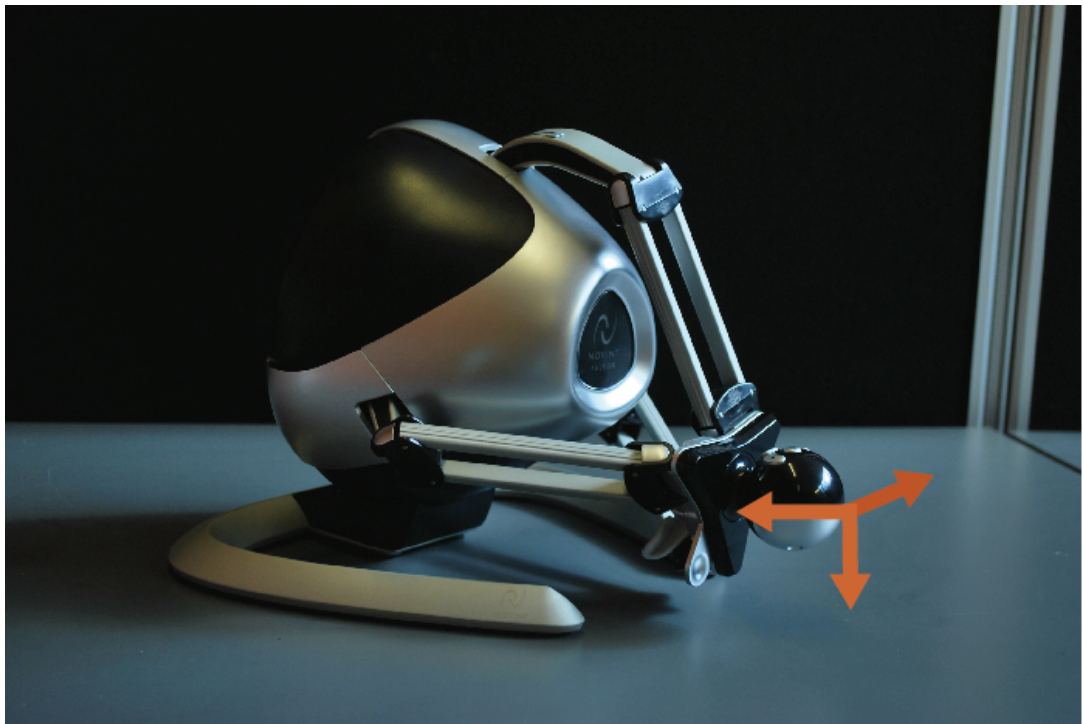


Figure 3.23: The NovintTM Falcon haptic device

Falcon has a slightly smaller physical workspace than the Omni of 4" x 4" x 4" dimensions. It is a 3DoF device providing only translation (Figure 3.23). A set of three robotic arms extend from the base and are joined at the tip where the manipulator is positioned. The manipulator is a detachable physical sphere which does not rotate. It has five buttons on it.

⁶Very few examples in games research have attempted to explore the kinaesthetic and tactile feedback in haptically-enabled games. One example is (Mora and Lee, 2006) who developed a game where the player controlled a virtual wand with the Omni haptic device. There were several types of wands which produced various haptic effects. The system could recognize gestures performed with the stylus which triggered haptic feedback

As with Omni, I assigned to the first button the action of moving the character and to the other button that of moving the character's bones. The Falcon works in a similar way to the Omni, employing motors on its base to produce force feedback. Like the Omni, the Falcon simulates the haptic sense through single point contact with objects in the virtual environment. The representation of the manipulandum in the virtual environment was again a sphere.

As each device provided different ergonomic properties, I designed different associations between their input parameters and the output motion which means that each device offered different kind of control over the manipulation of the character. I explored the appropriateness of the different controls. Alongside, I investigated the challenges and advantages as the animators moved from multi-point contact, such as the one provided by their fingers, to one point contact afforded by the haptic devices.

3.5.1 Object selection metaphors

Metaphors for selecting objects in a virtual environment include ray-casting, image-plane, and arm extension. Ray-casting, identified by (Mine, 1995), works very well for 2-D input and uses the metaphor of an infinite ray starting from the position of the virtual hand and extending infinitely. The first object on the trajectory of the beam is selected. Image plane based selection, identified by (Pierce et al., 1997), is based on an evaluation of a ray cast from the users' head through their hand onto the image plane. Arm extension metaphors like the Go-Go (Poupyrev et al., 1996) and HOMER (Bowman and Hodges, 1997) have been developed for reaching objects at a distance by introducing a non-linear mapping between the physical hand and the virtual hand to perform the extension.

For selecting the character and its part, I used the virtual hand metaphor where the virtual hand is substituted with the representation of the haptic device. The virtual hand metaphor was introduced by (Poupyrev et al., 1998) who suggested direct intersection between the object and the virtual representation of the input device.

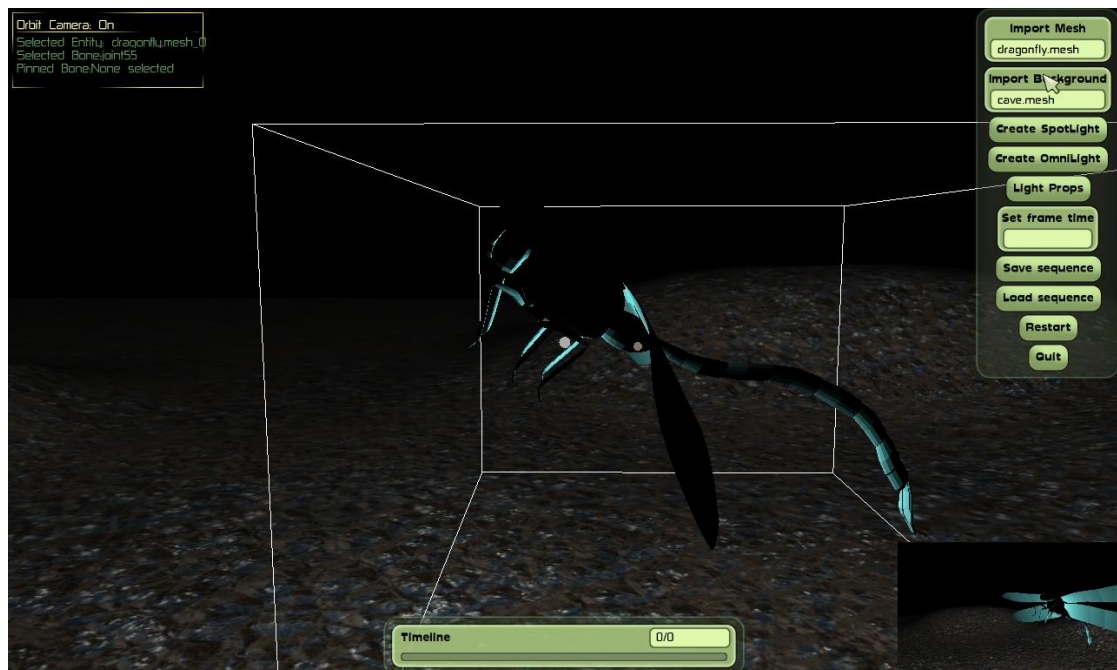


Figure 3.24: The bounding box

In the haptic workspace, once the sphere intersected an object in the virtual environment, such as the character or the lights, a bounding box appeared around the object to indicate that it is selected (Figure 3.24). The bounding box appeared only when the sphere was within a certain distance of the object. The selection process took place as follows: All objects had a bounding box which was by default invisible. The box was a cuboid with equal size to that of the object. The selection was done by checking when the sphere's bounding box was within the bounding box of another object. In the case where a large object included the bounding boxes of other objects, a distance-based function determined which bounding box will be selected for the inclusion algorithm. This function ensured that an object is selected once the sphere is close to it even if it is included in the bounding box of a larger object. Once the object closest to the sphere was identified, the object's bounding box became visible.

In this study, I tested the suitability of the FK algorithm. I used the different physical properties of each device to design two different mappings depending on the DoFs each device allowed. Rotation and translation of the bones were at the center of the design for this study. Figures 3.25- 3.26 gives a detailed visual description of how each device's manipulandum was used to manipulate the virtual character's bones.

All joints were ball joints which meant that they could rotate freely around the three axes. For the Omni, I exploited the three rotational DoF and created a mapping where the animator rotated the joints of the skeleton in order to move the bones⁷. Once the sphere was close

⁷For complimentary material on the Omni device's motion please watch the video entitled 'Omni-FK' in folder Chapter3 of the DVD

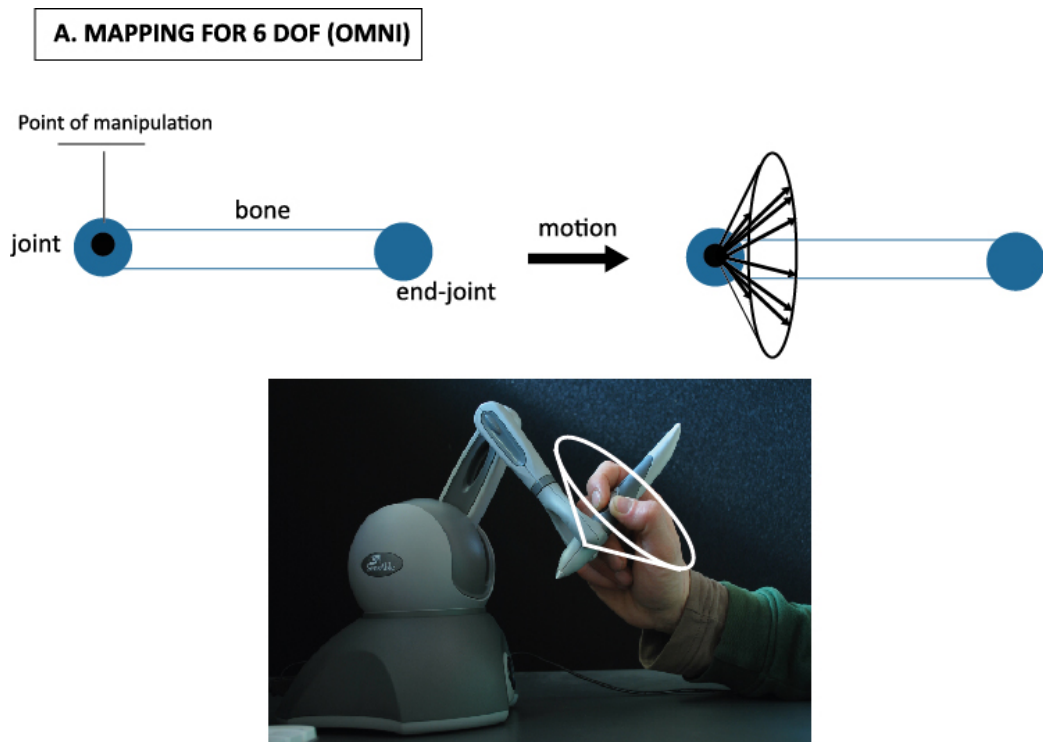


Figure 3.25: Mapping between the Omni motion and bone motion for FK

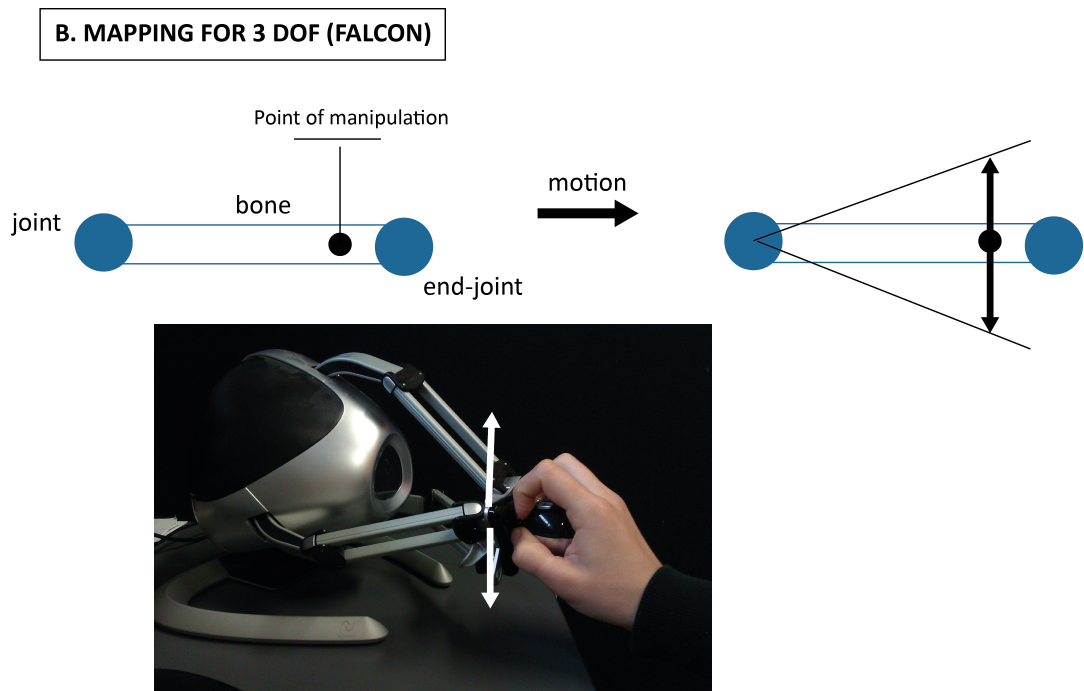


Figure 3.26: Mapping between the Falcon motion and bone motion for FK

to a joint, pressing the first button on the device locked the sphere into place. Keeping the button pressed, the animator used the 360° rotation in the three axes to rotate the joint which resulted in motion of the bone attached to the joint and of all bones in the chain after it. It

also activated the frictional forces and torque during the joint's rotation.

For the Falcon, which did not have the rotational DoF, the point of manipulation was the bone itself⁸. Translation of the bone was designed to produce rotation of the corresponding joint and motion of the bones that followed it. For example, if the animator pushed the arm, the shoulder joint would rotate and move the arm, forearm and hand towards the indicated direction. This could be computed easily by performing joint selection for each bone. In computer graphics, a *bone* is defined as the line between two joints. The coordinates of the joints are known but those of the bones, the mid point of the distance between two joints, are not. Thus, an algorithm had to be implemented to obtain them. In order to determine where the Falcon device is in relation to two consecutive joints, the algorithm ran some extra checks on the distance between the device's representation and the joints. The calculations gave fairly good results. In addition, for the motion of the bone I took into consideration the error angle (Figure 3.27). The error angle is the angle formed between the direction of the sphere's motion and the axis perpendicular to the bone. It indicates the divergence from a precisely perpendicular motion of the sphere to the bone's axis.

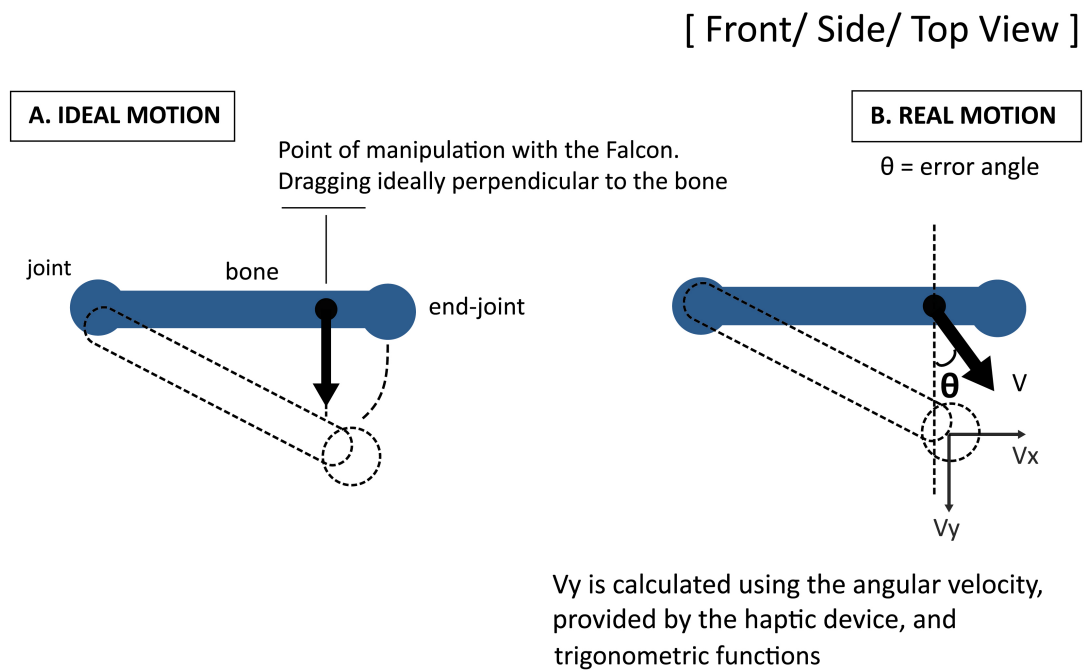


Figure 3.27: The error angle

⁸For complimentary material on the Falcon device's motion please watch the video entitled 'Falcon-FK' in folder Chapter3 of the DVD

Finally, I added a text area on the top left of the display which kept numerical track of the frames timeline in the form 'current frame/total frames' to give the animators a visual track of the frames. I did not implement the slider for this study as it was not the focus.

3.5.2 Reflections and Insights

The designed prototype was given to the animators in a one day design session in their studios. They were let to use it at their own pace. Their first responses showed that the Omni stylus device was preferred over the Falcon device due to the greater freedom of gesture it provided. As the study progressed, there were many issues identified in relation to object selection and manipulation and many of them were connected to navigation.



Figure 3.28: One of the animators working in the haptic workspace using the Falcon haptic device

Absolute and relative positioning

One of the first issues that was observed by the animators concerned the range in which they could move a bone. The issue was revealed when they used the Falcon device because they could grab and drag a bone with it, while with the Omni device they just rotated the joints. Often, when the animators manipulated the character, the device's manipulandum would reach the limits of its motion range before the animators had finished positioning a bone. When they moved a bone for a desired distance which the manipulandum could not cover they had

to stop the action, and re-position the camera so that the sphere was automatically moved to a new position closer to the bone, and repeat the task.

Apart from the motion range of the sphere, which could not be changed as it was calculated to reflect the kinaesthetic experience of working within the physical boundaries of the screen, this issue was mainly dependent on the position and angle of the camera in relation to the distance of the selected bone from the camera at the beginning of the gesture. If the bone-to-be-selected and the camera were in such a relative position that the animators had to move the sphere for some distance in order to grab the bone, the range of motion of the sphere would be too short to complete the gesture. This was a challenging issue to solve and we did not manage to provide an adequate solution.

Shifting mode to relative positioning complicated the task of manipulating the character, broke the experience of working within the physical boundaries of the screen and increased the cognitive load for the animators. I proposed the design of relative positioning which uses a clutching mechanism, 'a software mode which allows the spatial input device to be moved without affecting the 3D cursor' (Hinckley et al., 1994a, p.219). Once the manipulandum reached a physical barrier, pressing any button on the haptic device other than the one used for character manipulation would keep the sphere in place in the virtual environment and allow the animator to move and re-position the manipulandum before they release the button and repeat the dragging. However, when the animators tried this they felt that there was an inconsistency between the kinaesthetic and the visual cues. They were confused by the fact that they had to break the action, move the manipulandum in its physical space without the sphere following it and then resume the action. They felt that this process entailed too many discrete steps.

Together with the animators, I discussed the option of placing a slider through which the animators will be able to change the amount of scale applied to the motion. Still, we concluded that this solution might bring unnecessary discrete steps to the task. One satisfying solution could be to rotate the scene once the sphere is at the edge of a certain zone (e.g. towards the border of the display) so that the camera looks at the direction of the sphere. Bierz et al. (2005) have used this metaphor. With regards to what was discussed in Section 3.4 about agency in camera motion, this metaphor introduces some level of agency which can be potentially valuable for diminishing the cognitive load for the action of object manipulation.

Depth and precision

With regards to the observation about navigation made in Section 3.4.2 where the animators moved the sphere in the depth dimension with the camera instead of the manipulandum, responses in this study enforced my hypothesis that this happens due to the fact that the 3-D mouse afforded the actions of zooming in and out better than the haptic device. Evidence

during this study showed me that the animators constructed a navigation metaphor that was based on a 2-D workspace. These evidence were clearer when the animators used the Omni for rotating the joints, since using FK with rotation did not require big gestures. One of the animators said, moving the stylus around in a big gesture to demonstrate its full range of motion, 'so you don't really need all of this movement'. This response led me to conclude that he used the stylus as a 2-D device moving the sphere in a 2-D plane while the motion of the sphere in the depth dimension would happen by zooming in and out with the camera. This showed that, essentially, the animators used all the motions afforded by the 3-D mouse to create a reference framework in order to work on subtle details unencumbered.

The illusion of depth was clearly manifested with the visual increase or decrease of the sphere radius and its occlusion when it was moved behind any geometry. Therefore, I sought to understand why they would use the haptic device only in 2-D other than their choice to perform small gestures in order to animate the character. It is very common in puppet stop-motion to animate the character with subtle motions, although the scaling issue of the puppet not being visible as a whole and in detail simultaneously led them to work only in this way in the haptic workspace.

Further observation revealed to me that after working in the haptic workspace for a period of time during the session, they were aware of the 3-D gestural possibilities of the haptic device but chose to work with subtle motions and to use the camera extensively for the purpose of bringing more control to the task. Observing the animators more closely, I concluded that, for them, it was more an issue of precision and control than of misunderstanding the device's capabilities. Speculating on this observation, I discovered that the animators' choice of work method reflected the inability of the spatial input interface to enable precision in actions involving the depth dimension.

The significant observation made here is that they chose to navigate the virtual environment as if it was a two dimensional space in order to enable precision. One possible reason for this is the strong tradition people have of working with 2-D interfaces physically, such as writing on a piece of paper and digitally, such as software operated with the WIMP interface which include the post production software that stop-motion animators use. Another reason was, as I found out, the difficulty in perceiving depth in virtual environments. This occurs because while the two dimensions of width and height are perceived due to their direct projection onto the computer's screen which forms a 2-D plane, the depth dimension is not represented physically in the virtual environment. The difficulty in depth perception exists not only in perspective projection but also in stereopsis, parallax and holographic projection, and is causing difficulty in selecting and manipulating objects in these virtual environments. Even in physical spaces, people have great ability to position objects on a vertical or horizontal 2-D physical surface in front of them, e.g. a table, with precision but they do not have the same

control over precision when they move objects in depth. Consequently, from the high DoF that spatial input interfaces provide, those degrees that refer to depth should be appropriately used through interface metaphors in order to enable precise positioning of objects along the depth dimension. This insight was manifested in the preference for the keyboard over the 3-D mouse that was discussed in Section 3.4.2 and the need for visual cues that were suggested by the animators during the workspace intervention. Due to the inability of the haptic device to support depth precision, the animators used the zoom in/out action afforded by the 3-D mouse to construct a navigation metaphor that brought precision to the task.

One element of the design which the animators thought that, to an extent, eased controlled manipulation of the character was the production of a small amount of force feedback upon selecting a bone by pressing down the button on the haptic device. The feeling of grabbing and holding the selected part proved to enable a sense of control over its manipulation. One animator compared the sensation with that of snapping, commenting that she 'liked the fact that when you click the button it really locks into place'. Reflecting on this, I thought that enabling the touch sense on the character's body would ease precise manipulation further and decided to implement surface touch in the next study.

IK/FK and the locking chains model

The animators gave mixed responses regarding the kinematics of the character. On the one hand, the Omni design of rotating the joints provided more precision and control. One animator said:

There are elements of control there that already create live and satisfactory movement. I could never have achieved that with the other [kinematics] model. I already feel more content with what I am actually able to achieve there

In addition, the method of manipulation with the Omni which did not require movement in depth gave it a higher level of precision. Yet, according to the animators' account, the Falcon method of moving the bones to rotate the joints 'felt closer to stop-motion'. Despite being briefed in the beginning that they could use only the three rotational DoF of the Omni, they tended to move the bones instead of rotating the joints. It felt more natural to them to move the manipulandum instead of rotating it. When they did so, the joint would not move, neither would the bones attached to it. I would then remind them that it was the rotation of the stylus that drove the kinematics. Although they felt that moving the character's skeleton with the Falcon was more natural, they commented that the experience of working with the Omni provided more control. In addition, rotation only, provided subtleness and smoothness in the motions which the experience of using the Falcon did not provide.

As their experience drove the design, I resolved that IK was closer to how they naturally manipulate the character. However, my reflection on how IK responded to their actions in

Section 3.3 prevented me from using the algorithm in the way I had implemented it in that study. In that design all chains were connected to a root joint. This is mandatory for the IK algorithm but it also led to the motion of one joint affecting all joints to various degrees, which made manipulation difficult and broke the embodied interaction with the character. I concluded that the IK implementation needed a different level of control.

While discussing the two approaches, focusing on the IK implementation, the animators made a reference to the traditional technique which enabled me to propose a manipulation metaphor. In puppet stop-motion, bone manipulation is an orchestrated task which requires both hands. One hand holds the joint and the other hand either moves the end bone of the chain or rotates one of the joints of the chain below the joint that is held steadily with the other hand. As one animator commented, motion of individual parts happens by 'just holding the body and then you can secure the part and rotate it'. These comments inspired a manipulation metaphor for the IK implementation and resulted in a model which I called "the locking chains model".

The locking chains model was designed to eliminate unwanted influence between joints and provide more control to the IK implementation. I applied the IK algorithm to the character's skeleton without dividing it into chains. The hips were again the root joint that connected the rest of the joints together. I then designed a selection process. When the sphere was within the bounding box of one joint, by pressing the numerical button 3 on the keyboard the animators could select that joint. The selection isolated the joints that followed the selected one. In this way, the selected joint acted as the joint that they hold in place with the non-dominant hand in order to move the bones that follow it. Moving any of the bones after the selected joint, computed the joint's rotation as per the IK algorithm taking into account the error angle.

I tested this model with the animators using both haptic devices in another one day session. This time, they used only the translational DoF of each device. The animators found it a great improvement over the previous IK model. They thought that they could move the bones in a more controlled way performing actions similar to their traditional working method. However, I was conscious that although the locking chains model with the IK was overall preferred as an interaction mechanism, the rotational DoF of the Omni remained unexploited.

The Omni was found to enable more unencumbered animating experience than the Falcon and, therefore, was the device that was used in the rest of the studies. For this reason, I sought to integrate in the locking chains model and the rotational DoFs that the Omni provided. With the purpose of ensuring precision and subtleness in the manipulation of the character's skeleton, I combined the kinematics of both the IK and FK algorithms. The animator could select and move a bone within the locked chain and by using the rotational DoF of the Omni

she could also rotate the parent joint of the selected bone. A selection function was used for determining which joint was the parent joint. I tested the model during a third session⁹.

The combination of IK and FK was met with great success. Manipulation now felt more direct to the animators and there was greater control over the motion of the skeleton. The animators found that the combined algorithm allowed precise subtle displacements in accordance with the gestures which initiated them. In conjunction, the haptic feedback enhanced their navigation through the skeleton structure. A further development of this, which I proposed, is to have a slider on the screen which will indicate the level to which IK and FK should be computed. For example, the limits on each side of the slider can be 0 and 1, the first denoting only FK and the second only IK. Any values in between will be a fraction of each algorithm's output. The animators can set this at any time while animating according to their requirements. The issue with the absolute positioning and motion range of the sphere appeared again with the Omni device and the locking chains model which included IK motion. However, perhaps due to the lack of precision in the motions carried out in the depth dimension, the animators seemed to have found a work pattern based on small motions of the bones and so did not need to exceed the range of motion of the sphere often.

Joint constraints

In the study there were no constraints on the joints of the skeleton which meant that the joints could be rotated freely by 360°. I thought initially that for the humanoid models, it might seem strange to the animators that they are able to turn the bone further than the known range of the human body. However, this was not disrupting to them as physical puppets also do not have these constraints. In addition, the frictional forces and torque that was produced during the displacement of the bones were a constraint themselves. Yet, physical puppets have additional friction in their joints and with the first implementation of the IK algorithm, which was very sensitive to even small translations, the lack of constraints often led to the joints rotating freely and breaking the skeleton structure graphically. With the combined kinematics algorithm, motion of the bones was much more controlled and the issue was greatly diminished. Nevertheless, it would be useful for future designs to implement joint constraints and perhaps even more useful to allow the animators to place them according to their needs.

Gravity

One considerable omission in my set up of the prototype, which the animators indicated, was the feel of the virtual character's weight. Although reactive forces were exerted when a bone

⁹For complimentary material on the FK/IK motion please watch the videos entitled 'IKFKManipulation_0' and 'IKFKManipulation_1' in folder Chapter3 of the DVD

was dragged, the same response was not programmed in for when the whole character was moved around the space. This made the character feel weightless. The animators alluded that the weight of a physical puppet is one of its properties that facilitates the connection between the animator and the puppet. By holding the puppet in their hands, they understand how its weight is distributed over the different parts of its skeleton which is useful for actions such as calculating the relevant amount of force necessary for moving each part.

When asked about the necessity of feeling gravity, the animators responded that gravity is both an advantage and a disadvantage in their work. Reflecting further on this, they said that gravity in the physical world makes objects fall and stop-motion animators often use this to their advantage. Gravity assists them in making a character performing physically correct movements. It is also often useful in creating visual effects with physical methods. One animator said that 'the lack of gravity is what creates most anticipation in the end. It is a bit like doing special effects by being ingenious, tricking the camera, thinking that it does something different'. While observing them in the studio, I witnessed the creation of a visual effect with the help of gravity. The animator created a comet's tail by pouring salt in front of a light source on a black background.

On the other hand, they continued, the lack of gravity makes some actions in stop-motion less enjoyable as the animators have to animate the weight. For example, they have to invent mechanisms in order to make a character fly. When positioning the puppets, they constantly have to pay attention to parts of the puppet that might fall off or to be careful with how they gesture on the set so as not to move or drop any objects in the scene. In a virtual environment without enabled gravity, these issues would not exist. On the other hand, neither would the weight of the character.

I explained to the animators that a physically-based modeled character in a virtual environment with physics laws applied, i.e. enabled gravity, implies that the character will perform movements dictated by gravity even if it is not manipulated by the animators, for example it will fall if let free to move. They emphasized that this would not be an ideal environment to work in. They needed to feel the character's weight and the frictional forces that are created when moving bones and joints like it happens with the physical armature but the physical armature is made in a way which does not allow gravity to influence the puppet when it stands still. Thus, they welcomed an option to enable and disable gravity on the fly but warned that when gravity is enabled it should be adjustable and controllable.

Multi point to one point contact

One parallel reflection that I was making during the study was on the way the animators responded to one-point contact as opposed to the multi-point contact that they are used to in their practice. Puppet stop-motion enables the tactile component of haptic exploration

through multi-point finger contact with the puppet. In contrast, the force feedback produced by the haptic device is applied at a single point in the animators' hand. It was interesting to see that they had not commented so far on the absence of multi-point contact.

I found that the lack of multi-point tactile sense did not affect the perception-action loop. The multi-sensory information that the haptic device offers is a combination of the force feedback in the hand, visual feedback on the screen and simulated kinematic interactions in the virtual scene between the sphere and many objects integrated into the actual haptic feedback. This multi-dimensional information infers and evokes perceptions of complex multi-point interactions.

The haptic device is felt as an extension of the body, transporting motor capacities and mechanical sensory cues between the local physical space and the remote virtual environment. Upon touching a virtual object with the manipulandum's representation, forces, such as torque, are generated and felt physically at the hand that moves the manipulandum and perceptually at the place where the manipulandum's representation sits visually. The device has also the ability to infer complex forces that are generated when virtual objects collide with the object moved with the haptic device. This is particularly important for animating characters as the kinematics of the characters involve the simultaneous motion of the parts connected to the one moved.

Dynamic haptic sense of motion

One action the animators could perform with the 3-D mouse or keyboard, that was not designed on purpose, was to move the character by moving the camera and holding the character at the same time. This was a result of the camera-sphere motion dependence which made the character, when grabbed with the sphere, follow the camera's position and orientation. This can be seen as an object manipulation metaphor. I enquired whether it was useful to them. One positive point they highlighted was that changing the character's position in this way, solved the issue of the manipulandum's limited range of motion since moving the camera was the same as moving the sphere. Yet, they regarded this as a confusing method of positioning the character since, apart from the character's position, its orientation was changing in relation to other objects in space. The sphere, the viewpoint and the character were moved simultaneously and, therefore, shared the same reference system which continuously changed in relation to the constant reference system of the virtual environment. This caused difficulty in controlling the positions and orientations of all objects in the scene in relation to the viewpoint. The difficulty was increased when they used the camera to change the character's orientation. In the end, they did not perform this action at all.

Furthermore, the animators noticed that in the haptic workspace they are able to touch the characters while the frame sequence is played back. This gave them a dynamic sense of

the motion over time. They were very interested in the potential uses of this. One thing they mentioned was to intervene in the motion path of the character and adapt it. Utilities for previewing the animation loop, such as onion-skinning, which was described in Section 3.4.2, assists the animators in seeing the frames that have been animated already and have a sense of *what they have done and where they are going*, as one animator observed. Being able to dynamically change the motion path of the animated character provides instant feedback of how the character will respond to possible obstacles. In addition, the significance of this utility lies in the fact that it allows them to test different progressions of a character's motion without having to animate it. The frame sequence can be played back in a loop and each time the animators can intervene to change the character's path in a variety of ways which they can rapidly and instantly visualize. Similar research has been conducted by Bierz et al. (2005), whose work I described in Chapter 1, in which the user exerts forces on autonomous characters by means of a haptic device. The characters react to external cause following behavioural patterns. Also referred in Chapter 1, Garroway (2005) used the Omni device to edit the animation path of a pre-animated character. The path, modeled in Bezier curves, could be felt with the device. Although I did not implement motion adaption, I discussed its possible uses extensively with the animators and identified it as a fruitful field for future exploration.

3.6 Intervention 4 : Bi-manual interaction

The difficulties that the animators had in operating the 3-D mouse led me to investigate an alternative interface operated by the non-dominant hand to support unencumbered two handed practice. My first conclusion was that the use of the 3-D mouse input device for the camera motion control was not a successful choice and I set out to explore sensor-based tracking technology and compare it with the 3-D mouse. During this study, I realized that the key to satisfactory bi-manual interaction with the virtual characters was not so much the interface that was employed as the metaphors adopted through which the interface enabled bi-manual interaction.

3.6.1 The Wii Controller

Although the 3-D mouse provided accurate motion and 6DoF control, suggestions by the animators indicated that an interface for the non-dominant hand should be a less static device, one that feels less like a joystick and more like a natural mediator of their gestures. I researched available sensor-based technologies and concluded that an appropriate device for the non-dominant hand for this task is a tracker. A tracker records spatial data from gestures and then sends it to the computer. The animators agreed about the freedom of gesture offered by the trackers. One such tracker that I employed was the NintendoTM Wii Remote (Figure 3.29). I compared the Wii Remote with the 3-D mouse in terms of how the animators used it as navigation tool.

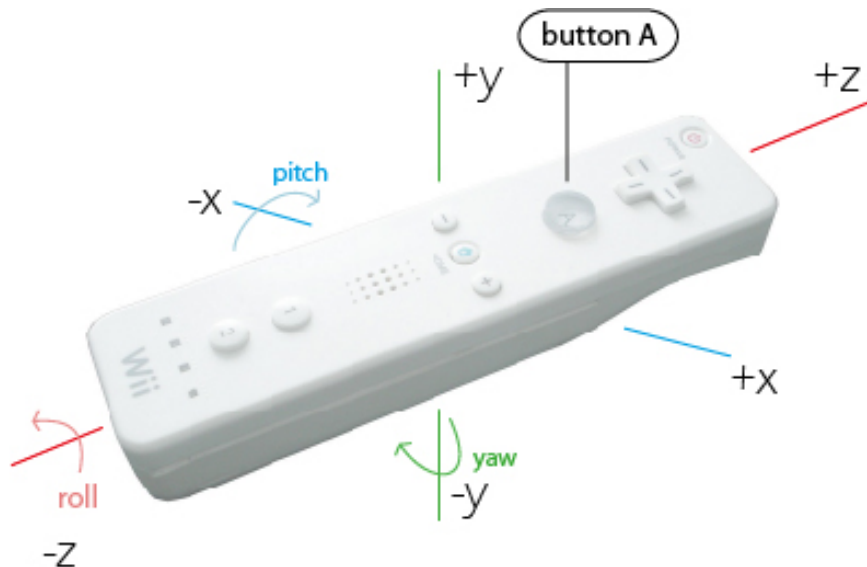


Figure 3.29: The Wii Remote with the three axes

The NintendoTM Wii Remote is a cuboid device incorporating one three axes accelerometer which sends out acceleration data, with respect to gravity, with no particular frame of reference. The device has several buttons, one speaker, two programmable LEDs and a rumble mechanism. In the front part of the device there is an IR camera which communicates with a receiver (called a Sensor Bar) which consists of two LEDs emitting infra red light. The bar is positioned at a certain distance from the Wii Remote and the camera on the Wii Remote uses this distance to perform triangulation (forming a triage by connecting the two LEDs and the camera) which facilitates the accurate calculation of motion. I tested two different designs for navigating with the Wii Remote which can be categorized according to its initial position (Figures 3.30- 3.32). If we consider the Cartesian reference system of x,y,z axes, z is the optical axis of the animator, x is the horizontal axis spanning from the left to the right side of the animator and y is the axis vertical to the x and the z axes.

Roll (z axis)

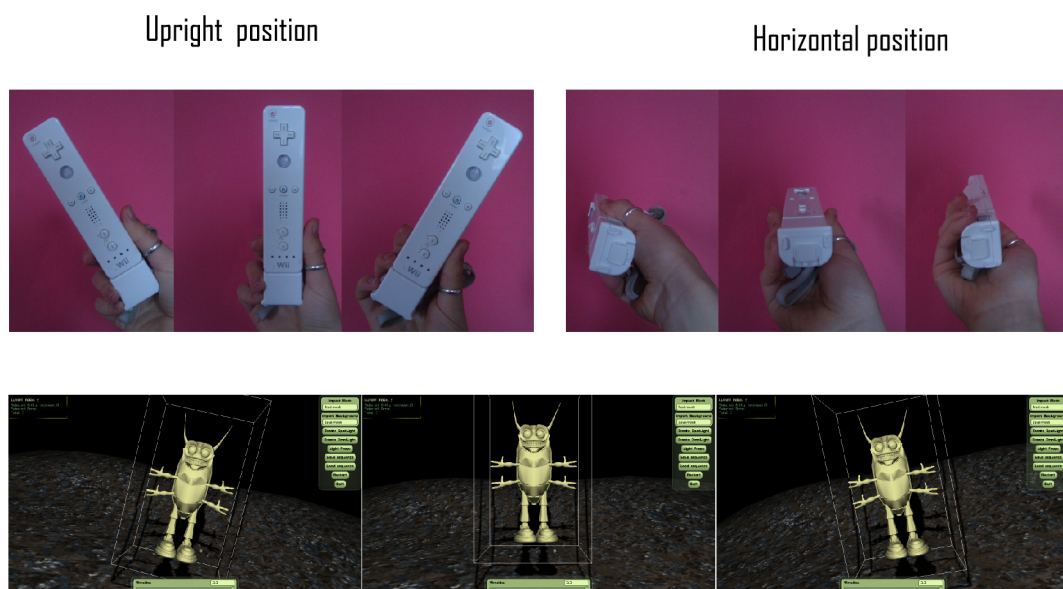


Figure 3.30: Wii rotation in the z axis

- Horizontal Position: The Wii Remote was held horizontally in its initial position. Rotating it in the x and z axes, pitched and rolled the camera respectively while the the IR camera was used for rotating it in the y axis (yaw). I used the IR camera because, in the horizontal position, rotation in the y axis is around the vector of gravity and thus the accelerometer cannot calculate this motion using this vector as it does for the other two rotations.

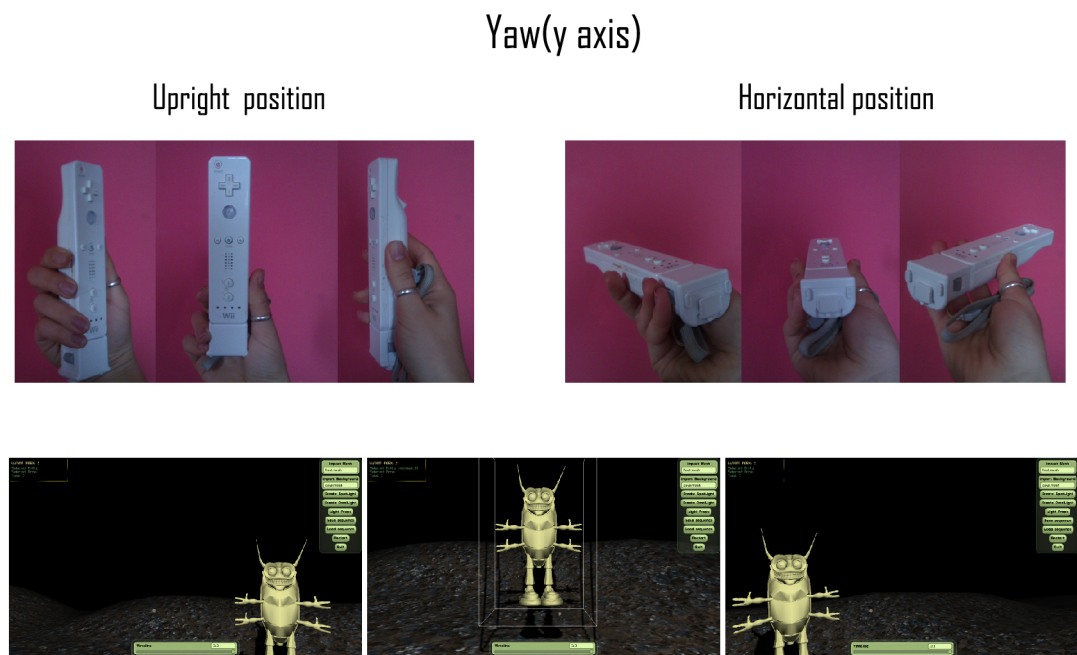


Figure 3.31: Wii rotation in the y axis

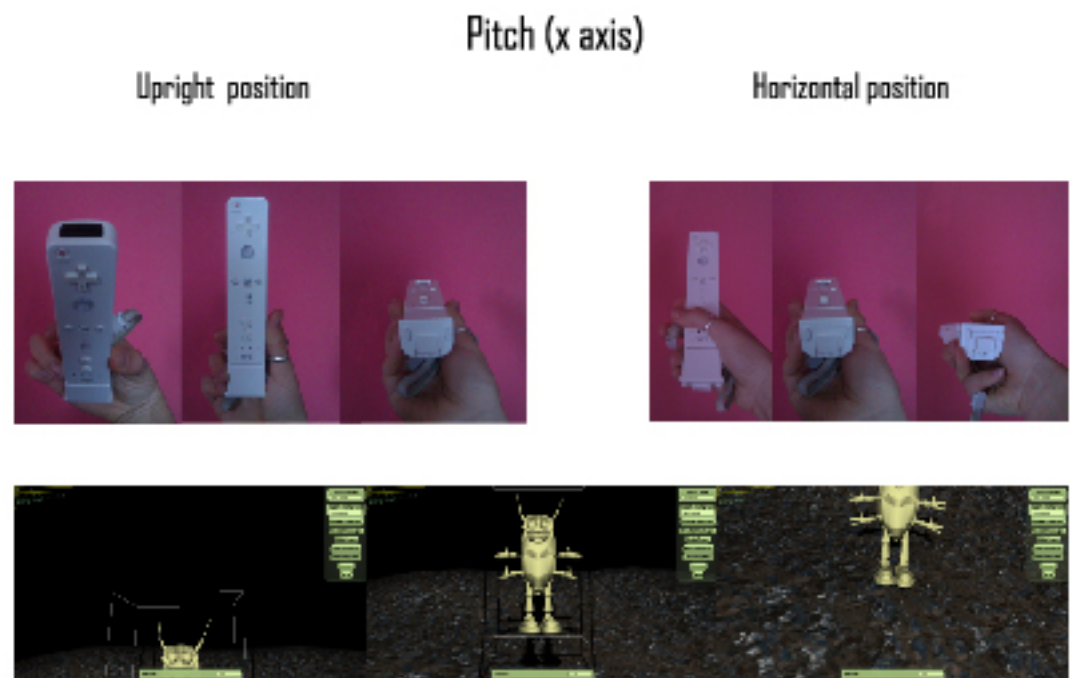


Figure 3.32: Wii rotation in the x axis

- Upright Position: The Wii Remote was held upright in its initial position. In this design, I did not use the IR camera and yaw was calculated by rotating it normally in the y axis.

When the A button on the Wii Remote was kept pressed the camera could be translated in all four directions by moving respectively the device in space. There was a level of acceleration during translation which sometimes was too fast and would break the navigation experience. Small adjustments to it helped to keep the overall motion at a stable rate¹⁰.



Figure 3.33: One animator working with the Wii

The ergonomics of the Wii Remote eased the design of the camera in orbit around the character as mentioned in Section 3.4.2 for quickly changing the angle of view. After discussions with the animators, we agreed on a keyboard button to change to the orbit camera mode and by keeping button 'A' pressed on the Wii, the camera traveled in orbit around the character. If the button was released, the camera stopped moving. Here I could have used the scene-in-hand (Ware and Osborne, 1990, p.177) metaphor and rotate the whole scene keeping the camera fixed. I preferred the metaphor of rotation around a point instead,

¹⁰The video entitled 'WiiMotion' in folder Chapter3 of the DVD shows an animator working with the Wii to navigate the haptic workspace

the point being the center of mass of the virtual character, because it was computationally faster.

In this study, I programmed in the ability to feel the character's body with the haptic device. Surface touch was an element I aimed to implement anyway in the progress of the design studies. I introduced it in this study because in the previous study I had made the hypothesis that the characters' manipulation would be more precise once its surface was felt. I did so while reflecting on the issue of manipulation in the depth dimension in Section 3.5.2.

In order to produce the touch sense of a virtual object's surface, a model of the virtual object is constructed out of the object's geometric data and is sent to the haptic device. This model is called the *haptic model* and is not visible on the screen but can be felt by the hand that moves the stylus. A haptic model can be felt even if the virtual object is not rendered graphically since it requires only the spatial coordinates of the object's geometry. Once the sphere collides with the surface of the object, in this case the character, force feedback is produced by the device and exerted at the stylus recreating the feeling of touching the surface.

I ensured that the haptic model was co-located with the graphic model at all times. The manipulation of the character changed its coordinates graphically so I had to synchronize both renderings spatially at each rendering frame¹¹ so that the graphic and haptic model were co-located at all times. I optimized the algorithm so that graphic rendering happened adequately fast. Haptic rendering was updated a lot faster than graphic rendering (1/1000th of a second for the Omni device) as slow rates would cause the haptic device to vibrate. It also ensured that there was no lag in the coordination between the haptic and graphic renderings. Learning from the workspace intervention, where the amount of force the animators put into dragging the bone did not correspond to how the sphere moved visually (see first issue in Section 3.3.2), I ensured this time that the haptic rendering (surface touch sensation and reactive forces) and visual rendering were synchronized. Graphics collision detection for the sphere was calculated so that once the sphere collided with a haptic surface this was reflected in the graphic as well as the haptic rendering.

3.6.2 Reflections and Insights

As with the previous studies, the designed prototype was given to the animators in a one day design session in their studios. My aim was to compare the Wii Remote with the 3-D mouse in terms of gestural camera control. My findings showed that the Wii Remote accommodated the animators' gestures in a better way than the 3-D mouse although the Wii Remote was more sensitive and, thus, offered less control over the camera motion. The most important finding

¹¹Rendering frame is the graphics rendering of the virtual models in the virtual environment which happens in the processor unit of the computer (CPU) or that of the graphics card (GPU) and has nothing to do with the animation frames that have been discussed so far. The rendering is updated many times per second depending on the CPU or GPU speed

of the study, however, was that neither of the two devices were deemed suitable for camera control by the animators. They would have preferred to use either device, with a preference for the Wii Remote, for the purpose of translating the whole character.

Mediating gesture with the Wii

According to the animators, the Wii Remote allowed more natural gestures than the 3-D mouse and the response of the camera motion felt more immediate. There was some occasional drift in the camera motion but it was not detrimental to the overall experience apart from when the camera was translated. The drift was due to the use of only one accelerometer. Since the study was carried out, NintendoTM has introduced the Wii Motion Plus, a magnetometer which is used in combination with the accelerometer to correct the received data. Many sensor networks employ gyroscopes which, in combination with accelerometers and magnetometers, provide very accurate results (e.g. (Arvind, 2005)). The use of only one accelerometer for calculating position was also the reason behind the difficulty in translating the camera. When the animators moved the Wii Remote they did so slowly and, consequently, the produced camera motion was very small even when the Wii Remote was moved in big ranges. The animators suggested to use instead the cross buttons for motion forwards/backwards and left/right as they offered more controlled camera motion (we discussed the reasons behind the need for controlled camera motion in Section 3.5.2).

The design with the Wii Remote held in the horizontal position was preferred to the one where it was held upright. The animators identified one important design issue. When the application launched, the camera was in motion until the animator pressed the button at the back once to stop its motion. They suggested that the opposite should happen and that pressing the back button and keeping it pressed should activate camera motion while releasing it should deactivate it. The ergonomics of the Wii Remote facilitated this task since the button was located at the back of the device and could easily be pressed with the index or the middle finger while the thumb operated the cross buttons. Hinckley et al. (1994a) describe how using the fingers in this way might present some difficulty in a similar example of an input device consisting of a 3D tracker encased in a pool ball, which had a clutch button mounted on its surface (they used the button to enable a clutching mechanism). When the user held the clutch button down, the virtual object followed movements of the pool ball, and when the button was released, movement of the pool ball had no effect. They observed that:

When a clutch button is mounted at a fixed location on a spatial input device, the user must have a fixed grip on the input device, to keep their fingers in a position to press the clutch button. Due to the kinematic constraints of the wrist, a fixed grip limits the possible rotations which can be performed. If arbitrary, large-angle rotations are required, the resulting interface can be very awkward (Hinckley et al., 1994a, p.219)

In our case, in which the animators performed small and diligent movements, the camera did not require large gestures and using the fingers in this way did not obstruct smooth operation. With regards to changing between the Wii Remote and the keyboard to store poses and move between frames, they commented that it was easier to change between them than it was with the 3-D mouse. Because they could still press down keyboard buttons and hold the Wii in their hand (with camera motion deactivated), they did not feel they had to interrupt their work by putting down one device and grabbing another. This made the change very smooth.

Haptic navigation

The character's surface touch was a significant addition to the simulation of the haptic sense and established an embodied understanding of the position of the character and its different parts. The animators commented that the physical dimension of the character helped them connect to it in an embodied way. I observed that their dexterity in manipulating the character improved significantly after this implementation.

They remarked that the haptic sense they were getting from moving close to the skeleton assisted them in navigating it. I observed myself that when the animators were close to the character with the camera they had a better sense of the location of each bone than when they were at a further distance from it. This was not only because when close they could see the position of the small details on the skeleton's structure more clearly. They also said that they calculated the distance of the device representation to the different bones by touching the bones which helped them form a *haptic map* of the bones' relative positions in an enactive way. After a while they were able to navigate the skeleton's structure at ease. The feedback was accurate enough to help them understand at which angle or position the character was at each time. This did not eliminate their need for visual cues entirely but it demonstrated the ability of the haptic device to create a haptic map within the virtual space which, in absence of any visual feedback, can be used for perceiving and making sense of the virtual environment.

In addition, this finding relates to the discussion about precise manipulation in the depth dimension in Section 3.5.2. According to the animators' comments, the force feedback generated by the contact between the sphere and the character's surface and the reactive force produced when moving parts of the character with the manipulandum eased to an extent fine-grained manipulation in the depth dimension.

The synergy between camera control and the haptic map that the animators formed certainly enriched their sense of orientation. However, the animators felt that while the choice of device hardware for the non-dominant hand was appropriate, its assigned use so far was not deemed suitable for them.

The puppet-in-hand metaphor

Working with the Wii Remote for a few hours, led the animators to an insightful comment which opened up an entirely new consideration of the actions carried out by the non-dominant hand. They would rather use the non-dominant hand to control the whole puppet rather than the camera. I named this metaphor, "puppet-in-hand" metaphor.

The animators suggested that it felt more natural to them that the device operated by the non-dominant hand is used to move or rotate the whole character while the dominant hand uses the haptic device to perform the subtle manipulation of the character's skeleton parts. In their practice, the two hands work synergetically in the same reference frame. Yet, this was not reflected so far in the haptic workspace. The structure of the bi-manual interaction that the animators suggested, brought the hand's coordinates in approximate convergence in both the physical and the digital workspace and created a stronger relation between the actions that each hand carried out. It also enabled an asymmetric way of working similar to that encountered in most artistic tasks. I observed that their perception of the virtual space was improved in comparison with when they had both hands doing different actions without being co-located in the virtual space.

It was interesting to observe that they were led into this insight while working with the Wii Remote although they had been using their non-dominant hand to control the camera for a considerable period of time with the 3-D mouse. Not one of the animators discussed the possibility of using the 3-D mouse to control the character. This implies that the Wii Remote translated their embodied knowledge better than the 3-D mouse did. In terms of the study conducted by Jacob and Sibert (1992), the control space of the Wii Remote matched the perceptual structure of the task space (controlling the whole character) in a more suitable way than the 3-D mouse.

The design that enabled the animators to make this suggestion was the one where the Wii Remote was held in the upright position so its shape could more easily relate to that of a puppet. In addition, its physical structure and the gestures that it enabled created a better reference framework for the manipulation of the puppet than that created by the 3-D mouse. The control space of the device offered to the animators the gestural freedom and the constraints that they have when they work traditionally, e.g. the physical constraints of their hands and wrists.

I have discussed so far the puppet-in-hand metaphor in the case where there is a direct mapping between the gesture performed with the Wii Remote and the character's motion, e.g. rotating the device rotates the character. Another control metaphor would be to reach and grasp the character with some type of visual representation of the Wii Remote, similar to that of the sphere for the manipulandum.

During the previous study, one animator suggested that another haptic device could be

used for the task of pinning down joints in the locking chains model. This was an interesting observation as it resembles the metaphor of puppeteer, similar to the work carried out by Kim et al. (2006) that I presented in Section 1.3.4. In this study, I reminded them of this suggestion and proposed that the Wii Remote could be used with this control metaphor. The sudden acceleration in translations and the occasional drift of the Wii Remote deterred the animators from regarding it as an appropriate device for the puppeteer metaphor. Selecting and pinning down joints requires very precise selection and, as we have discussed in Section 3.5.2, the Wii Remote was not suitable for this fine-grained task. The force feedback offered by the haptic device provided them with better precision. The Wii Remote or the 3-D mouse was not appropriate for them either. Enforcing their view, previous work in the area has indicated the lack of potential in the 3-D mouse for performing such task efficiently. Kry et al. (2008) have used the same 3-D mouse model to study selection and manipulation of objects in a virtual environment and concluded that an important issue encountered was that it limited the kinaesthetic and motor perception of depth cues severely.

Together with the animators, we concluded that the reach and grasp metaphor with the Wii would bring more cognitive load to the task than the direct mapping of motions. In summary, the Wii Remote matched the structure of the puppet-in-hand metaphor and a second Omni haptic device matched the structure of reach-and-grasp metaphor.

Reflecting on the aforementioned findings, I identified some parallel observations to the study where I had focused on the affordances of two haptic devices of different ergonomic attributes. From both studies, I concluded that in order to achieve unencumbered embodied interaction with the character in the virtual environment, it is important to identify first the limitations and abilities of the selected hardware interface and then to carefully specify how it will act as a mediator of the animator's gesture by designing the software interface. I also concluded that the animators' interpretation of the puppet-in-hand metaphor satisfied for them the application of the kinematic theory for bi-manual asymmetric labour in the haptic workspace in better terms than my initial design. Since they had a better understanding of their working methods than I did, they were in a better position to design the mapping between their gesture and the result they sought to achieve. This example validated the competency of the collaborative and user-driven design process.

Designing for a multitasking setting

Considering the puppet-in-hand control metaphor, there are now three actions to be carried out simultaneously:

- Skeleton selection and manipulation
- Whole puppet manipulation

- Camera navigation

We collaboratively designed the first two in a way that reflected the two-handed practice of the animators. The majority of animators suggested that camera operation could be carried out with the haptic controller in the dominant hand using the device's buttons on the stylus to switch between camera navigation and skeleton manipulation. I implemented this metaphor designing the motion of the stylus, for all directions and orientations, to correspond to the same motion for the camera once the second button on the stylus was kept pressed. A similar metaphor has been studied by Boeck et al. (2006), building on work by Anderson T. (1997).

Boeck et al. (2006) have used an Omni haptic device to control the camera naming the metaphor as the *camera-in-hand* metaphor. They also ran a formal usability test in which they proved that novice users who did not have any experience in virtual environments, could perform camera motion with the Omni in the same manner as an experienced user, while they performed much worse when they used the 3-D mouse. In my study of the haptic camera control, I found that the Omni was equally sensitive to the Wii Remote which was the most deterring element of this control metaphor. The hand that operated the stylus had to be remarkably steady to achieve smooth motion, something that could not be easily achieved. Small displacements were more appropriate for smooth navigation than big gestures. Throughout the studies, the keyboard provided the most steady output for translations and often the animators would come back to it for fine-grained camera control.

As we discussed in Section 3.4.2, the issue with gestural interfaces, such as the Wii Remote and the Omni haptic device, is that they provide rich spatial data which can bring more sensitivity than necessary to the task. A possible solution is to design in input constraints. For example, the camera can be constraint in the y axis so that it does not diverge despite receiving input from the gestural controller data on the y axis. This is the same strategy of filtering out received data as discussed in Section 3.4.2. Equally, a parametric camera model might be useful if it does not pose much cognitive load in the task. Parametric camera models allow the users to experiment with and tune the camera parameters such as force, momentum, acceleration and friction through valuator, until a subjectively 'best' set of parameters is found (Turner et al., 1991). These parameters can then be saved and restored when needed.

An additional drawback for translating the camera with the haptic device was the absolute positioning of the sphere in the virtual environment as described in Section 3.5.2. When the stylus reached the end of its working space the camera could not move further. Boeck et al. (2006) encountered the same issue. Their solution was to make the device generate a resistance force when the user reached the bounds of the Omni's workspace. By pushing against the force, the virtual camera was moved as if it was standing on a virtual craft. The *extended camera-in-hand* metaphor was enriched with auditory feedback proportional to the

speed of the craft. The authors cite that with the new metaphor there was a slight, but insignificant improvement in completion times for the task they had set. I did not implement this solution as the animators found it interesting but were not really keen on using the haptic device for camera navigation overall due to the sensitivity issues. Moreover, I reflected on the use of the extended-camera-in-hand metaphor and concluded that it is not clear that it does not pose restrictions or create excess cognitive load for the users. It is possible that other kinds of control metaphors are more suitable for multitasking settings. The animators reflected on some of them.

They were certain that they would rather have the camera in the non-dominant hand but they also discussed ideas for having the camera in an altogether different location such as the feet, e.g. a foot pedal. Using the feet in multitasking settings, where the two hands are not adequate for all the tasks, indicates that considering the whole body has a value in the construction of better interaction mechanisms. For example, a potter's wheel is an equivalent example in craft where a foot pedal is used. The foot pedal idea occurs in the work of Turner et al. (1991) suggested not by skilled users but by the researchers. In a multitasking setting, Turner et al. (1991) suggested that employing the feet for adjusting the values in their parametric camera model might remove much of the cognitive load from the hands. A foot pedal was also used by Hinckley et al. (1994b) to activate a clutching mechanism.

Apart from a foot pedal, relevant research ((Kumar et al., 2007), (Zhai et al., 1999)) and applications (Qvarfordt and Zhai (2005), (Isokoski et al., 2006), (Yanco, 1998)) have studied the use of eye gazing and head tracking for camera navigation. It is possible that the foot pedal metaphor is more advantageous than eye gazing as research has shown that the latter has some restrictions, one of which is the range of motion that the head is capable of. In any case, the extent to which such metaphors are useful within the context of camera control for puppet stop-motion forms an interesting research agenda.

Fatigue

Moving towards the end of the discussion, a significant and well-known issue that the animators addressed was the fatigue that can be caused by continuous and prolonged use of 6DoF gestural interfaces. In skilled practice, fatigue is not a rare phenomenon. Purves (2008) points out that puppet stop-motion is an incredibly strenuous physical job:

Stop-motion animators are usually on their feet for at least nine hour a day, working in hot, bright, necessarily airless conditions;[...].With the dexterity of Houdini the animator has to manipulate himself carefully at very odd angles, being careful not to knock the camera, and twisting to avoid large sheets of poly board and carefully positioned hot lamps.[...] Once into the set, the animator plays with the puppet, feeling every muscle in his lower back grinding away from such an unnatural position, before sliding out of the set backwards. Doing this some 250 times a day inevitably causes problems (Purves, 2008, p.223-224)

Since extended use of any tool that enables free gesture can cause fatigue, 6DoF gestural interfaces also have a limited time in which they can be used continuously. In the proposed haptic workspace, I tried to minimize fatigue as much as possible. The stylus, the Wii and the 3-D mouse, albeit not a gestural interface, can be put down at any time without any effect on the virtual workspace. Both the haptic device and the 3-D mouse suspend motion of the objects they control once they are put at rest.

From a design perspective, the important point is that once the devices are at rest, any activity in the virtual environment is suspended. The clutching button on the Wii activated and deactivated camera motion on demand so that the animators did not hold their hand in the air for longer periods than needed. Another solution the animators suggested was arm support.

Having studied how aspects of the stop-motion practice related to perceiving space and manipulating the puppets are transferred into the haptic workspace, I set out to investigate two other aspects of the practice, lighting and camera use. During the workspace intervention, the animators emphasized lighting as an integral part of the animation process. The following study is about lighting animation scenes in the haptic workspace.

3.7 Intervention 5 : Designing the atmosphere

Lighting accounts for much of the final animated story's atmosphere and ambiance. The aim of this study was to trigger reflection on the use of lights in the haptic workspace.

Natural light changes dramatically during the animating process and for this reason puppet stop-motion animators use artificial lights which they position around the scene. The lights can be moved although this is not without difficulty especially if they are not desk lamps, which is a low-cost way of lighting the scene. Figure 3.34 shows a common set up of lights in a puppet stop-motion animation scene.



Figure 3.34: Lighting in the scene

In the virtual environment, virtual lights are invisible sources which simulate the emission of light. They become visible by being connected with a virtual object and it is through the manipulation of the object that the lights can be manipulated. Light emission in the context of computer graphics is done by algorithmic processes that calculate the behaviour of light beams taking into consideration the geometry of the objects in the virtual environment, their surface properties and the materials through which the light is emitted. The beams' properties can change. To change the colour of the light emitted by a lamp, puppet stop-motion animators place coloured gelatin in front of it. In virtual environments, the colour of light can change with the press of a button or by adjusting the value of a slider. In digital character animation software, advanced functions can simulate the light emission to a very

fine degree. Light sources have a visual representation in the virtual environment depending on their type, for example a cone for spot lights.

In this study, I explored the selection and manipulation of lights as virtual objects in the virtual environment in the context of animating¹². I created two type of lights, an omnidirectional light which emits light in all directions and a spot light which emits light in a conical shape. The omnidirectional light was represented with a small bright sphere and the spot light with a model of a small cone. From the top of the cone protruded a straight line which ended a little after the base of the cone and indicated the direction in which the light was emitted. Both lights were manipulated with the haptic device. Only the spot light could be rotated and this happened in two ways. The first was by using the rotational DoFs and FK and the other by moving the outer part of the cone using the translational DoFs and IK in order to rotate it.



Figure 3.35: Light properties menu. The model is used under the Creative Commons License

Two GUI buttons were used to import the two different types of lights. A third button provided a menu for changing the lights' colour and intensity. When the light was selected with the sphere, pressing 'TAB' on the keyboard created a clutching mechanism where the light remained selected so that the animator could leave the stylus aside and use the mouse to press the GUI button. By pressing that button, the menu on the right disappeared and three sliders appeared in the middle of the scene with which the three RGB colours, red (R), green (G) and blue (B) could be adjusted (Figure3.35). While the three sliders were activated, the scene behind them was still visible and the animator could navigate it if she wanted to look

¹²An example of the way light could be manipulated in the haptic workspace can be found in the video entitled 'Lighting' in folder Chapter3 of the DVD

at how different setups lit the scene and the characters from different camera angles.

Moving the sliders along the same values, increased or decreased the overall intensity. If all pointers were on the left the intensity is zero and the lights are off and if all the pointers were on the right the light emitted with maximum intensity. The animators could import an unrestricted amount of lights into the scene. However, because the effects that each light had on the scene geometry and their combined effect was calculated in the computer's processing unit and rendered per frame, the presence of more than four lights reduced the overall rendering frame rate significantly.

For this study I established a second collaboration apart from that with the animators. Lighting is a quite complex activity, especially in digital animation software. In the big digital animation studios, the set-up and rendering of lighting is done by a team of specialists, called light designers, after the animation of the characters is done. As I wanted to discover the full potential of the lighting in the haptic workspace, I asked Tobias Feltus, who apart from professional puppet stop-motion animator was also an experienced analogue photographer, to use and reflect on the lighting in the designed prototype. Feltus's photography work involves great expertise in the creative and artistic use of light.

3.7.1 Reflections and Insights

The animators found that moving the virtual lights around the virtual environment was a quick and easy way to rapidly pre-visualise the scene's lighting as well as the lighting of the characters. One of the animators commented:

Light is quite a big thing in stop-motion that has effect because you are animating the character through shadows. If you have got areas on the set which are lit in a certain way and then areas which are darker, you can see how your character is to be lit, you can see that physically. I suppose in CGI my understanding is that they do the lighting after they animations are finished so probably it is hard to imagine what the characters and environments are to be like.

The ease in adding or removing any number of lights and the ability to change and animate the lights' colour rapidly, which in their practice is difficult to do, was found to be useful for the animators. Feltus suggested that the spotlight's cone diameter should be adjustable so that the area over which the spotlight spreads can be controlled. This is useful when combining all lights together for layered lighting. He also suggested that there could be an orbit function for the lights around a point of interest for small adjustments such as correcting the shadow underneath the eye of the character. Defining a point of interest on the model would rapidly move the light close to it and set it into orbit with an angle defined by the angle of the stylus. This metaphor demonstrates similarities with a viewpoint metaphor suggested by Mackinlay et al. (1990). In their approach, the key idea was to have the user indicate a point of interest on

a virtual 3-D object and use the distance to this target to move the viewpoint logarithmically, by moving the same relative percentage of distance to the target on every animation cycle. The *small-scene manipulation* metaphor, suggested by (Boeck et al., 2006), is also based on the same principle. The metaphor is presented in the context of interaction metaphors with haptics and proprioception in virtual environments and it does an automatic close-up of a part of the virtual environment the user has specified.

I noticed that the animators did not adjust the properties of the lights frequently. One reason for this could be habit. According to their account, due to the fact that it is difficult to move the artificial lights around the stage, excessive strain is reduced by planning the lighting ahead of time and filling in any light effects in the post-production using digital software.

3.8 Intervention 6 : Multiple viewpoints

During the design studies, in several occasions the animators mentioned viewing the scene from different camera angles. An example from the early stages of the design studies was that many of the animators commented that being able to view the character from different angles would give them a better sense of where the sphere is in relation to the bone structure. For many of them this would work as an alternative to highlighting the bones to which the sphere was close. This led me to understand camera use as an important aspect of the stop-motion practice and to envisage a plethora of potential applications in the haptic workspace based on the previous animators' comments. Therefore, I set out this study to experiment with different camera angles and investigate the use and appropriation of virtual cameras in the haptic workspace.

I set up eight cameras. Four were looking at the character from four directions, one was the original camera looking at the character directly and one provided the top view (Figures 3.36 and 3.37). A seventh camera was the orbit camera introduced in the bi-manual interaction study. In addition, while observing them in their studio I noticed that one of them had taken the puppet's head off and positioned the digital camera close to the neck so that she could animate what the puppet sees. This indicated that at least one more camera should be present in the virtual workspace, acting as the character's eyes. Following this insight, I created a camera which could be positioned looking in the direction that the character was looking.

The animators could switch between the eight cameras by pressing certain keyboard keys. Each selected camera used the animator's eyes metaphor and could be moved with either the keyboard, 3-D mouse or haptic device within its own reference system. For example, zooming in and out with the top view camera would bring it closer or further away from the character's head respectively¹³.

3.8.1 Reflections and Insights

As they had suggested in the previous studies, the animators used the multiple angles to get an overall view of the model. Being able to view the models and the distance of the sphere in relation to the models assisted them in orienting themselves in the virtual environment. It was also an aid towards positioning the sphere for bone selection and manipulation.

¹³The video entitled 'Cameras' in folder Chapter3 of the DVD shows an animator working with multiple cameras to animate

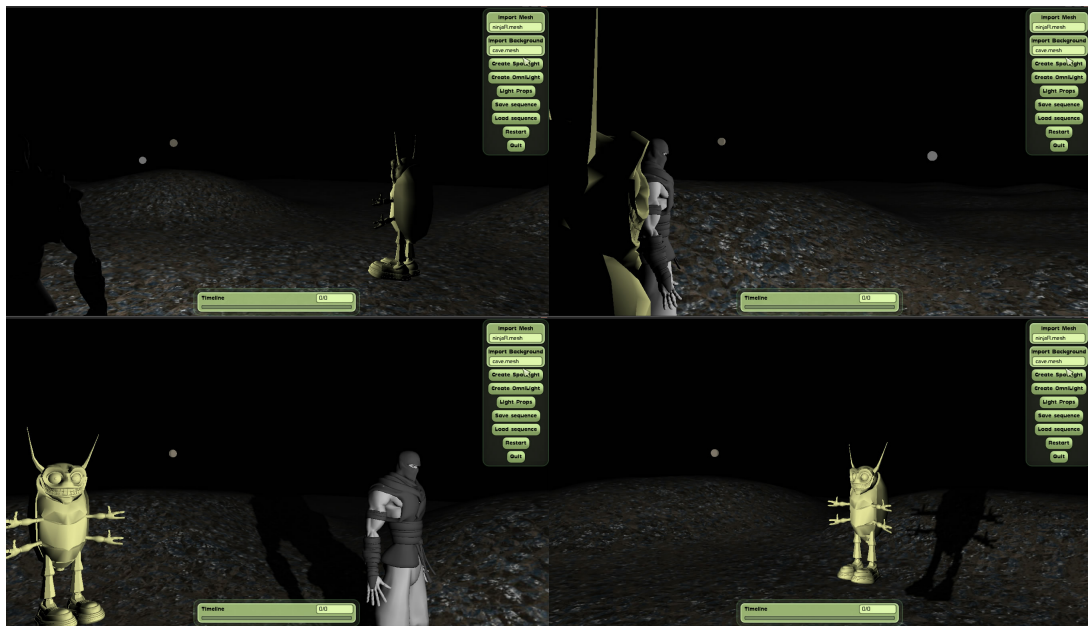


Figure 3.36: Multiple viewpoints (Models are used under the Creative Common License)



Figure 3.37: Camera showing the top view

Camera views

An experienced animation technician who worked in the haptic workspace for the first time, suggested that an even better approach is to avoid having to switch between the cameras and present the rendering by default from four views, three orthographic and a perspective view, similar to the way that digital software displays them (Figure 3.38).

Orthographic views are the top, side and front 2-D views of the virtual environment. The

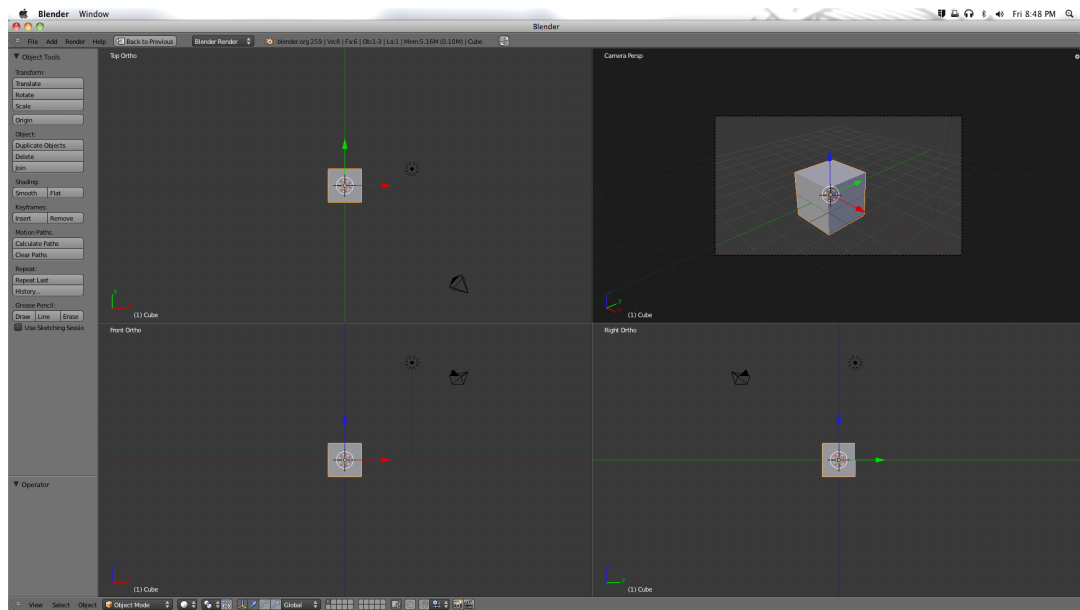


Figure 3.38: The four views in the digital animator's workspace (Blender 3D™)

advantage with this setup is that the animators can simultaneously watch all four views which immediately gives them the opportunity to control in detail the sphere's position in relation to the bones and the size of displacement and angle of the bone's motion. One animator compared this to racing computer games:

With the orthographic views there is a sense of some aerial space. Sometimes you can get some sense of how deep you need to go or how far you have gone into infinity and how far back you need to come. What I always think of is computer racing games. You know when you are driving there is this small map which you use all the time. Essentially, why is that not incorporated in three dimensional programmes so that when you advance through three dimensional space you know where you sit, where you are? It is a kind of anatomical layer

His comment described the *world-in-miniature* navigation metaphor identified by Mine (1996). The metaphor is based on the user performing manipulations on a small miniature model of the world visible in the bottom corner of the main viewpoint. It allows easy and fast large-scale operations. The miniature model can be used for navigation and also for selecting or manipulating objects. This technique is especially useful when manipulations over large distances is required, but 'lacks accuracy due to the small scale of the miniature representation' (De Boeck J. et al., 2005, p.6).

One possible issue I raised with this approach, was the processing power needed to render the graphics from four different cameras at the same time. To this, two animators responded that it can be rendered in wireframe which, in addition, would give them the opportunity to view the skeleton of the character. Interestingly, they were prepared to disregard the ability to see and sense the textured surface of the character if its absence meant greater precision and

control. So far, I had considered the graphics influential to their interaction with the character. Thinking of all the studies in retrospect, they never made a comment about the quality of the graphics which, while they were created to be as detailed as possible, they were not close to being realistic due to lack of processing power in real time rendering. I commented on this and they responded that computer graphics already have the capability of producing realistic rendering of graphics in real-time. Consequently, this was not an issue for them since they argued that it is only a matter of time until they will be able to work with characters that look and feel real.

The implementation of the multiple camera views was very close to the GUI tools that help digital animators orient and navigate their workspace. This observation seeded the idea of testing the camera interface with them which soon transformed into a more complete study. Exposing the digital animators to the haptic workspace was a study that I was aiming to do since the beginning of the research in order to record their responses to a digital animation environment that enables embodied interaction with the virtual characters. I decided to carry out the study after this one. Since it would be conducted as a parallel to the main research, I decided to conduct it in a similar approach to the workspace intervention in order to keep an open ended space for all kinds of experiential outcomes.

What is rendered interesting in the study with the digital animators, is the fact that one workspace which has been designed with the traditional animators will be used by the digital animators. Consequently, emergent properties and functionalities seen from the perspective of digital animators can provide knowledge with regards to identifying areas where the two techniques converge. Design insights could be connected to the previous findings and all can be brought together using the multiple streams of reflection.

Camera angles

The animators were particularly interested in the camera that could be positioned in front of the puppet's eyes and turn the viewpoint to what the puppet sees. While experimenting with this camera, they suggested that they should be able to animate it in the same way in which they take snap shots of the scene to portray what the puppet sees in their practice. According to their comments this makes the animating process in the virtual workspace more interesting because it enables direct change of animating angles, otherwise called movie sets. They proposed that the camera itself can be animated and capture the part of the virtual environment which is visible through its viewpoint. By easily positioning the camera in various places, they will have instant feedback of the view and can adjust it directly before animating the camera. I raised the question of how the animator can have a view at all times of the animated camera viewpoints and the overall view of the virtual scene.

So far, each camera has its own viewpoint which displays the relevant part of the virtual

environment that is visible through this viewpoint, the animator's eyes. However, in the physical puppet stop-motion workspace there is one more camera, the digital camera which is positioned in a fixed point at every frame. The image that this camera records is the final image that is displayed in the digital software and the one which will eventually be displayed at the corresponding frame in the final animated movie. This is the extra camera that the animators proposed as the haptic workspace had one camera for both the actions of working on the puppet and capturing a frame. The cameras that provided the alternative angles, were taking the role of the animator's eyes every time the animator switched to one of them. As a result, when the sequence of frames was played back, it could be viewed from the angle of the selected camera, but there was not the view of the animated sequence from a fixed viewpoint, the viewer's viewpoint.

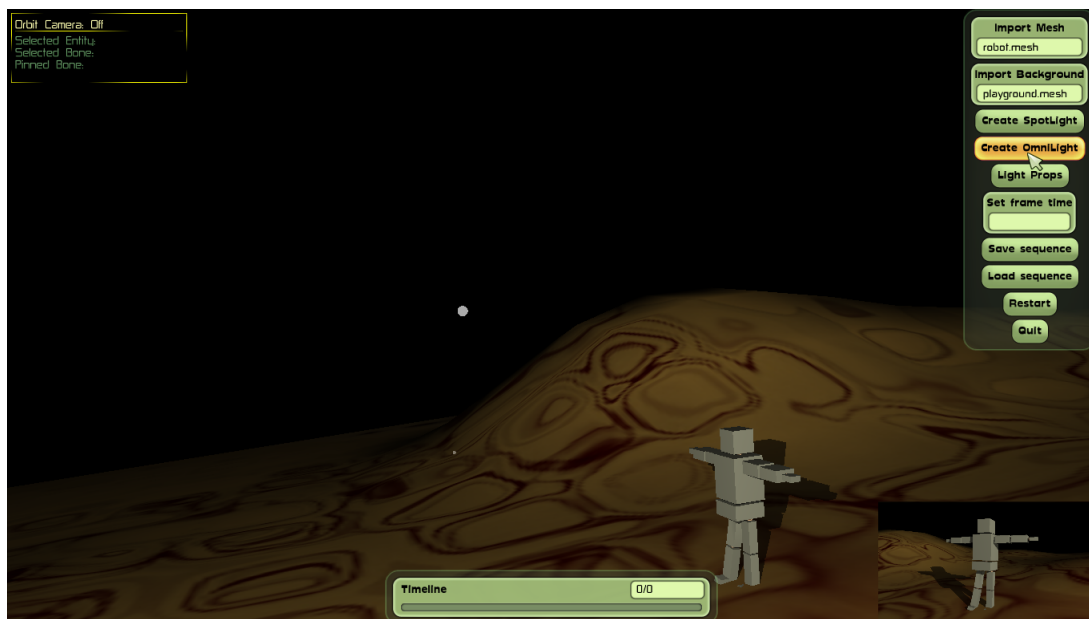


Figure 3.39: The fixed viewpoint on a layer at the bottom right corner

I created the camera which could be animated and placed in an overlay at the bottom right of the screen which displayed the part of the virtual environment that the camera looked at (Figure 3.39). The parallel rendering on the main display and the small window overlaid on the main display made rendering slightly slower.

The study that follows this one is not an intervention in the puppet stop-motion animators workspace but in that of the digital animators. However, before I conducted this study, I sought to explore one of the most commonly used stop-motion software animation packages. I carried out this exploration at this point because the haptic workspace was at a development stage where the puppet stop-motion animators could work in it unencumbered. Thus, I could review the animation software's functionalities and check whether any of them were missing

from the haptic workspace. I explored the software on my own but asked the animators questions regarding some functionalities that I considered important and which they had not been suggested so far.

3.9 Review of digital software for puppet stop-motion

Having reached one of the final stages of the prototype development, I spent some time exploring professional stop-motion application software in order to gather information about the type of functionalities and metaphors that they offer and evaluate to see if some of them could be incorporated into the design of the haptic workspace. The reason for doing this at this stage and not at the start of the design process, was because I did not seek to replicate existing functions of digital software but to be lead to the appropriate design solutions for an enactive animating experience through the collaboration with the animators.

Stop-motion software are the computer applications which communicate with the digital camera, receiving and storing the captured images in a timeline and allowing their further rearrangement alongside further functionalities such as controlling the FPS. My goal was to further inform the development of the haptic workspace with additional functionalities that had not been suggested by the animators. My decision to do so, derived from noticing that occasionally the animators used in their comments examples of functionalities available in commercial stop-motion software. A small scale survey amongst the animators showed that the most complete software and the one that is most frequently used is DragonframeTM. In my study, I found one major functionality that had not been designed into the haptic workspace, the ability to create, view and place comments on the storyboard of the animated movie, a method of drawing the major frames that show the progression of the story. I also noted down some interesting functionalities present in each channel which I discussed with the animators. The discussion sparked ideas for further implementations in the haptic workspace. I discuss them below.

DragonFrameTM has six main channels, Animation, Cinematography, DMX, Dope sheet, Audio and ARC Motion Control. The Animation channel has all the necessary functionalities for capturing and storing the frames, setting the FPS, enabling onion skinning and providing drawing tools to sketch on the image for design purposes. This channel included the same basic animation maker as the one implemented in the haptic workspace. Onion skinning was discussed in Section 3.4.2 as a possible addition to make the timeline more visual. Sketching on the image leads to considering the two dimensional act of drawing. Drawing on the images can be done in DragonframeTM using the mouse. Seeing this functionality, led me to think of 2-D animation and of potential applications of the haptic stylus to 2-D animation as a 3-D device. Research on the design of haptic pens exists in HCI literature and most of them are

for interacting with touch screens (e.g. Lee et al. (2004), Iwata (1993)). I was interested in the interface design implications of using a 3-D device for 2-D animation. In addition, early in the design studies I had made the observation that the virtual environment offers a 2-D representation of a 3-D world (see Section 3.5.2). Using the 3-D haptic device for animation techniques which traditionally require 2-D input, would offer me the opportunity to explore the practical constraints and the new possibilities of this mapping. Discussing with the puppet stop-motion animators, I concluded that the best approach would be to study this with 2-D animators. The relevant study is presented in Appendix A.

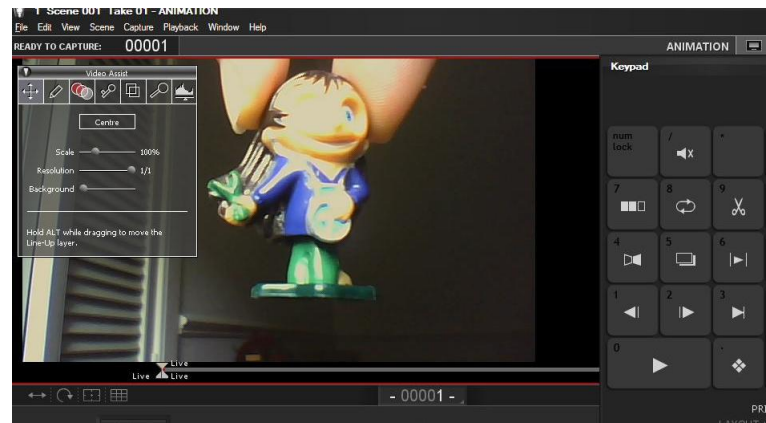


Figure 3.40: DragonframeTM's Animation channel

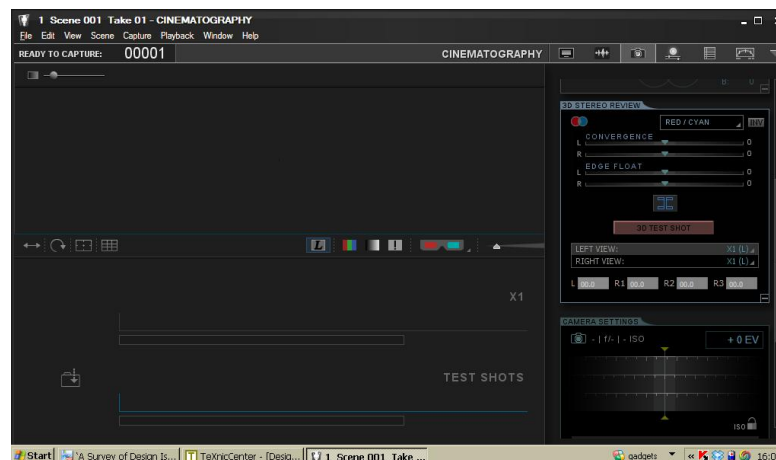


Figure 3.41: DragonframeTM's 3-D view function

The Cinematography channel provides remote control for the digital camera and live viewing of the animated sequence with an option to view it in 3-D. This last option is rendered quite important as currently, and for the past few years, the 3-D animated movies industry is blooming with many big animation studios producing motion pictures for 3-D viewing experience. Constantly improving computer technology is available which supports 3-D viewing of the desktop virtual environment without the need of polarized glasses. I anticipated that such research would be a large scale project, however, I suspected that

explorations of navigation and object selection and manipulation in a 3-D view-enabled virtual environment will lend further support to the research findings presented in this thesis. The 3-D displays are an example area where evidence found in this research project can comprise input for further studies, under the holistic appreciation of the design process.

The DMX channel provides the DMX protocol which is used to control the lights of the scene. The DMX panel in DragonFrameTM offers tools to set-up, customize and visualize the lighting conditions. External DMX-enabled controllers can be attached for remote control. The haptic workspace provides interactive lighting in a similar rapid and easy way with the addition of adding or removing lights instantly. The GUI for adjusting light properties is hidden and is brought out only when needed. DragonFrameTM's sequencer-based DMX workspace allows the cut-copy and paste functions for the frames including the lighting conditions. The puppet stop-motion animators have suggested these functions for the haptic workspace and they have been implemented.

In the Dope Sheet channel I found one functionality I thought was a major aspect of the stop-motion practice that was not implemented in the haptic workspace. The Dope sheet channel is the digital version of the storyboard paper sheet (Figure 3.42). The dope sheet was originally used in traditional 2-D animation for expressing visually and planning the characters' motion but it is also used by puppet stop-motion animators for assembling the sequence of frames with notes on anything pertaining to the structure of the animating process such as timing, camera moves, the number of exposures for each frame and the camera angles.

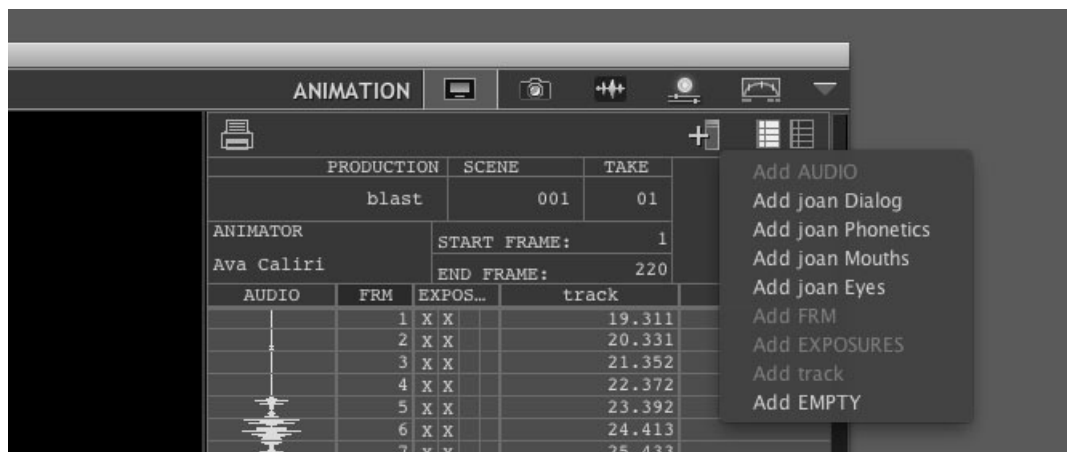


Figure 3.42: The Dope Sheet in DragonFrameTM

Although the dope sheet was outside the scope of my research on embodied tacit skills, I questioned the reasons it was not mentioned during the design studies since it was a major aspect of stop-motion animation. I mentioned it to the animators and their responses showed that it was not a process that they had imagined integrated in the workspace. In addition, they said that some of the data on the dope sheet, such as camera exposure, were not used

in the haptic workspace. The option to have side notes with information on the scene did not seem important to them at this stage of the development at least.

One of the stop-motion animators with background in software development, suggested that the data that is stored when the animators work in the haptic workspace can be made available in order to be adjusted manually. The same data which is normally logged on a dope sheet is available in the present haptic workspace and it is easy to produce a log out of it. An example is the xml format of the animated sequence which keeps track of the frames in a sequence and stores the coordinates of the virtual objects and the lights' properties in each frame.

The ARC Motion control channel provides a GUI for programming the camera motion with the possibility of connecting peripheral controllers for this purpose. The haptic workspace already provides this functionality with three different controllers, the 3-D mouse, the keyboard and the haptic device.

The Audio channel is dedicated to sound. The animators described how sound is an important part of the animation process and how it accounts for a great deal of the final animated movie's atmosphere. Usually a professional sound designer is employed to create the sound effects after the animated movie is finished. The part where the sound is configured in DragonFrameTM was a simple sequencer for sound and motion synchronization. In my research I did not investigate sound in-depth except for a few discussions with Lauren Hayes, a sound designer from the University of Edinburgh's Sound Design department who was also experienced in using haptic devices for audio installations. We collaborated on some initial designs around creating sound effects for each frame and controlling their properties with the haptic device. However, I felt that embarking on such research was beyond the scope of this thesis. There are some very interesting questions to be asked and areas to investigate regarding research on sound, haptics and animation which could form a research project on its own. Evidence in this thesis can provide a basis for such research.

3.10 A study with digital character animators

In Chapter1, I emphasized the fact that digital animation workspaces do not support the embodied ways of working with physical puppets of the puppet stop-motion animators. Digital animators have different tacit skills, which do not involve the same dimensions of embodied working as in puppet stop-motion. Instead of physically manipulating puppets, they use the WIMP and pen-based interfaces to work with them. Because of the lack of direct physical manipulation of the virtual characters, digital animation software have introduced a number of small workarounds and interaction metaphors that digital animators use to address this lack. Therefore, I considered significant to observe how the digital character animators would

approach the haptic workspace given that it uses a digital interface but one that enables enactive response and embodied interaction with the characters. In this study, I was interested in the digital animators' reflections on the existing functionalities and metaphors as well as the changes they would bring design-wise.

Moreover, digital animators are more familiar with working in a virtual environment than the puppet stop-motion animators are and their work methods illustrate proficiency in navigating the virtual environment and selecting/manipulating objects in it based on two dimensional input. Asking them to animate in the haptic workspace offered the possibility of identifying a common ground between both practices.

Another reason which led me to this study was my reflection on the findings of the study on multiple viewpoints. In particular, it was the suggestion by a very experienced animation technician that the cameras in the haptic workspace could be arranged to provide the four different views, three orthographic and the perspective, in the same way as in digital animation software. Although I argued that this setup would not enable enactive understanding of the workspace but would only be a visual help, I acknowledge that his suggestion was the result of his long background experience with the puppet stop-motion technique and some experience with digital character animation. This made me realize the possible new areas of research that can derive from a study with digital animators. In addition, I thought of the areas of convergence between the two techniques in the haptic workspace in relation to the ways the workspace could support it.

The study was conducted over two one day sessions in collaboration with Thaleia Deniozou, a professional digital character animator. In the first session, in March 2011, I described and demonstrated to her the different functions of the haptic workspace and asked her to spend as much time as needed to familiarize herself with it and explore its functions by animating a virtual character. The second session took place one month after the first one in April 2011. This was done intentionally in order to allow her time to assimilate the animating experience in the haptic workspace and speculate on potential changes in the way she animated through the WIMP interface after this experience.

The setup of the haptic workspace consisted of the 3-D mouse and the haptic device. Both devices and the keyboard were used for camera navigation. My decision not to employ the Wii Remote was primarily because of its occasional drift which would not provide seamless interaction. The locking chain model was used for character manipulation.

3.10.1 Reflections and Insights

Overall, Deniozou felt that using the haptic device was for her an immensely intuitive way of navigating the space and animating the character. In addition, she was able to understand the mechanics of navigation with the haptic device in the virtual environment and work on the

character with ease in less time than the stop-motion animators did. This can be explained by the fact that digital animators work in virtual environments so they already have a good perception of the virtual workspace. Notwithstanding, she experienced some difficulty in navigation, object selection and manipulation.

Visual aids

Deniozou considered that the range of motion of the sphere was not large enough in the depth dimension, something that I had already identified together with the stop-motion animators (see Section 3.5.2). In relation to this, on many occasions she was uncertain as to when the sphere was close to a bone. Interestingly, she did not form the haptic map that the stop-motion animators were able to form. This was possibly due to the fact that physical interaction is not part of her skills in combination with the fact that she did not have the equal amount of time available to practice animation production in the haptic workspace as the puppet stop-motion animators did. Visual feedback was discussed as a solution repeating the process with the stop-motion animators in the beginning of the design studies. Deniozou brought a more dynamic approach to visual aides by suggesting that the sphere could change its colour when moving closer to the bone. She also suggested that a visual representation of the Cartesian axes on each bone would help her know the angle at which a bone or joint is rotated at all times.

Her second comment related to visual aids was that it was necessary to indicate the root joint when it was selected as well as the joints that were pinned down each time. Her suggestion was to assign to them a different colour upon selection. I had designed a text box that displayed the name of the pinned joint and the name of every joint the haptic device's representation was passing from. However, Deniozou argued that changing the colour would be less distracting than constant eye travel between the space and the GUI text box. Essentially, she was advocating the maintenance of the loop between kinaesthesia and cognition.

Automation

Deniozou argued that some level of automation is a requirement in digital animation. Some of her suggestions overlapped with automated processes suggested by the puppet stop-motion animators while some of them significantly reduced the level of control over the tasks involved, which would not have been acceptable for the puppet stop-motion group.

Her first immediate comment was that automated processes which calculate motion rapidly and easily were missing from the software design. In contrast to stop-motion animators, digital animators do not require total control over the motion of the character. They usually set a target position to which the character or part of its skeleton will move and algorithms such as interpolation calculate the most realistic path towards that goal. Some digital animators move

to the field of programming and work with pure data to construct controllers for complex motions such as detailed animation of the whole or a specific part of a virtual character (e.g. special controllers for moving the hand in a realistic manner) or correction of captured motion with Motion Capture techniques. These controllers are made available in the form of tools, often called plug-ins, for commercial digital animation software.

Another comment on automation that Deniozou made, was the ability to copy and paste frames on the timeline. This, she explained, is very useful in the context of digital animation and a basic function in digital animation packages. We have seen in Section 3.9 that this functionality is included in professional stop-motion software. At times, poses need to be repeated, often for creating cycles of movement such as walking cycles. Stop-motion animators have also indicated the copy-paste method as a very useful element of digital software so both stop-motion and digital animators would benefit from this addition.

Deniozou considered the haptic workspace itself as an automatic tool. The word automatic was used by her in a metaphorical way to denote that the haptic workspace allowed natural bodily motion to guide the animating process and made interaction with the virtual space and objects much more intuitive. In particular, she said:

One can do a variety of things with the haptic workspace without analyzing them or breaking them down in discrete parts. For example, there is no need to get closer and select the particular visual element that represents a bone or the armature representation and there is no need to bring out visual elements to assist in space transformations such as the wheel for rotation. In that sense you know less things! It seems to me more natural to work in this way

Her comment implies that the haptic workspace supports embodied cognition. What she described was essentially the difference between working with 2-D input as opposed to 3-D input in a virtual environment with reference to the metaphors used for mapping the bodily actions in each case. With a 2-D device, the action of manipulating the character includes many discrete steps that exist to facilitate perception of space whereas with spatial input devices manipulation is performed in a more direct and natural way. For example, the wheel for rotation that she mentioned, is a visual aid for rotating joints in digital character animation software with the mouse. It consists of a representation of the three Cartesian coordinates and the possible angles of rotation in each axis which is visually displayed as a spherical area (Figure 3.43). Rotation is performed, usually with the mouse, individually in each axis in discrete steps as opposed to the same action carried out seamlessly with the haptic device.

Reflecting on agency, Deniozou preferred to give agency to the camera instead of moving it herself. Her suggestion illustrated a camera control metaphor similar to that proposed by Boeck et al. (2006) (see Section 3.6.2). When the manipulandum is moved towards the limits of its range of motion in depth, the camera will move accordingly towards the same direction. This solves the problem of the limited range of motion because the motion of the camera

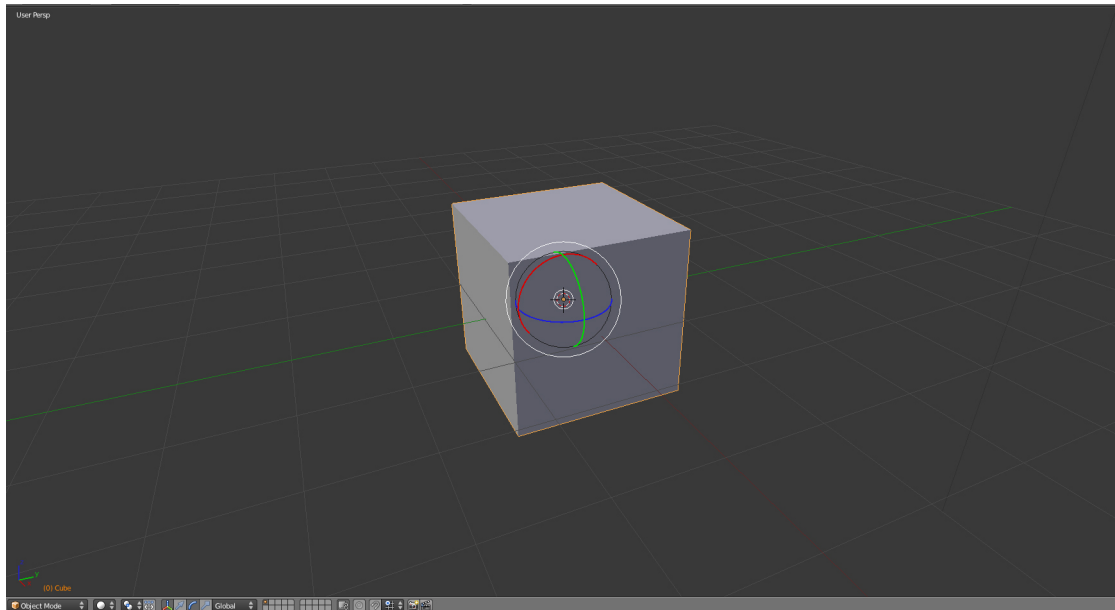


Figure 3.43: Wheel of Rotation in digital modelling and animation software (Blender 3D™)

triggers the motion of the sphere so the sphere obtains a new initial position without the manipulandum being moved in physical space. She suggested this metaphor for the zoom of the camera, however, the concept can be extended to all directions.

Cameras

Deniozou found the 3-D mouse quite difficult to use and she would not prefer it for camera control resonating with the stop-motion animators' experience. While she showed no preference for controlling camera motion with the non-dominant hand, she did not comment on what actions could be performed with it instead. I observed that she used her non-dominant hand to work closely with the keyboard in order to place the frames and switch between cameras. This way of working pertains to the regular way she uses her non-dominant hand in her normal work and this was possibly the reason she did not consider further actions with it. Respectively, the puppet stop-motion animators had suggested the puppet-in-hand metaphor which pertain to their working method.

Furthermore, she found the existence of more than one cameras and the rapid way in switching between them very helpful. She also highlighted the importance of having a fixed camera that would be the viewer's viewpoint which was also mentioned by the puppet stop-motion animators and discussed in Section 3.8.1.

Per-gesture vs per-frame synthesis of motion

One of Deniozou's comments regarding the capturing of frames, revealed an important design aspect of the animation maker with implications not only for its design in the haptic workspace but also in digital animation software as well.

Deniozou asked if each frame corresponded to one second in time. I responded by outlining the way the FPS worked and that depending on the FPS rate, she could create 12 or 24 frames to be displayed in the time of one second. Deniozou then observed further that instead of creating frames and calculating how many frames will be needed for one second of animated movie, a per-gesture division of time would be a more convenient way to manipulate motion over time.

I want to calculate the amount of motion for each frame. For example I often want to gesture in different speeds, to start with slow motion and then to make it faster

What she essentially described is a real-time recording not only of the motion of the character but also of the dynamics of the motion, the acceleration and speed with which each part is moved or rotated. This translates also into the dynamics of the gesture. In order to record those dynamics, the recording of the motion must be done on a per-gesture rather than on a per-frame basis.

In a per-frame synthesis of motion, such as in puppet stop-motion, the animators need to calculate the character's pose in each frame and simultaneously picture the overall motion as will unfold over time. In a per-gesture motion synthesis, the duration of time that one motion lasts for is directly determined by the animator's gesture. Instead of calculating the overall motion using frames, it is calculated directly through gesture. The per-gesture method is an excellent way of connecting gesture with time, the most important dimension in the animating process 'that gives meaning to movement' (Whitaker et al., 2009, p.2).

One of the first research towards per-gesture synthesis of motion was carried out as far back as 1969 by Ronald Baecker (Baecker Ronald, 1969). Baecker developed *Genesys*, an animation system which used a predecessor of today's pen-based interfaces and the TX-2 computer, a transistor-based computer built at Lincoln Labs in MIT. Notably, the work of Baecker was one of the first user-centered design approaches to system design as he developed and iteratively tested his system with animators specialized in hand-drawn animations¹⁴. With *Genesys* the animator could draw an object with the pen and then draw the path the object will follow. The tablet on which the pen moved, captured the dynamics of the animator's gesture while she drew the path. The animation was played back with the dynamics embedded in the motion of the object. The dynamic construction of the path was possible 'by timing the pen's movement and recording its position at short, uniform intervals such as every 24th of a second' (Baecker

¹⁴The relevant video can be found in: <http://www.youtube.com/watch?v=GYIPKLxoTcQ/list=UUT9jsoLE1TIkf98tononxcg/index=5/feature=plcp>, accessed 21 December 2011

Ronald, 1969, p.77). Baecker explains that in the architecture of his system, a *path* description does not only capture the change of x and y coordinates but also that of variable parameters such as size and intensity. To understand this better, I should explain that *Genesys* was a picture-driven animation system. It did not limit itself to playing back static images existing at single instants of time (frames). Rather:

Dynamic behavior is abstracted by descriptions of extended picture change. These descriptions may themselves be represented, synthesized, and manipulated through pictures, both static and dynamic. Thus dynamic control can be exercised globally over the entire sequence(Baecker, 1969, p.274)

Baecker achieved dynamic control by modifying continuously variable parameters that accompany each static drawn image such as location, size, thickness, density and intensity.

Their instantaneous values determine the picture's appearance at a given moment. Thus the static picture may be animated by specifying the temporal behaviour of such parameters. [...] Since the behavioural descriptions of the parameters apply to entire intervals of time, the animation is liberated from a strictly frame-by-frame synthesis(Baecker Ronald, 1969, p.76)

Because stop-motion uses a frame-per-frame synthesis of motion, representing changes in intensity and other variable parameters that Baecker refers to, is done by adjusting the rhythm of motion through the frames. For example, stop-motion animators can freeze the character in the same pose for a couple of frames so that it seems to be moving slowly when the frames are played back. According to the stop-motion animators, the number of frames that will display the same pose is decided in the beginning of the process and stays the same for the whole sequence. One pose may be shown for every one frame or every two frames. This means that, for example in a movie with 24 FPS, 24 poses will be created in the first case as opposed to 12 poses in the second case. By showing one pose over two frames, the character appears to be moving at a slower pace.

A similar method is used in digital animation since digital animation packages borrowed from the stop-motion technique, with the difference that the capture of poses is not done as linearly as in stop-motion. These packages offer methods which use time more fluidly, such as the application of kinematic algorithms and the drawing of motion paths, however they still do not offer the opportunity for direct application of the dynamics of the animator's gesture into the motion of the character. For the kinematic algorithms, the animators define the period of time that the produced motion will last and then apply the algorithm. Any changes in intensity or speed are made by fine-tuning the relevant parameters throughout the character produced poses. For the motion paths, 2-D or 3-D depending on the kind of animation software, the animators draw the path and then assign virtual objects to follow it. The speed of the object following the path can be adjusted only after the paths have been drawn. The difference of

these approaches with Baecker's system and what Deniozou suggested is that they do not capture the dynamics of gesture directly but require one more step in-between.

Moving from per-frame to per-gesture synthesis will change the architecture of the method that stop-motion animators use to create motion. Learning how this affects their practice and exploring how they adapt to it is a significant thread to follow for future research. For example, in Chapter 1 we saw how timing and acting are two fundamental qualities of the puppet stop-motion practice with acting being strongly present in their practice without being reflected in the various animation interfaces that exist. The use of per-gesture motion synthesis can enhance these aspects and bring acting into the animation workspace.

It is interesting to note, for two reasons, the fact that Deniozou made this comment when she animated in the haptic workspace. Firstly, it reveals that the spatial capabilities of the haptic device enabled her to redefine her working methods in enactive ways she might not have anticipated while working with the mouse. Secondly, her observation has a value as a strong example of user-driven design. It led me to consider the 3-D input of the device not only in spatial terms but also in temporal terms. Although this architecture was not implemented in the haptic workspace, it is an important contribution towards the design of more intuitive interfaces for animation, which connect time with gesture.

The animating experience in the haptic workspace

After the second session, I conducted an informal discussion with her to trigger her reflection on the overall experience of animating in the haptic workspace. Since the first session was one month before the second, I asked her if she could indicate any differences in her normal work after her experience with the haptic workspace. She responded that she felt a little bit more comfortable working with the mouse and keyboard but thought that this is because she is used to it and because of the comparatively short duration of animating in the haptic workspace. She thought that this had to do more with her intuition rather than the technology and that if she continued working with the haptic device she would not return to the mouse. She was very impressed with the haptic workspace and shared her view of being able to work in the future with similar interfaces.

The mouse and keyboard is more comfortable for me because I am used to it but it feels more technical. With the haptic device you feel more like you move things with your hands and with the mouse you are more aware of the in-between technology

Another question I asked was whether there was something she felt was lost or gained while working in the haptic workspace in comparison to her existing work methods. Her reply was that she did not think there was anything lost and in her response she affirmed that the ease of navigation she exhibited derived from working normally in a virtual environment.

I don't think there is anything lost. If you have previously worked with animation technology it is much easier for you to understand how to use the application in general because you have the knowledge of your things and that you know where they should be. But if you were able to use your skills in a way that it is more creative, that is the best combination

As she mentioned creativity, I asked her if she felt she could be equally creative in the haptic workspace as she is in her existing practice. Her response drew on the freedom the haptic workspace allowed towards creative endeavours.

I feel I can be more creative in the haptic workspace because you have the feeling that you are more free. You feel that you have more space to do what you want. You feel like you are more in control of the space, something is in your reach and you can touch it instead of always looking at a grid and having to do everything with the mouse

In depth discussion on the creativity of a tool is rather challenging as it can be viewed from multiple perspectives. Creativity in HCI and the evaluation of digital tools in relation to creativity is a research field in its own merit. Instead, I considered Deniozou's response from the perspective of embodied cognition and concluded that, in her regard, the haptic workspace offered embodied ways of working. Further in the discussion, she enforced this view by recognizing the advantage of bringing physicality into the digital animator's abstract workspace, which, according to her view, opens up creative avenues for developing new kinds of skills. In particular, she mentioned that the production of believable motion for a digitally animated character is a measure of the skill of digital animators, and that manipulation of physical objects can assist the application of believable motion due to all their constraints and physical properties. As digital animators do not work with physical objects, they try to bring physicality into the digital workspace and develop this as a skill. The haptic workspace makes the formation of this skill easier because it offers the sense of physicality and also induces immediacy, the sense of absolute directness, in the animating process.

I think [the haptic workspace] takes out the mediation feeling. Although you are using machines again, you have the feeling of working with your hands and you are not so aware of the technology. So you get the feel of reality which is very overwhelming for a digital animator to feel

Convergence of the two techniques in the haptic workspace

My reflection on the responses by the puppet stop-motion animators and the digital animator indicated the differences in how each practitioner approaches the animating process. Most interestingly though, the comparison revealed areas where the two techniques converge.

Digital animators prefer automated processes and a strong degree of agency to assist them in their work. Stop-motion animators favor simple processes and control over the puppet's motion at all times. It could be said that those differences derive from the different

kind of interaction that each practitioner has with the characters. Two handed practice is evident in both techniques but in different forms. Puppet stop-motion animators have a more embodied understanding of the actions they perform with their hands as they have a more advance haptic sense than digital animators. Digital animators have developed intuitive skills in working with 2-D devices and WIMP interfaces but they use their haptic sense to a small degree in their actions. Thus, the nature of their interaction with the characters is not direct, physical and embodied as is that of puppet stop-motion animators. However, both techniques aim at constructing a captivating narrative and at creating believable characters. The art of animation shares common aspirations with the art of storytelling. The aim of any animator is to construct an interesting plot, a charming story that will engage and entertain the audiences. The storyline progresses with the planning, choreographing, direction and execution of the animated sequences. Similar to storytelling, at the core of the process is to infuse life into inanimate characters. Of all the objects that are being animated, the articulated models are the ones which should appear convincing to the audiences so that the latter empathize with them and forget that they are just models. The animators, being storytellers, must captivate their audience and cause them to 'suspend their disbelief', the situation where a non-realistic narrative appears to be realistic. This happens when, as Meir (2011) suggests, 'The audience feels that the character's actions are the result of its own inner motives, and not the animator's inner motives'.

Deniozou said that this is easier to do when the character is physical but when animating virtual characters, digital animators have to develop certain skills to overcome the lack of direct physical interaction in order to imprint believability in the characters' motion. By enabling enaction in the digital environment, the haptic workspace recreated the sense of direct physical interaction and, according to Deniozou, added a dimension of embodiment in the animating process.

Being able to animate in the same embodied way, the puppet stop-motion animators and Deniozou had numerous ways of engaging with the haptic workspace and forming their animating experience based on their existing tacit skills. A comparison between the insights gained with Deniozou and those derived from the design studies showed that in many ways they followed the same route.

They both experienced difficulty with conceiving depth and being able to work with precision in this dimension. They both suggested visual cues for coupling haptic and visual senses with the difference that puppet stop-motion animators were able to form a haptic map of the characters' structure which assisted them in navigating it and also in performing precise manipulation in all dimensions. The reason that the digital animator did not construct a haptic map might have been because she did not have the embodied physical aspect of animating a character inherently developed as digital animation software create a disembodied workspace

for animating.

Furthermore, both practitioners did not prefer the camera being operated by the non-dominant hand. This shows that their focus in terms of bi-manual interaction is placed on character manipulation. Deniozou did not suggest the puppet-in-hand metaphor but used her non-dominant hand for actions she is used to do in her normal practice, namely operate the keyboard for controlling functionalities such as capturing frames, assigning properties or carrying out automated processes. Conducting in-depth research with digital animators was not a focus for this research but I acknowledge that further investigation with digital animators might yield interesting results with regards to bi-manual interaction.

Moreover, it is interesting to discuss how Deniozou approached a haptic animation workspace which was designed together with the traditional animators. Overall, she had very little additions to make. She enjoyed the embodied way of working, something that she felt was missing from digital software. She also enjoyed the simple and minimal GUI interface and the immediacy and physicality that the haptic workspace provided, which, she considered, facilitated her intention to animate believable characters. Her further suggestions concerned automated processes which ease tedious tasks, for example copying and pasting of frames to create repetitive motions such as the turning of car wheels. This was also suggested by stop-motion animators. The difference was that in the beginning of the study she mentioned the need for automated calculations of motion which she said is very common in digital character animation. According to her, unlike puppet stop-motion animators, digital character animators are not trained to think of the in-between poses of a character so processes which calculate motion are very assistive to them. However, during the study and as she explored the haptic workspace further, she explained that the inability to haptically feel the virtual characters creates a set of skills around animating believability as if the characters were physical. As this changes in the haptic workspace, interacting haptically with characters leads to new methods of animating them in which automated process might be of little use.

This study showed that the haptic workspace has the potential of expanding to digital character animation. It highlighted that the ways haptic workspaces can support new kinds of embodied work for digital animators is an interesting area for further research. In addition, the study indicated that the haptic workspace can be used by both traditional and digital animators with immense possibilities for exploring its artistic and creative potential by each group individually and through their collaboration.

3.11 Conclusions

This chapter presented and discussed the design insights, comments, ideas and challenges that surrounded the development of the haptic workspace. It led the reader through the design

studies drawing on the connections between them as they were shaped by the experiential and multi-reflective co-design process. The haptic workspace prototype that was designed and developed for each study embodied the outcomes of this process.

With the completion of the design studies, the haptic workspace was a prototype in which the puppet stop motion animators could work unencumbered. Since the focus of my research was to design the haptic workspace, I did not aim to conduct a separate evaluation of the overall difference the workspace made to the community of puppet stop-motion animators and of its ability to become a new tool for them. Such an evaluation would require the animators to practise animation in the haptic workspace for a considerable amount of time. However, I sought to explore this kind of evaluation within my design methodology. I set up an evaluation study with the aim to trigger reflection on the potential of the haptic workspace to transfer the puppet stop-motion animators' embodied skills, which I present in the next chapter. I conducted this evaluation with a different group of stop-motion animators who did not participate in the design of the workspace.

Chapter 4

Qualitative evaluation of the haptic workspace

In Chapter 2, I mentioned that under the holistic approach, the design process is never ending and includes a series of stages each one of which can present a complete and working prototype, subject to further design. Upon the completion of the design studies, one such milestone was reached. The haptic workspace had reached a point where the animators could work in it unencumbered. In this chapter, I present and discuss a qualitative evaluation of the prototype at this stage.

This evaluation was a short evaluation which aimed at triggering reflection on and provide indicative results of the potential of the haptic workspace to transfer the embodied nature of the puppet stop-motion animators' hand skills and mediate the animators' artistic intention. It was not set to be a large scale evaluation of the ability of the haptic workspace to successfully transfer the embodied skills of the puppet stop-motion animators. Such process would be outside the remits of this thesis as it would be a long term project requiring a methodical approach which would involve carefully constructed methods possibly both qualitative and quantitative. The qualitative evaluation particularly, would require a large period of time over which the community of stop-motion animators would practise animation production in the haptic workspace so that any value that the workspace can add to their practice can be clearly identified and articulated.

The following sections introduce the methods that were used for the short evaluation that I carried out, describe the evaluation stages and discuss the insights that derived from the different streams of reflection that occurred during the process.

4.1 Evaluation methods

Two types of evaluation in HCI which occur during and after the design process are *formative* and *summative* evaluation respectively. The terms have been originally defined by Scriven (1967) in his methodological framework for performing evaluation of instructional materials and have since been adopted in HCI literature (e.g. (Williges, 1984), (Hix and Hartson H. R, 1993)). According to Scriven (1967), 'formative evaluation is typically conducted during the development or improvement of a program or product (or person, and so on) and it is conducted, often more than once, for in-house staff of the program with the intent to improve'. A summative evaluation 'is done after completion of the program and for the benefit of some external audience[...]'.

The evaluation of the haptic workspace's functionality was embedded in the co-design process and occurred during each design study. I argue that a thorough summative account of the value the haptic workspace can add to the community of stop-motion animators and to the different creative ways in which the animators may use it, can be possible once the animators have practised with an advanced version of the haptic workspace prototype for a considerably long period of time. The importance of practising with new digital tools has been highlighted by Dourish (2004) who considered practising to be an essential method of extracting those fundamental elements that 'develop the meaning of the use of technology as it is incorporated into practice'. Equally, and closer to the experiential ground, McCullough (1998) suggested that continuous *play* with the system has the potential of unveiling important information about the way 'our tools shape us as we shape them' (McLuhan, 1964). His suggestion pertains also to investigations about the new spaces for exploration that the haptic workspace can offer to puppet stop-motion animators. I consider practising to be an essential step for embodying the transferred skills and start building a new vocabulary for producing animation in the haptic workspace. However, the nature of the design work I conducted with the animators did not provide adequate time for long term use of the haptic workspace. Each study was of short duration and the required changes in the workspace's setup for each study produced many different designs.

In consideration of these issues, I decided to incorporate evaluation in my multi-reflective design methodology in an explicit manner, by carrying out a short qualitative evaluation with the intention to gather indicative results. My evaluation can be described as summative evaluation. However, Ellis and Dix (2006) give a more appropriate definition to it, explorative evaluation, which is evaluation 'that help us see new things about our ideas and concepts, which are useful to us' (Ellis and Dix, 2006, p.7). I set out to conduct this explorative evaluation study with the aim to trigger reflection on the potential of the haptic workspace to successfully transfer the embodied nature of the hand skills and mediate the artistic intention of the puppet stop-motion animators. In order to evaluate this, I tested whether the haptic

workspace is able to carry forward the artistic signature of the animator in the animated movie. If this is held true, then the tool which was used to mediate the skills of the animator transfers the mediation that the hands achieve. Elements that define the animating style of an animator include the way that the animator designs the motion of the puppet and the combined motion of all puppets, the atmosphere of the story, the cinematography and the choice of the storyline. In the following evaluations, the element that was most prominently explored by the participants in order to tell their story was the motion of the characters.

I used three methods for my evaluation. The first method involved the identification of the animator's artistic signature in her animated movie by her colleagues who were familiar with her animating style. Three animators who were familiar with each other's work animated the same character in the same scene set up, without sharing between them any information about each other's animated movie. Following this, each one was presented with the animations of the other two and was asked to identify the creator of each animated movie.

At this point it is important to acknowledge that there is not any relevant literature on the ways an artist's signature can be recognizable. I have built this test on evidence from discussions with the puppet stop-motion animators and other artists to whom I have explained the test, who all agreed that they are able to recognize the authorship of their colleagues' works. The ways that the authorship is recognized relates to studies about the senses and neurobiology, which is outside the remit of this thesis. However, I believe this is an interesting area where evidence from those studies can be applied to.

The second method that I designed was based on the recognition of the stop-motion technique. I asked four professional digital animators to watch all three animated movies and give their opinion on whether they have been made by a digital or a puppet stop-motion animator. This would address the question of whether the animated movies produced had the imprint, however tacitly this may be defined, of the puppet stop-motion technique. All four animators had extensively watched stop-motion animation films and had experimented with puppet stop-motion animation.

How appealing and entertaining the characters appear to the audience, was considered as an additional parameter of the second evaluation method. In their work on evaluating creativity, Candy and Hewett (2008) have suggested that one area in which the creativity of the artist can be evaluated is the *Artefact Creativity*. Artefact Creativity is, according to the authors, an area of evaluation that falls mainly within aesthetics and related subjects. They suggest that artefacts may be judged by features such as composition, visual and aural aesthetics, pleasing and challenging affect, content and well executed technique. The aforementioned features of the animated movie reveal the aesthetic whole that characterizes the technique used to make it. The choice of narrative, atmosphere and cinematography are important elements as is the motion of the characters. Particular for the characters' motion, puppet

stop-motion animation, like digital animation, is concerned with creating thinking characters, whose actions will look convincing and make them appealing and entertaining. It is perhaps the only art form that attempts to deny the truth of the technique, the actual process that led to the final outcome, that 'the audience feels that the character's actions are the result of its own inner motives, and not the animator's inner motives' Meir (2011)¹. I consider aesthetics and creativity a multi dimensional and challenging subject of research which is outside the remit of this thesis. However, the work by Candy and Hewett (2008) inspired me to use the audience response to the animated movies produced in the haptic workspace as an evaluation parameter. After the end of the evaluation with the digital animators, I presented the animations to a general audience and recorded their response to the three animated movies.

My third method involved one post-evaluation interview and asking the group of puppet stop-motion animators with whom I ran the first evaluation to reply to one question which I handed out to them on paper. I returned to collect the responses after a period of time in order to allow the animators time to assimilate the experience of producing animations in the haptic workspace having also returned to their existing practice.

4.2 Carrying forward the artistic identity of the animators

The haptic workspace was made available to a team of four puppet stop-motion animators from Edinburgh College of Art over a nine day period, in March 2011. All animators were fourth year puppet stop-motion students. The haptic workspace was set up with the 6 DoF Omni haptic device. There were three ways to control the camera available to the animators, with the Omni device, with the 3D mouse and with the keyboard arrows.

In the first eight days the animators got acquainted with the workspace spending one hour each every day exploring it. I set up a brief in order to provide them with a specific exercise that would facilitate their exploration of the haptic workspace. However, it was not mandatory to follow the brief. They were asked to compose a short story corresponding to approximately 10-15 seconds of animation and provide a storyboard for it. Based on the storyboards' guidelines, I created the sketched models in a commercial 3D modeling software and imported them into the haptic workspace available for use. The articulated characters had their skeletons and rigs built as specified by the animators. The goal was to produce the animated movie according to the storyboard that each animator had provided (Figures 4.1 - 4.8).

¹www.animationarena.com/acting-and-animation.html, page accessed 12th September 2011

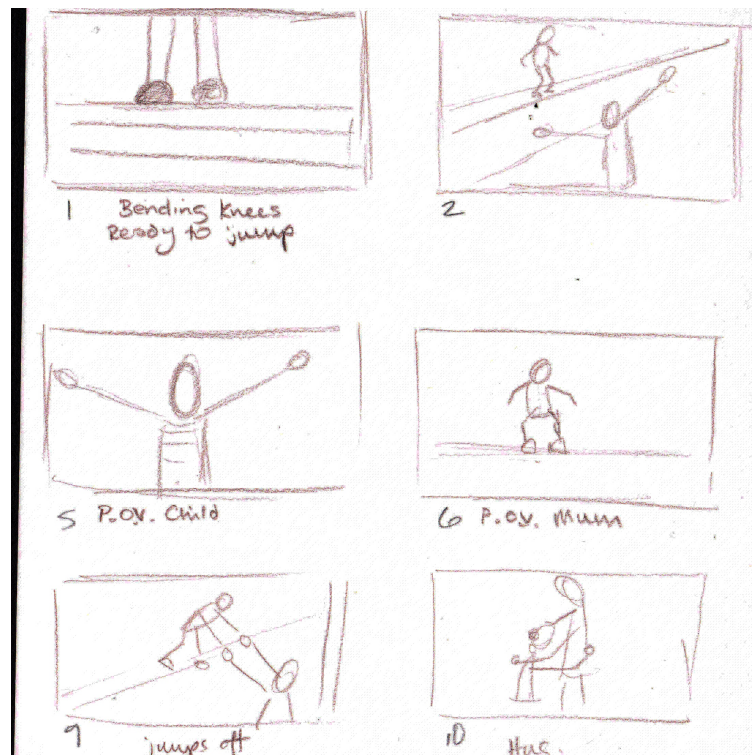


Figure 4.1: Lamond's storyboard

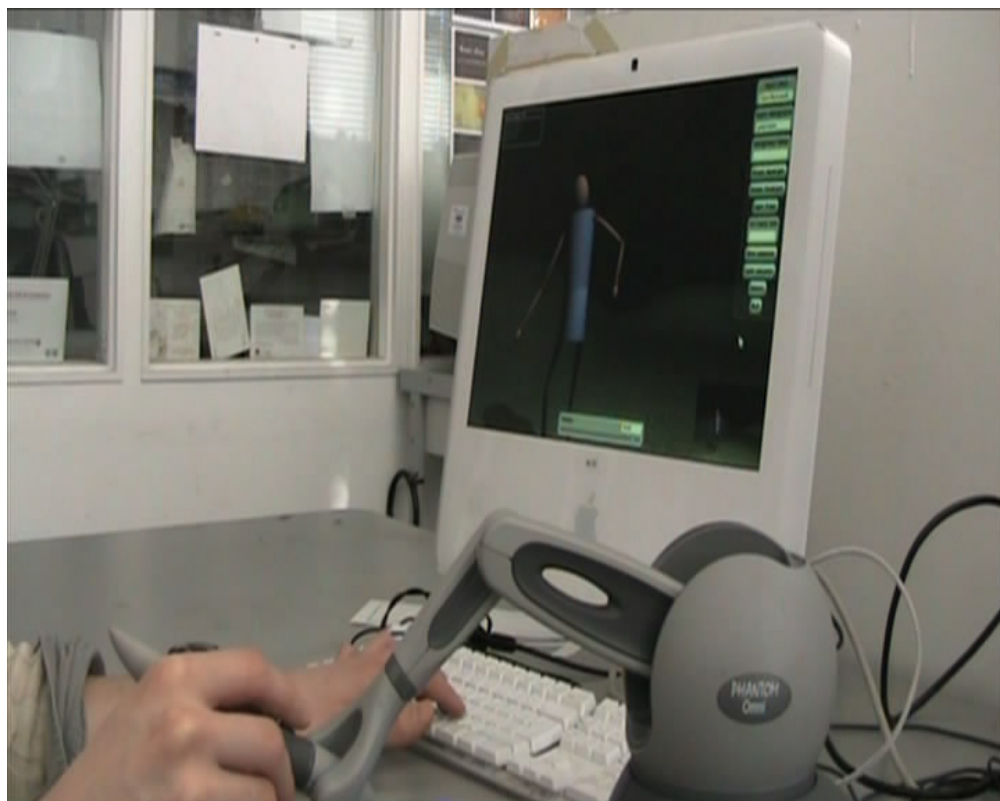


Figure 4.2: Lamond's model

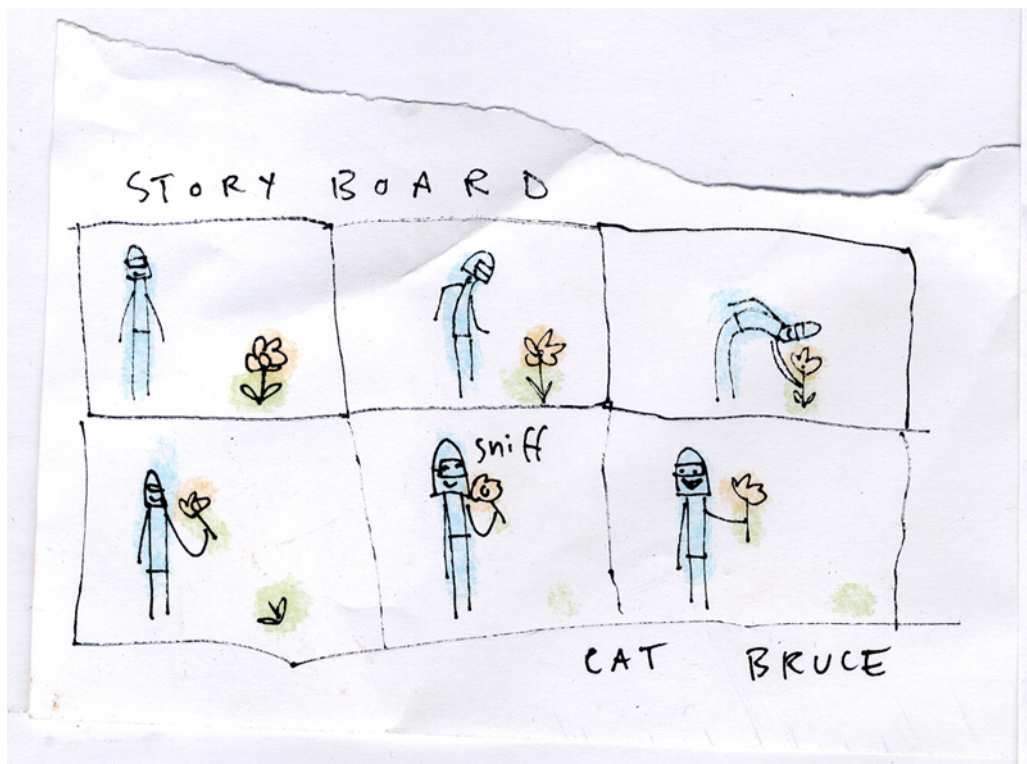


Figure 4.3: Bruce's storyboard

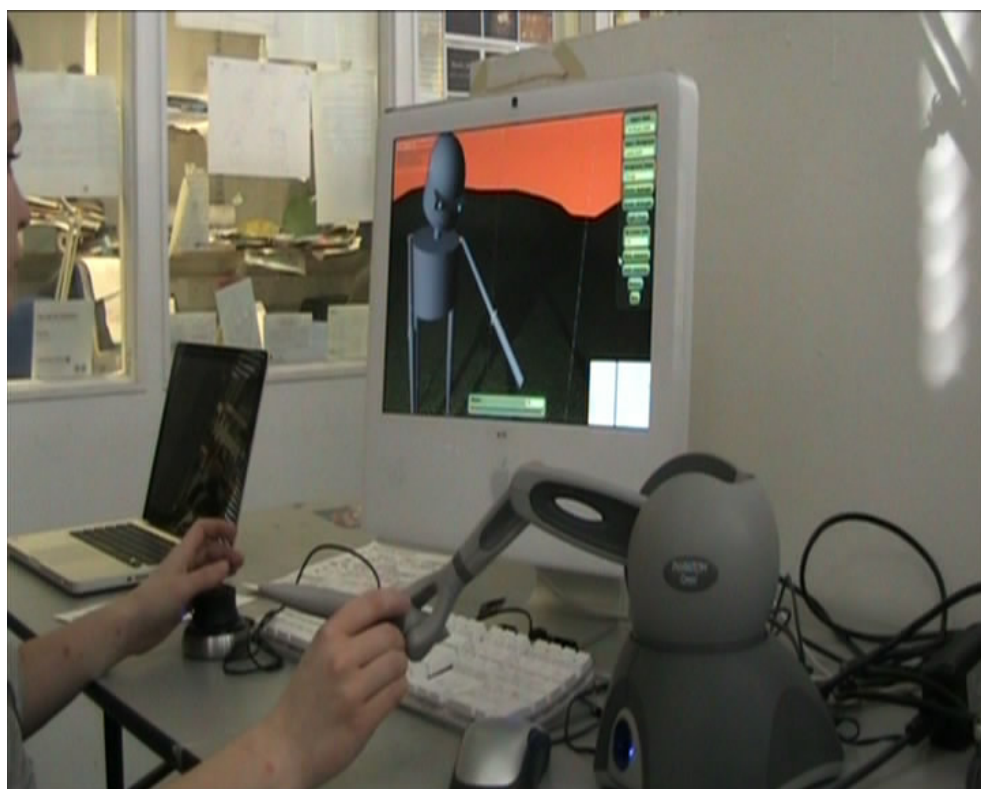


Figure 4.4: Bruce's model

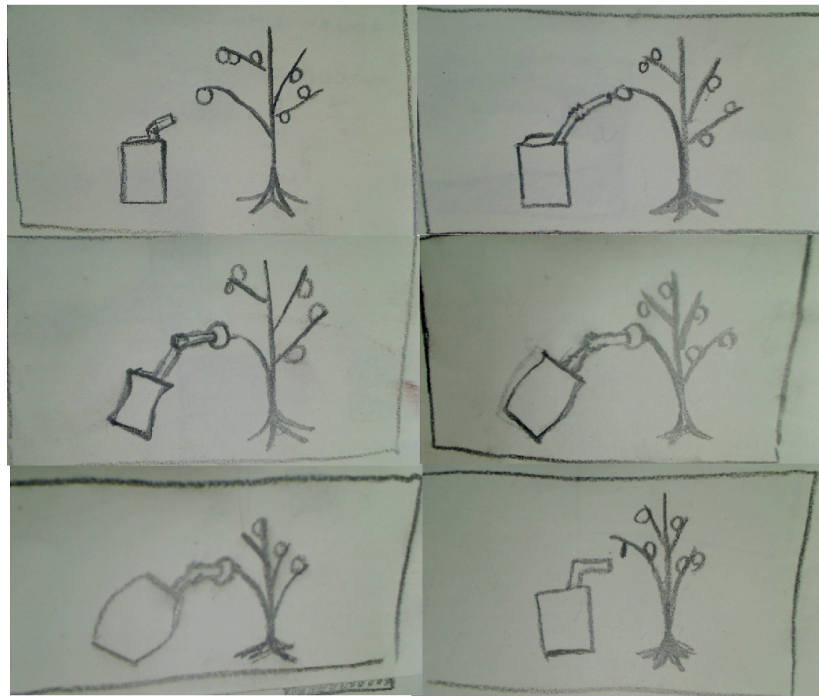


Figure 4.5: Howley's storyboard



Figure 4.6: Howley's model

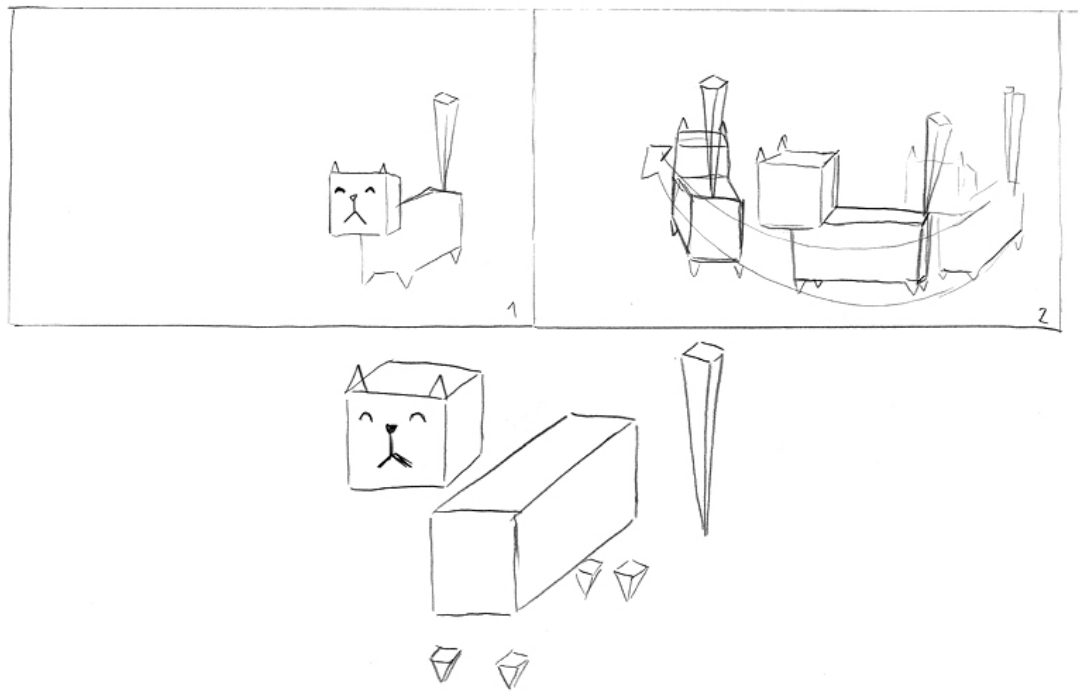


Figure 4.7: Gierasimiuk's storyboard



Figure 4.8: Gierasimiuk's model

On the ninth day, I carried out the first evaluation. The evaluation took place at the animation studios in Edinburgh College of Art and lasted half a day. I collaborated with three of the four animators, Cat Bruce, Kate Howley and Claire Lamond because they were the only ones that were familiar with the animating style of each other. I also asked Donald Holwill, the Head of the Animation Department, who was their tutor, to participate in the identification stage since he was familiar with their style of animating. Although he did not participate in the design experiment, puppet stop-motion and 2-D animator Adam Gierasimiuk gave his view on the three animations voluntarily. Prior to the evaluation, I openly explained the motivation behind it and my objectives.

Each animator was provided with the same virtual character and background, a robot positioned in a rocky surrounding and was asked to create a short animation of about 15 seconds. Each one was asked to spend some time exploring the model and thinking of a story that would best express their personal style². Although they could work with the lights and cameras to set up the ambiance and cinematography, they all decided to tell their story concentrating on designing motion into the character because that was what they focused on during the eight days of working in the haptic workspace. At no point was any of the animators observing while their colleagues were animating the robot. After all the three animations were made and stored on the computer, each animator was called separately and was presented with the animations of her colleagues. She was then asked to identify which of her colleagues was the creator of each animated movie. The same process was repeated with the Head of the Department. Each animation was played back once or twice in the frame rate that was set by its creator. The experiment was followed by a 30 minute semi-structured interview with the three animators.

I then asked the four digital animators to watch all three animated movies and give their opinion on whether they have been made by a digital or puppet stop-motion animator. I explained to them my research project and the reason behind my question after they had given their answers.

Finally, during the month of April 2011, I presented the animated movies to a general audience and recorded their responses.

4.2.1 Responses and reflections

After the presentation of both animated movies, each animator was asked to correlate the animations to their creators. Below I present the responses and the reasons behind their selections.

Kate Howley. Howley was successful in mapping both animations to her colleagues which she did without any hesitation about the correctness of her answer. When she was

²The three animations can be found in folder 'Chapter4' of the DVD

asked to justify her decision she said:

I am more familiar with Claire's [Lamond] work than Cat's [Bruce] but I also think that this [speaking about Lamond's animation] has a kind of curious form. Yes, I figure the other one is Bruce's because of the way it moves, I think it has her personality in it.

Adam Gierasimiuk. While playing Lamond's animation one more time, Gierasimiuk, a 2D animator who was familiar with Lamond's work, approached and asked us if this was Lamond's animation. When he was asked how he concluded this, he responded:

I guess this it is responsive to the kind of work that Claire [Lamond] would do more. She has these ideas about animation which reveals what exactly is is the item she is looking at. She had this movie where there was a puppet that was a full body with all the clothes and all the garments and there was just wire sitting next to it. And the wire was sad because it is just wire. And the full body goes like '..Right...'. I think it is this movie actually where the puppet starts to call the other one 'wire'

He then enquired about Bruce's animation which I played back for him. In the animation he identified Bruce's style. In particular he responded,

Yes, because Cat [Bruce] is more of a cheerful person, something that is I don't know, hard to describe but something in the movement reveals her personality..Cat even stands like that [like the robot]

Claire Lamond. Lamond also successfully and with strong assurance recognized the animations of her colleagues. She thought that Howley's work is dynamic which was apparent in what she thought was Howley's animation and for Bruce she said:

I think Cat's [Bruce] work is quirky. And that [the animation] is kind of quirky - it has kind of a strange movement and is kind of slightly funny

Cat Bruce. Bruce was not successful in corresponding the animations to the correct creators but, equally, she did not appear very certain about her decision. When asked about her hesitation she said that she was could identify Lamond's style but she was not very sure of Howley's work. Thus, she was almost sure that Lamond's animation was indeed hers, but her final answer was that it was Howley's.

Donald Holwill. Finally, the same procedure was repeated with their tutor. Holwill's final responses were not correct for any animation however his initial responses upon seeing the animations were in the two cases correct. Although he did not manage to successfully correlate the movies to their creators, his comments on the way they presented motion were in accordance with the justifications given previously by the group. For example, he described Lamond's animation style as quite careful and methodical, almost exploring the movement. Lamond's work was described as such by her colleagues. However, he did not recognize these traits in her movie. His comments are presented in table 4.1 as a companion to my description.

Table 4.1: Holwill's answers

Playback Order	Creator	Holwill's response	Holwill's comments
1	Claire Lamond	Cat Bruce	A more content piece of work. Something that Cat would do
2	Kate Howley	Claire Lamond	This explores the movement. I am almost certain that it is Claire's
3	Cat Bruce	Kate Howley	I knew I wouldn't get this right

He thought that Lamond's animation was either hers or Bruce's but when he saw Howley's animation he thought it was Lamond's. He attributed Bruce's animation to be Howley's work. When I responded that it was not Howley's he said 'Then this is Cat's [Bruce]', which was correct. For what he thought was Lamond's animation, which was, in fact, Howley's, he commented:

It was much more free and much more spontaneous, quite hard and ambitious complex movement in a sense. The whole figure was in movement. I thought it was the slightly different one than the other two. The other two were more controlled and stable and I was trying to match that to Claire [Lamond]

This description is not in line with the 'quite careful and methodical, almost exploring the movement' animation style attributed to Lamond. For Bruce's animation, which in the end he identified correctly, he commented:

This is a more content piece of work which is something that Cat [Bruce] would do. She goes from one end to the other, she does some subtle things but she would also do more incumbriant things. That's why I thought it was hers

Holwill's comments reveal that there is an error range in the evaluation which depends on the level of familiarity that Holwill had with his students' animating styles. It is important to recognize the difference between the animators that knew each other's work well and the tutor who, due to the fact that he knows the work of all the students, might not be able to recognize in detail each one's technique but who has a more holistic knowledge of their animating skills and is able to make less literal and more combined connections. Holwill commented after the end of the session:

I was finding different connections coming out from different directions trying to see what the students did. Knowing the right answers I can see how it connects, each animation to each animator

One week after this evaluation, I presented the animated movies to the digital animators. All of them identified correctly the puppet stop-motion technique in Bruce's and Lamond's animations and only two of them identified digital techniques in Howley's animation.

For all of them Howley had created the most complex motion, the robot turning around and falling down on the ground in a funny way. The two animators who recognized the digital technique in it explained that the motion of the character seems as if it has been automatically calculated between two extreme poses. One of them commented:

At first I thought 'puppet stop-motion' because every movement was distinct from the other one. But then I thought that because the movement is advanced, it has to be done by someone who has done rigging a lot and know very well how the skeletons work and I am not sure how much knowledge there is on something like that for the puppet stop-motion artist, while for the digital artist is very clear where all the bones are and how they work and rotate. So this is why I thought that it was a digital animator behind it. Because of how the skeleton was moving

The other one said that it could have been done by a stop-motion animator trying for the first time a digital animation tool. At the same time, the rest of the animators recognized certain twitches in the movement that revealed to them the stop-motion technique. One said that the movement was flowing but there was some occasional hesitation in the way it moved. To the other animator, it seemed as if it was missing some frames and as if it was a puppet animated in faster motion than usual in stop-motion. These different responses make a positive indication that the haptic workspace can provide to the puppet stop-motion animators the opportunity to create easily complex motion that resembles motions produced by digital animators.

In Bruce's animation the animators identified characteristic elements of the puppet stop-motion technique, such as fluid organic movement and believability. With great assurance that this was the work of a puppet stop-motion animator, one digital animator said:

I get the feeling that there is a distinction between the frames, between the motions that the model does in each frame. So I think this is the way that people that do stop-motion think : Having to do something for one frame and then change something else but they are used to seeing the in-between. That is why it looks like a movement that a person who has done a lot of animation would probably think of doing, with the hand moving, very human-like

Lamond's animation was the most fascinating one. All animators were assured that there is a stop-motion animator behind it because its movement was exploratory, well thought and flowing. Some of them said it was the most advanced one of the three. One animator emphasized the advanced nature of the character's motion by commenting that 'it could have been done by a digital animator with background in stop-motion who intended to give the puppet stop-motion feeling in a digital animation'.

Knowing the technique for each of the three animations, one animator commented that Bruce's and Lamond's animations reflect more clearly the way a stop-motion animator approaches things: they want to explore what the character can do because they have the character in front of them.

After this session, I presented the animations to a general audience that were outside the field of animation. They all seemed to enjoy watching the animations despite their short duration. In the case of Howley, the motion of the puppet turning upside down while running and falling gracefully to the ground made them laugh and they would replay it more than twice. The same reactions were recorded with Bruce's animation, the robot running, stopping and waving at the viewer. Most of the audience smiled and watched with curiosity as Lamond's robot explored its limbs at a slow pace. This animated robot made the biggest impression to the audience and triggered the most enthusiastic responses.

4.3 Reflections on the haptic workspace

The positive outcomes of the evaluation demonstrated the ability of the haptic workspace to allow the artistic identity of the animator to be carried forward. The results attested my initial hypothesis that the haptic workspace has the potential to transfer the embodied nature of the hand skills and successfully mediate the artistic intention of the animator. In addition, the results gave an indication that the design methodology that was followed worked towards the creation of a beneficial new digital tool for stop-motion animators.

After the first evaluation with the puppet stop-motion animators, I conducted a one hour semi-structured interview with Howley, Lamond and Bruce where, in accordance to my design methodology, I encouraged their reflection on the experience of animating in the haptic workspace. Seeking a complimentary method to trigger their reflection and to encourage their critical thought towards the workspace's future development, I was inspired by the editorial article on *Physicality and Interaction* in Ramduny-Ellis et al. (2009) which read:

As we design more hybrid physical/digital products, the distinctions for the user become blurred. It is therefore increasingly important that we understand what we gain, lose or confuse by the added digitality (Ramduny-Ellis et al., 2009, p.64)

Using the wording of this question, I handed to Bruce, Howley, Lamond and Gierasimiuk one piece of A4 paper with one question written on the top of the sheet:

After working in the haptic workspace for a period of time, what would you think is lost, gained, transformed and confused during the transition from working with real puppets to working in the haptic workspace for the purpose of producing an animated movie?

The rest of the sheet was separated into four equal spaces, one for each case (Figure 4.9). I asked them to answer the question anonymously at their own leisure and left the sheets with them for two weeks before I returned to collect them. This was done on purpose as I sought to leave them some time to assimilate the new experience of animating in the haptic

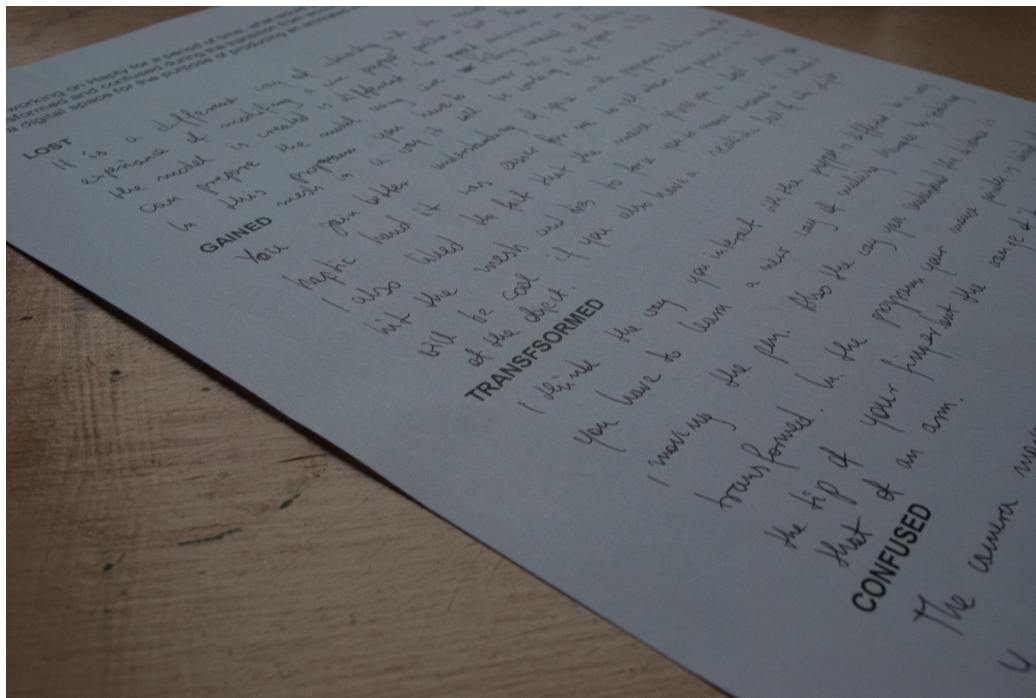


Figure 4.9

workspace while they carried out their usual animating tasks. With this method, I aimed to enable qualitative comparison between the old and new workspace.

Most of their responses to the question on the sheet, repeated also during the interview, reflected the benefits of the haptic workspace and discussed some issues which had been found during the design studies.

Flexibility with the camera and the lights was considered a significant gain in comparison to camera and light manipulation in the traditional workspace where they are the most rigid aspects of the animating process. For two animators, the haptic workspace successfully eliminated the task of physically moving continuously between the scene to the computer and made the workspace uniform. The combination of viewing the scene and the sequence of frames in the same location and the fluid way of operating the 3-D camera made the navigation simple and direct for them. However, one of them found camera control with the non-dominant hand confusing, while another two animators thought that, the ability to use both hands was lost. This attests the conclusion reached in the design studies that in order to transfer the bi-manual activity of the puppet stop-motion animators into the haptic workspace, an analogous bi-manual activity should be considered in order to design the control in the non-dominant hand. In the design studies, the animators indicated the structure of the transferred activity with the puppet-in-hand metaphor. I mentioned this during our interview and they attested that this would be a very appropriate way of using both hands in the haptic workspace.

The co-location of the animating scene and the screen where the frames are viewed made the manipulation of the frame sequence more malleable for the animators. The ability to add, delete or swap frames with the press of a button exists in commercial digital animation packages and digital software that stop-motion animators use, however, bringing this to the haptic workspace made the animating experience more direct and flexible.

Reflecting on the way frames were captured in the haptic workspace, Gierasimiuk suggested that their recording could be done automatically instead of manually. In particular, frames could be captured by the software based on some rule. When I remarked that in traditional stop-motion capturing a frame is a manual action where the animator takes a picture with the camera, he responded that if the intention was to transfer the usual process, it would be important to give some indication of the frame capture in the haptic workspace. He suggested that upon taking a snapshot, the recorded image should be made visible on the timeline to inform the animator that she took one picture and that this picture corresponds to the frame. He brought up the example of the animator who is not informed about how the haptic workspace is operated.

With the puppet you do some changes and the changes are there. If I did not read the manual and I started the application and do stuff with it, I will probably make a couple of frames and then I would be wondering why I don't see the changes in the frames because I would not know that I would have to press buttons to save the changes. I think that it is more natural for people if they do something and the program saves it by itself

Gierasmiuk's suggestion, automatic recording of frames, is often used in performance animation, which can be resembled to real-time digital puppetry. The use of automatic recording relates to the per-gesture animation method that was discussed in 3.10.1, which records the dynamics of motion over time as directed by the animator's gestures. This method can bring more directness in the animating experience and make it more embodied. My reflection on the current software interface design, led me to think that a necessary addition would be the clear indication of the point the changes for a frame are complete so that the frame can be saved. For automatic recording this point could be the completion of a single continuous gesture. Following the per-gesture idea, and disregarding the frames, the continuous gesture can specify the corresponding time interval on the timeline in time units, e.g seconds. Finally, automatic recording would be very useful for animating the camera. The haptically-mediated exploration of the camera view, led by seamless gesture, has the potential of enabling enactive cinematographic experience.

The calculation of distance was for most of the animators transformed. In the haptic workspace, the animators consciously considered the angle of their viewpoint in relation to the character's position and their distance from the character as well as the sphere's distance from the character, while in the physical workspace they do not explicitly check these parameters. Thus, fluid motion was considered harder to create and was something that was lost for

one animator. Controlling the distance was mentioned as a transformed element by another animator who compared the device's representation as 'the tip of your finger but with a range that it is different than that of an arm'. In relation to this, the inability to see the whole puppet while animating, identified as a scale issue in 3.4.2, was mentioned by one of the animators as a confusing aspect of the haptic workspace. However, three of them considered the haptic map that they were able to form while using the haptic device as instrumental in overcoming, to an extent, the issue with distance perception. Two animators noted that the haptic map in combination with the different camera angles provided them with a better understanding of the 3-D environment in comparison to existing digital animation packages. It appears that the formation of the haptic map was an important aid for the animators since it was also mentioned twice during the interview that followed the evaluation.

The most prominent issue that was raised during the interview and mentioned as 'lost' on paper was the feeling of tactilely working with puppets. Lamond said that she did not feel she could establish a true connection with the virtual puppet, a feeling which is defined as *being in their skin* when animating physical puppets. She spoke about the special connection with the puppet that is created while making the puppet and rigging it, a process which seems to carry particular weight for the animators, yet was not offered by the haptic workspace.

The process of physically making a puppet..at some point you say "Oh, hello"! (laugh) and suddenly you kind of see that you have got a character. You kind of get a sense of how it is going to move about, you are making it physically

Holwill emphasized during the evaluation:

I think the important thing is that you connect with the material you are working with so it does actually in a funny way communicate back to you as well as you to it. And I think that this is why good animation is about characters you recognize, thinking entities. There is a sort of dialogue, a two-way communication in a sort of funny way

The 'true connection with the puppet' was one of the distinct lost qualities mentioned by two animators on the paper. However, on the paper the animators highlighted the fact that a transformed feeling of connection with the virtual characters substituted the tactile interaction with the puppets. They suggested that the different way of interacting with the character produced a novel animating experience for them which, according to their comments, transformed the physical relationship they normally establish with the puppet and, thus, influenced the way they animated.

One animator recognized in the 'transformed' section, that the way in which the virtual armature is bent in the haptic workspace creates a whole different way of working with the character. This transformed feeling was partially due to the new kind of physicality as mediated through the haptic device. One animator commented on this transformation:

The range of resistance in various joints made the digital transition a lot easier. This made the puppet seem more like a material than a digital image because it retained a set of physical boundaries

Similarly, Howley expressed on the one hand concerns about losing the pleasing work of making and rigging the puppet with the surroundings and objects, a work which incorporates the tactile feeling of working with materials and the armature, however, her comment was not foregrounding a negative aspect of the haptic workspace. She connected this loss primarily to the different nature of the haptic sense in the haptic workspace, as opposed to the physical workspace and she added that she was not used to this new way of working. It is interesting to note at this point that the digital animators thought that Howley created the most complex motion, which, in terms of technique, resembled application of kinematic algorithms for moving the puppet.

The animators emphasized the different haptic sense as the most distinguishing transformation from the traditional to the haptic workspace. When I returned to collect the sheets, I asked them to think of what they felt was different when they returned to their traditional practice. They considered the physical two-handed practice easier and more 'hands-on' in comparison to animating in the haptic workspace. At the same time, they acknowledged the different experience when animating in the two workspaces emphasizing that with the haptic workspace they can perform many of the tasks involved in puppet stop-motion, as they have been outlined in this section, more fluidly and easily. One animator commented that the new animating process 'changed a little how I am thinking about animating the model. It feels different from stop-motion so the feeling is transformed'. Another one added:

Altogether it is just a completely different art-form and the way of working to puppet animation - being able to *feel* the character is good but it is still 3-D computer animation which feels like an entirely different medium approach

The animators' responses revealed a positive reception of the new workspace, even for those who were most defensive of their traditional practice. Their appreciation of the haptic workspace's potential as a tool for computer generated puppet stop-motion animation was evident in their suggestion for keeping it in their studio for long term use, which will assist their transformed animating experience to become grounded and evolve.

4.4 Reflection on my practice and research

After the end of the evaluation interview, I sought to enable their reflection on my practice and research goals. I asked them to interview me in order to trigger the stream of reflection from them to my practice and become the one who was confronted with their considerations

for the haptic workspace. This stream existed throughout the design studies but the method of asking them to interview me triggered it in a more conscious manner.

They asked three questions. Their first question was whether there had been people working in puppet stop-motion that have tried the haptic workspace before. My response included the collaboration with the first group of puppet stop-motion animators with whom the haptic workspace was co-designed. As I wanted to expand on the views of puppet stop-motion animators outside the co-design process, I described some discussions I had with one professional puppet stop-motion animator before the practical part of the research had begun. I told them that from my descriptions of what I intended to investigate, he had envisaged that a digital tool for puppet stop-motion animation can be used as a pre-visualization tool and a great way to rapidly demonstrate commissioned work to all stakeholders. In addition, he considered it a tool that would give puppet stop-motion animators, who currently work in a small niche, the opportunity to extend their work in the digital animation industry. Lamond, then, agreed immediately that it is a great tool for 'putting together something quickly and demonstrate it to people'. She also highlighted the benefit of animating from different angles or see an animated sequence from different cameras that the haptic workspace provided. Howley added that it is great comfort to be able to move equipment which is difficult to move in puppet stop-motion, such as the lights and cameras, around the space. I brought up examples from innovative camera moves that I had seen in puppet stop-motion movies which triggered conversation on different ways of using the cameras in the haptic workspace in order to achieve interesting cinematography in the animated movie.

Their second question asked whether what I had expected to happen, happened in the end. This was an interesting question which gave me the opportunity to expand on my research approach. It also enabled me to clarify, having already explicitly explained it to them in the beginning of our collaboration, that the haptic workspace was not developed to substitute the traditional puppet stop-motion working methods, but to open a new space for research and development. In terms of the experiment, I described how my hypothesis was attested and what this indicated for the new workspace emphasizing the fact that I had found their animations amusing. At this point, Lamond said that she really enjoyed animating in the haptic workspace in the end, despite some confusion she had in her first attempts. Then, I explained the value of the collaborative design process in shaping the haptic workspace and emphasized that I did not expect the process to result in a predefined outcome that I had in mind. Rather, anything that was observed and contributed as idea or comment was a building block of the workspace and an essential part of the process.

Finally, Lamond challenged me with the question of which of the two groups of animators I envisaged would use the haptic workspace, the puppet stop-motion animators interested in digitally-mediated animation or the digital animators. I outlined the benefits for both

groups and said that it was designed for puppet stop-motion animators as digital animators would require a different design that would reflect their approach to the design of the haptic workspace. I referred to the fact that many of the digital animators' requirements that I observed in the short time that Deniozou explored the haptic workspace, were not different than the ones of the puppet stop-motion animators working in a haptic workspace. These observations have showed me the points where the two techniques converge. They agreed on this last point that the two techniques have similar goals and that research on the points where they converge would be interesting and extremely useful.

The interview ended with an observation made by all that by practising with the haptic workspace for a further period of time will support and augment their creativity in a different way than in their current practice.

4.5 Conclusions

In this chapter, I described my evaluation of the potential of the haptic workspace to transfer the embodied nature of the hand skills and successfully mediate the artistic intention of the animator. I conducted this evaluation from an exploratory perspective with the aim to trigger reflection on the ability of the haptic workspace to be a new digital platform for puppet stop-motion animators rather than to provide solid results about its success. As I argued in the beginning of this chapter, I believe that an evaluation which can yield solid results must be carefully constructed and is a research project on its own merit.

The positive results of my short evaluation affirmed my hypothesis. The animators' responses to the questions I posed to them did not foreground any new functionality issues giving a first indication of the success of the design methodology. Additional information from the interviews, discussion and the single question indicated that the puppet stop-motion animators acknowledged the transformed animating experience and spoke of the haptic workspace as an interesting tool for creative explorations.

In addition, they affirmed that long term use of the haptic workspace would provide them with new levels of awareness of their craft. Once the haptic workspace is placed in long-term use, further studies can address questions about the abilities of the haptic workspace as a new tool for haptically-mediated puppet stop-motion animation and the values it can bring to it. Much of the commentary during the interviews and discussions, provided some additional information on the future role of the haptic workspace and its position in the puppet stop-motion animation community. The next chapter will expand my insights in a broader reflection on the design insights, the design methodology I followed, and the haptic workspace itself.

Chapter 5

Discussion

One of the main goals of my research has been to explore the design of a haptic workspace for puppet stop-motion animation which has the potential to transfer and accommodate the tacit embodied skills of puppet stop-motion animators. I have investigated this design innovation by co-designing and developing a haptic workspace with a team of puppet stop-motion animators, following an experiential and holistic design approach. In parallel, I have introduced reflective methods in order to identify and articulate the issues that rose in each step of the iterative design process. While the design studies and the development of the haptic workspace were progressing, I sought to validate my design methodology.

This chapter will discuss the three interrelated research contributions, the design insights that were collected from the design studies, the methodological framework that was used for designing the workspace and the haptic workspace as a tangible outcome of my research.

5.1 Reflection on the design insights

The practical studies produced significant insights regarding the design of haptic interfaces for virtual environments, from the perspective of embodied cognition. The majority of the identified issues were related to the design of navigation metaphors for the haptic workspace as well as metaphors for the selection and manipulation of the characters.

Depth perception

It was first found that placing the animating scene and the screen that the animators used to view the capture images in the same location, enhanced their embodied experience and made their work more focused. One important issue that I observed regarding embodiment, was the difficulty in perceiving the depth dimension and performing actions that required certain precision in this dimension, such as positioning a character, when the character's surface touch was not implemented. As I discussed in Section 3.5.2, perceiving depth in a virtual environment

is difficult because although the two dimensions of width and height are represented physically in the virtual environment due to the physical boundaries of the screen, the depth dimension is not represented in a physical way. This makes actions in depth more difficult to achieve, and from the point of view of embodiment, disrupts the perception of the virtual environment as a 3-D space. The haptic device, and generally all spatial input interfaces, provides the necessary degrees of freedom for actions in the depth dimension, but when depth cannot be easily perceived visually the user actions fail to be transferred appropriately. Stu Card has recognized this issue and suggested that 'a major challenge of the post-WIMP interface is to find and characterize appropriate mappings from high degree-of-freedom input devices to high degree-of-freedom input tasks' (in (Jacob and Sibert, 1992)). The advent of cheap consumer 3-D high definition displays are an important aid for depth perception, however, extensive research will still be needed in order to identify the best interaction metaphors for this type of virtual environments.

Haptic map and navigation

The implementation of the character's surface touch offered additional sensory information that was particularly catalytic to the animators' embodied understanding of the character's structure. The haptic map they formed, within the virtual space, helped them to navigate the character and manipulate its different parts with increased precision in all dimensions, in comparison to how they performed when the surface touch was absent. The simulation of the touch sense also partially solved the depth perception issue.

One important contribution of the haptic map towards the embodied experience, lies in its use for haptically sensing the dynamics of motion during the playback of a frame sequence. The ability to haptically sense the motion while it was played back introduced a level of embodied haptic control of motion with immense possibilities for the field of motion adaption. As the animators suggested, one future design consideration is the ability to change the path of an animated character by exerting forces on it with the haptic device. According to them, one difficult part of the animation making process is to understand how the character will move once it collides with an object. For this, they must take into consideration and calculate in the motion of the character factors such as physics laws. This process is inherent part of their embodied skills. I have observed that animators spend quite a lot of time on experimenting with different motions until they find one they are satisfied with. By introducing perturbations to an animated character's motion with the haptic device and watch the different ways the character reacts when it receives them, the animators could produce a plethora of possible movements in little time. Their haptic interaction with the moving character could provide them with embodied understandings of the different motion paths a character can follow in the next frame, and animate it accordingly.

The multiple cameras that are available in the haptic workspace allow the motion to be viewed from different angles, before and after the change. This offers additional visual understanding of how motion will progress, which in combination with haptic feedback enhances embodiment in the haptic workspace. There already exists a vast amount of research in motion adaptation based on physics laws, with some projects investigating haptically-enabled motion adaptation, such as that of Bierz et al. (2005) which was presented in Chapter 1. The connection of this research with research on how haptic technology can enhance embodied interaction with pre-animated characters can lead to fruitful results and exciting technological innovations.

Importance of egocentric representation

Another issue which disrupted the embodied experience in the first design studies was the incorrect transformations of the virtual characters when the animators changed the camera position and orientation. The issue did not only occur in character manipulation but also in the control of the haptic device's representation where it altered its direction depending on the camera position. This pointed out to the importance of egocentric representation which is an embodiment issue. From an interface design perspective, in case there is an interface where all actions have an egocentric frame of reference, it is significant to ensure the coordination of all transformations so that these actions are meaningful to the user.

In connection to the egocentric representation, the design studies highlighted the necessity of having both visual and haptic cues present in order to enforce the perception of space and the precision in manipulating the characters which enhances embodied cognitive understanding of the virtual environment. Equally significant was the alignment of the visual and haptic perception. The distance that the haptic device's representation moves should always be in line with the rendered forces at the hand that moves the manipulandum.

Scaling the maximum range of motion of the device's representation for the axes parallel to the screen to reach the screen's physical boundaries, increases the visual coherence between the task of moving the physical manipulandum and visualizing its motion in the workspace. This bridges the physical gesture with the visual output closing the action perception loop. For the depth dimension, the changes in the sphere's radius must be big enough to make the traveled distance better perceived. For the above insights, further testing with 3-D displays are required in order to provide deeper understanding and new considerations of the ways haptic and visual experiences can be coupled with the aim to enrich embodied experience of animating in the haptic workspace.

Precision and navigation

The lack of precision in the motion of the virtual camera, due to the continuous reception of unconstrained translational and rotational data from all devices that were used to control it, disrupted the animators' embodied experience. I repeatedly observed this issue when the animators used the 3-D mouse, the Wii Remote and the haptic device when it was set up to control the camera. The issue, which extends to all spatial input interfaces, is particularly a detriment to camera navigation because the specific action depends mainly on visual feedback. The haptic device and the other two devices produced continuously transformational data. However, the haptic map that animators formed, reduced the issue of imprecise gesture for the haptic device to a significant extent. Before surface touch was possible, the animators used the 3-D mouse to navigate depth and used the haptic device as a 2-D interface, limiting the manipulandum's motion to a 2-D plane parallel to that of the screen in order to maximize precise manipulation. The haptic map enforced their embodied spatial perception of the workspace and the geometrical structures in it with the haptic device and helped them interact with the puppets. Such a solution could not be applied to the other two devices.

The use of the 3-D mouse provided better precision in navigating depth than the Wii Remote and the haptic device because it afforded more controlled actions of zooming in and out in comparison to the other devices. The only device that outperformed all was the keyboard. Discussing this issue with the animators set the idea to design in a level of agency in the motion of the spatial input interface when defining the camera navigation metaphor. I had the opportunity to test this practically when the animators suggested the implementation of a camera that would be set on orbit around the character, with its orientation specified by the animator. The orbit camera had a constrained circular motion path that it followed with the press of a button. The use of the orbit camera proved to be beneficial for their work as they often had to move quickly around the character for purposes such as checking how the character looks from all angles and animate it.

An opportunity for further research on more appropriate navigation metaphors appeared after the introduction of the puppet-in-hand metaphor. The animators suggested that the camera should be controlled with other parts of the body, such as a foot pedal. Investigating other parts of the body for camera control can help improve the precision issue with navigation metaphors that will impose controlled navigation to serve the animating purposes and preserve the embodied experience.

The puppet in hand metaphor replicated the asymmetrical way of working with the physical puppet and enabled an unencumbered, and embodied method for animating the character. The physical properties of the Wii Remote assisted the animators in devising this metaphor. Through trials of the IK and FK kinematic algorithms in separate studies and after a few

design iterations, we devised the locking chains model, an algorithm that combines IK and FK in 3-D space for manipulating the character and uses all the DoF offered by the haptic device. The model enabled natural direct manipulation in 3-D space and promoted embodied interaction with the virtual character. The implementation of joint constraints was considered a beneficial addition which would further assist precise manipulation. However, according to the animators' feedback, the lack of joint constraints was not detrimental to their embodied animating experience.

Dimensions of the workspace

One significant observation that derived from the practical studies was that the virtual environment can be approached both as a (pseudo) 3-D environment and also as a 2-D image on the computer screen. This realization has immense implications for the design of metaphors as each consideration offers a different set of properties which can be exploited according to the requirements that are set. As it was mentioned before, all digital animation software provide numerous workarounds and interaction metaphors in order to simulate direct manipulation and depth perception. All these metaphors are found based on the two dimensionality of the screen, as for example clicking on the perspective view, which is projected on the 2-D screen, in order to select a joint of the character that might be at the back of the character. The design of metaphors for an enactive interface can exploit the three dimensionality of the environment. Thus, relevant research can produce significant new insights on the design of novel metaphors, which can also involve multi-modal responses. Again, further research with 3-D displays, and future technologies that will display 3-D worlds without perspective projection, will be catalytic to the design of these new metaphors.

Time, space and acting

The study with the digital animator revealed the potential of the haptic workspace to enable new embodied ways of working. The per-gesture animation used time and space intuitively to enhance the embodied animating activity making links between the animators' gestures, the sense of timing and the characters. This method does not only record the motion but its dynamics that are captured as they occur within a time unit. Interestingly, it was not the puppet stop-motion animators who suggested the per-gesture method but the digital animator. For stop-motion animators, the animation controller that I originally designed was suitable for them in terms of functionality as it replicated the normal method of capturing poses in the stop-motion practice. On the contrary, the digital animator was used to more dynamic ways of working, using a variety of digital tools for creating motion. According to her, the fluidity of the haptic device combined with her experience of using digital tools led her to think about per-gesture animation.

Another significant contribution of the per-gesture method of synthesizing motion is that it brings acting into the animation making process. Animators of all techniques constantly make gestures and facial expressions in order to empathize with the characters they animate, something that remains absent from commercial animation packages. Animator and cinematographer Norman McLaren famously said that 'Animation is not the art of drawings that move but the art of movements that are drawn'. The per-gesture method reflects this statement.

5.2 Reflections on the design methodology

As discussed in Chapter 2, there is an absence of a coherent methodological framework for developing digital workspaces that evoke an embodied animating experience and allow non-digital skilled practitioners to work in them unencumbered. The design perspective that I adopted and followed throughout my project facilitated the identification, understanding and articulation of design issues and tacit information regarding the transfer of the puppet stop-motion animators' embodied skills into a digital setting. Therefore, it contributed one appropriate framework for conducting this research. Although my design methodology served the purpose of this research, I believe it can be enriched and complimented further in future investigations. My design methodology was based on four key elements:

- Designing in collaboration with the practitioners I seek to design for placing importance on their experience as it unfolds during the design process
- Considering the experiential phenomena that take place during the process valuing my experience in equal terms to that of the animators
- Establishing a holistic appreciation for the design process
- Enabling multi-streamed reflection in all participants, including myself, as a tool for capturing, recording and analyzing significant information and articulating design decisions

User-driven design

The participation of the puppet stop-motion animators in the design of the haptic workspace has not only been invaluable but also necessary. It has been necessary because, by being experts in their practice, they could provide insights on the design context at each stage of the development process. Through their engagement with the several prototypes they were able to foreground outstanding issues, propose solutions that inferred embodied ways of animating, make suggestions for further developments and indicate omissions or elements that were not necessary to include in the design. The animators were enthusiastic and eager to participate,

they were very actively involved and offered interesting perspectives. Some animators were more reserved with regards to the infiltration of digital technology in their work mainly because they were concerned with the potential of the technology used to transfer to a satisfactory degree the relationship they have with their hands and the connection they establish through them with the puppets. I argue that while valuable feedback can be obtained by those who are very open towards interventions in their practice, the designer should facilitate the conversation with creative makers who express concerns. With appropriate facilitation of the dialogue, their comments can lead to the emergence of challenges for the design that may pass unnoticed otherwise. The role of designer as facilitator allowed me to identify the reasons behind their reservations and to confront them with practical designs and further experimentations. For example, during evaluation Lamond expressed her difficulty working with the IK controller. I presented her then the haptic workspace prototype with the FK algorithm, which gave her a good level of control over the character's manipulation. Working with this for a few days, she was able to better understand the character manipulation with the haptic device and felt more secure to proceed with using the combined IK/FK algorithm.

Dialogic discourse

The experiential approach towards the collaboration connected the knowledge and experience of the animators and that of myself, and brought them into a dialogic relationship. The exchange of expertise and the synergy of the creative abilities and different ways of thinking between us drove the research towards interesting paths. I believe that the designer has an important role in orchestrating the circular process of information exchange and production of new knowledge by constantly reflecting on the strategies, actions and procedures of the design activity. The dialogic discourse supports this role by bringing the designer in constant dialogue with the design experience, and enabling her to inform her conduct based on the phenomena which occur during this dialogue with respect to previous work in the field. In this way, the designer sets the conditions for the possible user experiences.

In order to gain a deep understanding of the design context, I immersed myself in their working environment prior and during design. All design studies and interviews took place at the animators' studios while I spent time observing them working. I did so not as an external observer but as a collaborator who was interested in being informed about their practice. This process helped me gather information and identify issues and opportunities that I confronted with design studies later in the design process.

Reflection

Multiple streams of reflection was an important design tool for supporting my broader understanding of the different processes during design. Continuous and multi-streamed reflection

assisted the observation of the smallest details which can be of importance in the design of enactive interfaces where action is fundamental to how the design will progress. User and designer's reflection can be used as a tool to design for appropriation of technology which, according to Salovaara et al. (2011), is 'the creative ways in which individual users, groups and communities adapt and repurpose technologies to serve their own goals, sometimes doing this in a different way than that which was envisioned by the designers'. Höök (2004) has questioned the design for appropriation of media by asking 'How can we design for good appropriation of media, a sound user-centered perspective, for actively interpreting users, but not abandon our responsibilities as designers?' (Höök, 2004, p.2). Salovaara et al. (2011) acknowledged the need to link the design process and the process of studying the users and called for related methods, approaches, design principles and theories. Dix (2007) has discussed a few guidelines for appropriation with practical examples and positioning his approach within the holistic design framework. He writes:

Ethnographies often show that users appropriate and adapt technology in ways never envisaged by the designers, or even deliberately subverting the designers's intentions. As design can never be complete, such appropriation is regarded as an important and positive phenomenon. (Dix, 2007, p.27)

My method of multi-streamed reflection within the experiential approach to design provides one response to this call. In contrast to Höök's reference to user-centered perspective, I believe user-driven design to be the most appropriate approach for my proposed method as it provides more design space to the users than user-centered design does.

Through an iterative cycle of discussions, comments and hands-on experiences of prototypes of the haptic workspace, I triggered the animators' reflection on their working methods, while confronting them with the possibilities of the haptic tools. The prototypes were the mechanism which supported the animators' reflection through practical experimentation and led them to suggest interaction metaphors that supported embodied animating experience, such as the locking chains model and the puppet-in-hand metaphor. I believe that in order to capture the full potential of the experiential phenomena that occurred during their work in the haptic workspace, they should have as much time as they needed to explore it. Therefore, there were no time restrictions and time was in no case measured as a quantifiable parameter. This enabled them, when they explored the prototype, to be as relaxed and comfortable as they are in their normal practice. Many would listen to music on their earphones while they were animating.

Throughout the design studies, I practised self-reflection in order to ruminate on my own experience as a designer. This helped me to articulate design issues and learn from them, explore further the cases where explicit or implicit issues were raised and think creatively about the next designs. In some cases, critical reflection led me to establish new collaborations

to investigate some elements further. In all collaborations, the results provided deeper insights often revealing unexpected aspects and opening avenues for further research. For example, my method of involving the digital animator proved to provide valuable insights on certain aspects of the haptic workspace with some of them, such as the per-gesture motion synthesis, contributing to the general field of digital animation.

The method of asking them to interview me in order to encourage their reflection towards my practice, both design and research-wise, triggered also my critical reflection on my research. The dialogue that was established, described in Section 4.4, not only addressed their questions but also led me to fruitful considerations of the broader scope of my research and to making a review of its progress up to that point. As a final remark, my methodology of iterative prototyping, the hands-on sessions and the multiple streams of reflection created a suitable framework for eliciting the embodied tacit knowledge and for informing the design in a thorough but not rigid manner. My collaboration with a group of highly creative skilled practitioners provided a fascinating grounding for engaging in HCI design by creative practice.

5.3 Reflections on the haptic workspace

In the first chapter, I made the observation that skilled practitioners cannot easily work in digital workspaces because the latter are not designed to support body-driven and multi-sensory embodied skilled practice. Following this observation, I carried out this research in order to investigate the transfer of skilled activity in digital workspaces by practically designing and developing such a workspace using haptic technology. As such, the haptic workspace embodied the design concept of a haptically-mediated digital environment for doing stop-motion animation. The series of prototypes built during the co-design process revealed aspects of the traditional practice which were integrated in the design, transferred and re-appropriated in the haptic workspace. The process of transfer and re-appropriation uncovered embodiment issues related to the interface design which I identified and discussed from the perspective of embodied cognition. The majority of the issues were resolved collaboratively and informed the design of the proceeding prototype each time. Therefore, the prototypes acted as a means of exploring the transfer of the animators' embodied tacit skills from the physical to the haptic workspace. The issues that could not be resolved due to technological limitations were noted and possible solutions were discussed with the aspiration that those discussions will enable further research.

Immediacy

One important aspect of the haptic workspace was the immediacy that it created which enforced the feeling of embodiment during animating. Immediacy was particularly referred to

by all animators, including the digital animator, who all regarded that the embodied interaction that it induces can act as a layer upon which they can develop new skills. One puppet stop-motion animator explained that 'there is a nice immediacy about [the haptic workspace], an ability to control things with the force feedback'. He also commented on the intuitiveness the workspace offers to the creative side of animation which allows the direct act of animating on screen without additional devices on the head such as Head Mounted displays which, to him, were disruptive to the animating experience.

The immediacy was given a spatial dimension as most of the animators thought it was very useful to capture a frame and see it simultaneously on the screen without having to move from the scene, currently a disembodied practice in puppet stop-motion. Although it was not implemented, the per-gesture animation method of recording the characters' motion adds a temporal dimension to the immediate animating process as it connects the animators' gestures with the character dynamically over time.

Perturbations

Another quality of the haptic device on which the animators referred to as invaluable to the animation making process was the freedom it offered in spatial gesture in relation to the possibility of introducing tiny perturbations, most of the times unintentional, during making, as in the traditional stop-motion practice. According to the animators, in terms of craft appreciation, these perturbations add value to the artifact. During the training time, more than one animator observed that the haptic workspace offered much freedom in terms of gesture and increased the possibility of accidental errors when manipulating the puppet which were embedded into the motion of the puppet. Some of them explained that an interface, either digital or not, that does not allow space for human evidence will not be intuitive enough for the skilled practitioner.

This position has been discussed by numerous skilled practitioners in the academic context. Tavs Jorgensen, a craftsman who has been working with digital tools, suggests that 'the making process has been a significant component in the appreciation of craft products, often as an integral part of the aesthetics in the finished piece' (Jorgensen, 2005). The crafting process is often characterized by inconsistency and unpredictability and mistakes are not uncommon but neither are unwelcome by the practitioners. The inevitable risk involved in manual work attributes to the artifact the *human evidence*, momentary glitches which add extra value to it. In contrast, the development of digital tools is based on workspaces that reduce the possibility of error to a minimum. Naturally, then, the products of work become less flawed, uncannily perfect and look mechanically identical. As Dormer (1997) states, 'Ubiquity: The commonest feature about technology, with its distributed knowledge, is that everything begins to look the same'. In his account on how digitally based techniques have the potential

to form the concept of the post-industrial artisan, Jorgensen comments that:

Perhaps the greatest danger presented by the move towards IT based tools is the potential loss of core qualities such as the 'human' and 'personal' elements, which have sustained 'the persistence of craft' and still continues to drive the interest in the subject amongst practitioners as well as the buying public.

The animators expressed similar views. According to one animator,

Crafting motion, frame-by-frame, is characterized by momentary failures and intuition. Movement in each frame has *manuality* and a sense of fluidity. It's called *Manual Aesthetics*, this is how it is called, when it works more with intuition rather than precise, accurate settings

The existence of flawlessness in computer generated artifacts, and the absence of it in hand-made artifacts denotes one difference of the aesthetic quality of both outputs. Pye (1995) highlighted this distinction by naming the first as the *workmanship of certainty* and the latter as the *workmanship of risk*. He argued that the aesthetic quality of our environment depends as much on its workmanship as on its design. However, although many practitioners have advocated the unpredictability of the aesthetic result of the workmanship of risk, according to Dormer (1997) it should also be recognized that 'regularity is as much a human desire as irregularity and some people feel warmly emotional towards the precision of a motor vehicle, an aircraft component or a machine tool as other do towards carved stone or textured pots'.

5.3.1 Further developments

A few developments of the haptic workspace were suggested during the studies. The stop-motion animators considered the possibility of being able to model and rig the character in the haptic workspace since the majority of them, outside big animation studios at least, build their own puppets. The more experienced animators though, expressed the view that it would be better to have the characters already made and rigged according to their instructions, so that they could focus on animating them. The animators who preferred to model their own character did not prefer the modeling and animation to be carried out in the same workspace. Their argument was based on the premise that separate software interfaces are more easily updated individually. For each of the functionalities, specialized sub-functions are needed to provide the software with the capabilities of the tools that are demanded by the processes. The animators argued that because it is very demanding in terms of time and resources to research and develop for two functionalities (or more) simultaneously, current commercial packages are updated less often. Their response advocates focused and specialized development.

Many times during the studies the animators commented on the potential use of the Omni device for other forms of animation that involve deformable objects, such as clay animation, because of its appropriateness as a sculpting tool. The potential of the haptic device as a

sculpting tool has been proven by the commercialization of software tools such as ClayTools™, FreeForm™ by Sensable and Cloud9™ by Anarkik3D which are haptic workspaces for sculpting 3-D models. Clay animation is a stop-motion technique in which the puppets are made of clay and can be easily deformed. One animator commented that it would feel very natural to carve facial expressions with the stylus as it resembles the tool they use for this purpose. Using deformable characters would broaden the variety of motions which can be created with the haptic device to motions such as stretching or squashing. It will be an interesting research project to explore haptically-augmented virtual clay animation with regards to the design of metaphors for manipulating the characters.

Another useful development that was mentioned by one of the digital animators who participated in the signature test, was the possibility of having an 'Animate as' function. This function would apply the animating style of famous puppet stop-motion animators, or stop-motion animation companies to the motion of the animated character. The haptic workspace provides a more embodied and multi-sensory way of exploring the motion dynamically, experimenting with and learning from it. Related work in the literature is that of Costello (2006) who made a short analysis of how the quality of movement in puppet stop-motion animations can be replicated in digital character animation. Costello worked for Dreamworks, a well known digital animation company. The reason behind his analysis was that DreamWorks sought to recreate, in one of their digital animated movies, the style of the animations made by Aardman Animation, a UK-based company renowned for their puppet stop-motion animations. The 'Animate as' function, as the animator envisaged it, applies the part of the animator's signature style that relates to character motion but might equally be extended to cinematography and atmosphere.

5.3.2 Reception

The animators' interaction with the abstract virtual characters through the haptic sense introduced new dimensions to the animating experience. They identified a plethora of creative paths to be discovered by animating in the haptic workspace and considered it a new tool and concept that they would use in parallel to their traditional practice. They enquired about keeping it in their studio for practising with it at their own leisure and for educational training. Those who were students included the animations they made in the haptic workspace in their end-of-year portfolio. One animator suggested that animation companies could use it as a tool for rapidly viewing and understanding the abilities and potential of job candidates.

An important observation related to the impact of the haptic workspace to the community of animators, is that it has been very positively received by the digital character animator. The positive reception by both digital and puppet stop-motion animators indicates the potential of the haptic workspace to be used as a means for bridging the two techniques.

Chapter 6

Summary and future developments

The aim of this design-led research was to investigate the transfer of the puppet stop-motion animators' embodied tacit knowledge into a digital workspace. This transfer was explored by developing a haptic workspace that supports enaction and enables immediate and tactile interaction with the objects in the virtual animation world. The haptic workspace has been co-designed through my established collaborations with puppet stop-motion animators, following an experiential design perspective. In this design perspective, the experiences of the animators and myself were catalytic to the development of the work and I proposed multiple streams of reflection as a very important tool that can support this approach.

In this final chapter, I will summarize the contributions of this research project and discuss them in view of recent explorations and technological advancements in this and similar fields.

6.1 Summary

In the first chapter I discussed the different dimensions of embodied activity between the physical skilled practice of stop-motion animation and the animation practice that is carried out in a digital environment. I emphasized the fact that existing digital animation workspaces cannot facilitate skillful actions, as their design does not consider the multiple processes that take place during embodied activity.

I believe that stop-motion animators, as well as all non-digital creative artists, carry important embodied knowledge that should be able to be seamlessly transferred to emerging digital workspaces. The driving force behind this research has been the aspiration to identify, record and transfer the multi-dimensional skilled knowledge of puppet stop-motion animators to a digital workspace that supports and augments their current working methods.

Reviewing advanced technologies that have the ability to support multi-modal activity

in digital workspaces, I selected haptic technology as the main mediator of the animators' gestures into the virtual environment. I did so because of its ability to invoke simultaneously kinaesthetic, tactile and proprioceptive senses and thus enable enactive interaction with the virtual environment. I set out to investigate how haptic technology can transfer the puppet stop-motion animators' embodied skills through a series of design-led practical explorations, which involved the design and development of a haptic workspace prototype.

In these explorations, I established collaborations with members of the stop-motion animation community with whom I designed the haptic workspace. Within these collaborations, I placed the knowledge and experience of both the animators and myself at the center of the design process with the aim to facilitate the identification and articulation of issues and opportunities related to the interface design, the design methodology itself and future developments of the haptic workspace. Using multiple streams of reflection has been an important design tool that successfully supported exploration of these three aspects. This research made the following contributions:

- Provided insights on the design of a haptic interface for skilled practices through the lenses of embodied cognition
- Developed a prototype of a haptic workspace for computer-assisted puppet stop-motion animation
- Explored the use of the haptic workspace by digital animators investigating points on which the digital and puppet stop-motion techniques converge
- Applied a design methodology for capturing and transferring the embodied skills of the puppet stop-motion animators into the haptic workspace
- Proposed multi-streamed reflection as a method for identifying and articulating the different processes that take place during design

These contributions are detailed in this thesis with the aspiration to ground further research and open up avenues for future creative explorations in HCI design and related fields.

6.2 Future directions

Digital technology that enables multi-sensory interactions with virtual environments advances rapidly and offers significant opportunities to transfer, support and augment puppet stop-motion animation practice, alongside several skilled practices, in a digital workspace. However, irrespective of the digital technology employed, its limitations and capabilities should be identified and appropriately used towards the best possible result. As such, an important contribution this research project has made towards future research in the field is the

adoption of a design methodology that brings together HCI designers with knowledge of the available technology and its limitations, and skilled practitioners with expert knowledge of the design context. Their collaboration under the experiential design framework, facilitates the recognition, understanding and articulation of design issues, and the transfer of aspects of skilled practice into the digital workspace. Following this methodology, the process of transferring these aspects transcribes valuable design insights that advance relevant knowledge in the field. A thorough evaluation of the haptic workspace will provide further insights into its appropriation and integration as part of the stop-motion animators' practice.

In the field of haptic technology, haptic exoskeleton gloves provide the combination of force feedback with multi-point contact, which makes them able to support precise and dexterous complex manipulation of virtual objects. However, off-the-shelf exoskeletons and those developed in research labs are still an expensive commodity.

Lately, 3-D displays, which can project a three dimensional image in full instead of using stereoscopy, have become widely available and are rapidly improving. 3-D displays offer immense possibilities for animating in 3-D without the need for extra equipment for the eyes, with particularly beneficial applications in the digital animation industry. The use of 3-D displays can provide greater insight into the issue of depth perception and drive further research on multi-camera views. Incorporating this technology in the haptic workspace could make it useful for the production of 3-D enabled animation movies.

The research that I carried out can be expanded to other animation techniques, such as 2-D animation and performance animation which can bring more insights into the design of the haptic workspace. Towards the end of my research, I carried out a study with 2-D animators which can be found in Appendix A. My preliminary results indicate areas where haptic input could be beneficial in transferring the embodied skills of 2-D animators in a successful way.

A small part of my research was to explore the potential of the haptic workspace from the perspective of digital animators. The evidence indicated that bringing the workspace to the digital animation community can set the basis for constructive explorations, new designs and novel developments. Extending the research to other forms of animation can assist investigations on how the haptic workspace can integrate elements of different animation techniques and create new embodied ways of animating.

6.3 Epilogue

As discussed in the first chapter, recent research endeavours that have inspired my approach have highlighted the close relationship between embodied activity and haptic interface design. Visell (2009) noted that it is necessary to study and better understand the multi-sensory experience evoked by enactive interfaces in order to explore their design. Gillespie and

O'Modhrain (2011) proposed a central focus on embodied activity in order to assist the design of haptic interfaces. In my practical work, I followed this research perspective grounding it on an experiential design-led approach. I strongly believe that this approach can provide an appropriate baseline for bringing together embodied skilled knowledge and enactive interfaces in order to study how best to create a synergy between them. The insights that this thesis provides can support and inspire researchers and practitioners towards new collaborations and creative explorations, and maintain the ongoing dialogical discourse.

Appendices

Appendix A

Bringing spatial input to 2-D animation techniques

This study in the use of the haptic device for 2-D animation took place towards the end of my research. Although it is not directly related to the transfer of the puppet stop-motion animators' skills into a haptic workspace, it provided me with evidence on the potential of haptic workspaces for 2-D animation.

During the previous studies, I observed the relationship between the dimensions of the input device and the dimensions of the world that is displayed in the puppet stop-motion movie. While the movie is viewed on a 2-D display, the world that is illustrated in the story is always 3-D. The focus of my research on navigation of virtual environments and manipulation of virtual objects, led me to consider the possible discoveries in the areas of character manipulation and atmosphere creation if I used the 3-D haptic device for animation techniques which traditionally require 2-D input.

To achieve this, I selected the 2-D technique of hand-drawn character animation as a case study. I collaborated with three Master level 2-D animation students from the Animation department at Edinburgh College of Art. After an initial contextual enquiry on the way they work in 2-D, I followed the pattern of the workspace intervention study, and reconfigured the haptic workspace using the animators' comments and on my reflection of our initial discussions. The hardware interface remained the Omni haptic device and the 3-D mouse but the software interface and the mappings between the gestures and their result were redesigned in two different ways. Both reconfigurations were given to the animators with the intention of exploring the transfer of their skills to the haptic workspace. This study took place during December 2010.

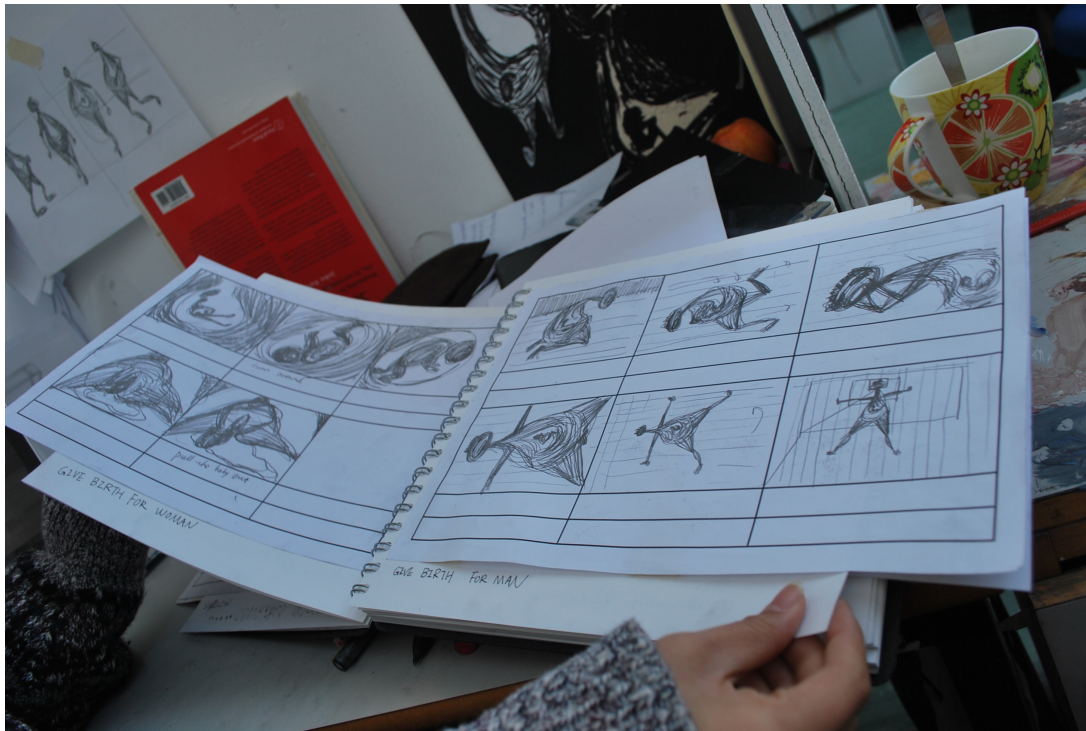


Figure A.1: Storyboard example

A.1 Hand-drawn character animation

Hand-drawn character animation uses a sequence of hand drawn images of characters which if they are placed in order and played back rapidly produce the motion of the drawn characters. Each drawing is one frame in the sequence. Traditionally the drawings are made with several types of drawing tools, such as pens and pencils. With the advent of computers, the technique has evolved and drawings are now scanned into the computer and are digitally painted in software or are created entirely in it. This software typically has a WIMP interface and often pen tablets which simulate the two dimensional action of drawing with pen-shaped tools.

According to the 2-D animators, the hand-drawn character animation production steps include:

1. The formation of the script idea
2. The sketching of the characters, background and atmosphere
3. The creation of the storyboard which is a set of illustrations of the frame sequence displaying character poses, angles of view and lighting (Figure A.1)
4. The selection of the drawing materials
5. The creation of the background and the perspective

6. The creation of the hand-drawn images
7. The addition of sound

In computer-assisted hand-drawn character animation, the creation of the images happens either directly in the software using the mouse or pen tablet or the images are drawn by hand and are then scanned into the computer. The scanned images are vectorized which means that their lines are turned into the same format as that of those drawn directly on the computer and can be easily manipulated by digital processes. This is followed by the rendering of the *in-between* drawings before the sequence is exported in video format. In-betweening is a process in which the software calculates the procedural progression of motion between two given poses using interpolation¹. In-betweening is the digital equivalent of the traditional process encountered in animation studios where the lead animator draws the main character poses and a team of junior animators produces the in-between poses.

A.2 Reconfiguring the haptic workspace

Discussions with the 2-D animators revealed that one of their aims when they draw characters on two dimensional paper is to create a correct sense of perspective. Geometry, lights and shadows are drawn in such a way so that they give to the drawn objects and scenery the illusion of depth. In computer assisted traditional animation, it is difficult to draw the correct perspective or retain the objects' volumes and the main reason for this is the lack of 3-D information. According to Di Fiore and Van Reeth (2002):

To retain the frame-to-frame coherence, the applied painted strokes may not suddenly appear and disappear, nor move or deform with respect to the object. Without such coherence, the temporal aliasing would make the final animation hard to enjoy. Existing software to assist traditional animation lacks the 3D representation needed to tackle this kind of shortcomings. (Di Fiore and Van Reeth, 2002, p.183)

I developed the first software around this argument, aiming to explore if the haptic device assists the depiction of 3-D information of the world that is traditionally drawn on paper. The application, which for clarity I will call *Virtual paper*, consisted of an initial screen displaying a touchable white plane positioned vertically to the animator's optical axis (Figure A.2). The plane simulated an A4 paper in landscape mode. Force feedback was generated on the device once the manipulandum's representation, the virtual sphere, came in contact with the plane so the sphere could move in depth only up to the plane. The sphere, and any objects grabbed with it, could be moved in the range bounded by the dimensions of the virtual paper, for the axes parallel to the plane defined by the paper.

¹Interpolation can be applied to scanned images only if they are vectorized

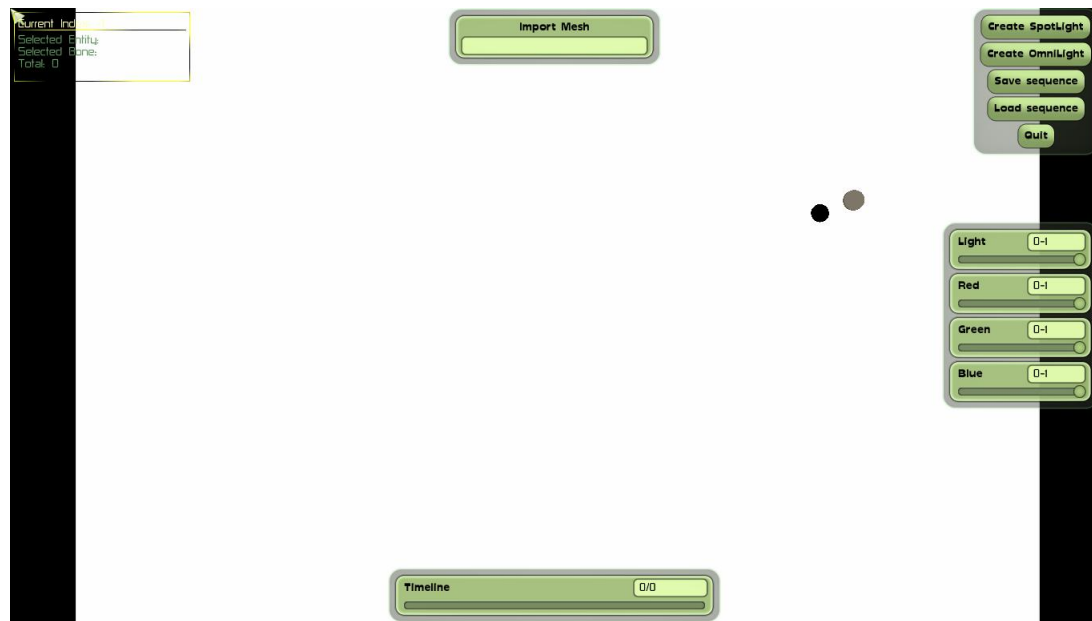


Figure A.2: Virtual paper - default screen

The characters were the same 3-D models which were used in the previous studies and were imported onto the virtual paper from a drop-down menu. They were rigged and could be manipulated with the FK algorithm, utilizing the Omni's rotational DoF. In line with the aim of this study, I did not constrain the skeleton's manipulation to two dimensions and aimed to explore how 3-D manipulation assists 2-D animators to create the 3-D world. Patterson J. W. and Willis P. J. (1994) have previously suggested the use of 3-D models in computer-assisted 2-D animation software for the purpose of overcoming issues with the software during automatic in-betweening, examples of which are the distortion of the individual shapes that form the character and self-occlusion. (Catmull, 1978) has identified the absence of 3-D information as the cause of these issues.

I deliberately chose not to implement the locking chains model. From the previous studies, together with the puppet stop-motion animators we concluded that the FK provides a simple and precise method for the initial steps of animating in the haptic workspace. Given that the 2-D animators were unfamiliar with the 3-D techniques, I concluded that the locking chains model might impose unnecessary cognitive load for the task of animating a 2-D character.

The lights were imported with the corresponding GUI button and they could be moved in the area above the board. This design did not include navigation as most of the work of a 2-D animator does not require traveling around three dimensional structures.

With the second design, which I called *Virtual storyboard*, I sought to explore the creation and handling of storyboards which I encountered during my review of the Dragon™ professional stop-frame software. In this second design of the haptic workspace, I aimed to investigate its effectiveness in arranging and rapidly visualizing a sequence of drawn images.

The virtual environment was an empty 3-D space with only one ground texture of a grid. The grid consisted of white lines on a black background and, as the background colour of the whole environment was also black, it created a sense of perspective (Figure A.3).

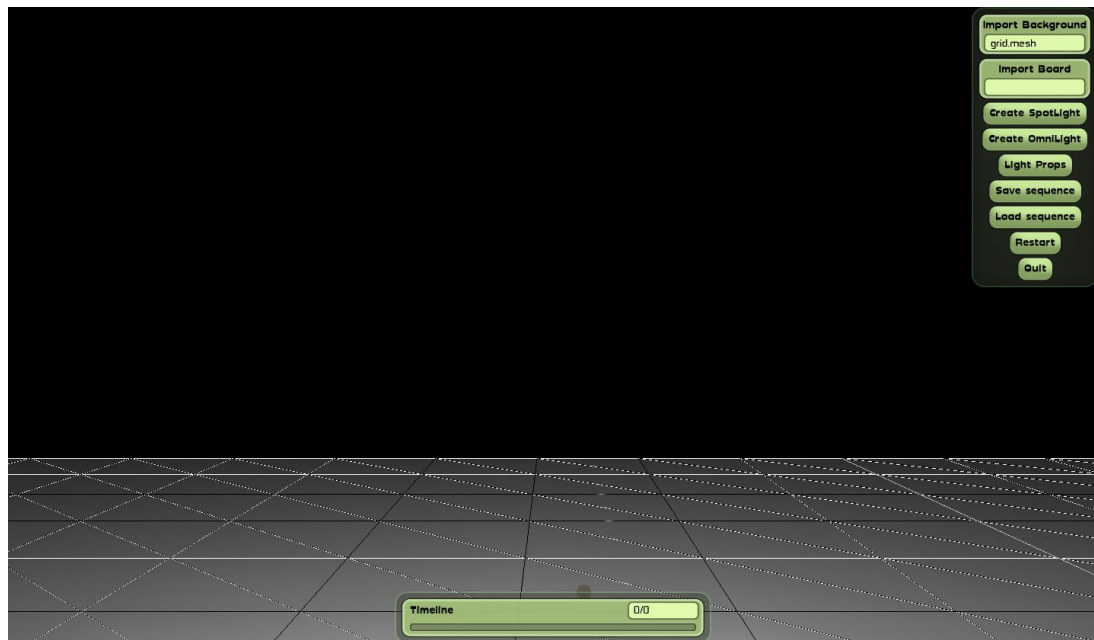


Figure A.3: Virtual storyboard application: Grid

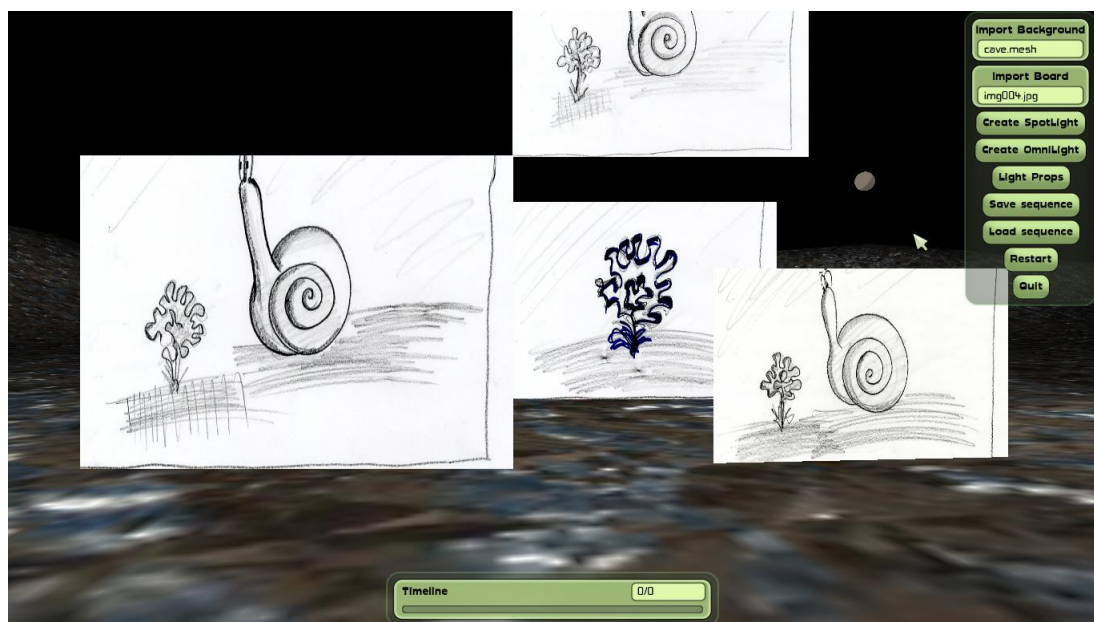


Figure A.4: Scanned drawings in the VE

Scanned images were imported from a drop-down list. The images appeared as textures mapped on touchable rectangular boards which could be moved in the virtual environment with the haptic device (Figure A.4). The boards had weight so once they were grabbed and

moved with the manipulandum the animators could feel their weight. The drop-down list was populated from a folder which included the scanned images in JPG format. The 3-D mouse was used for navigating the virtual environment.

Both designs were presented to the animators during a two days session in December 2011. For the virtual storyboard application they were asked to explore the virtual workspace and contribute insights on if and how this design assists their practice. The same brief was followed for the virtual paper in which I additionally asked them to animate the characters and setup the atmosphere of the scene.

A.3 Reflections and Insights

3-D lighting

The most prominent insight that this study contributed was the fact that working in 2-D with a gestural input added a new embodied dimension in the creation of the atmosphere. Initial discussions with them had revealed that the drawing of lighting is a very tedious process and not many useful software tools exist that ease the task. Working with the virtual paper, they found the ability to move the spotlights and adjust their properties to create three dimensional lighting effects directly and easily very interesting and useful. The effects were accompanied by the corresponding shadows (Figures A.5 - A.7). The adjustment of the spotlights was made possible through the haptic device and direct orientation and position of the stylus was translated into orientation and position of the light. Thus, the animators could depict the 3-D lighting setup that they had in their mind on to the paper without the need to think carefully about how to accomplish this. This immediacy established an embodied way of lighting the scene. In addition, it provided them with flexibility in experimenting with different light setups in a short amount of time.

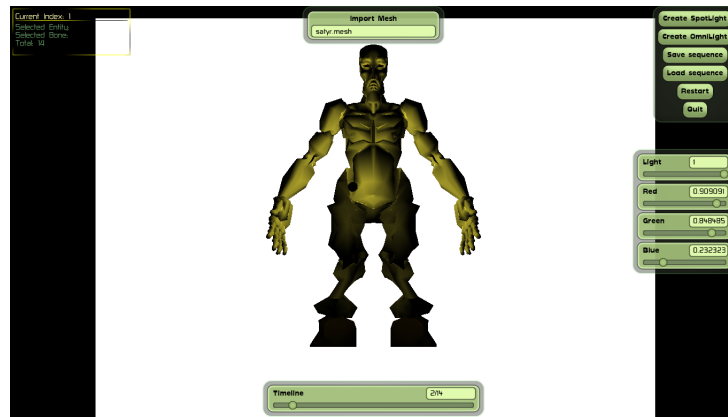


Figure A.5: Experimenting with lighting effects - 1

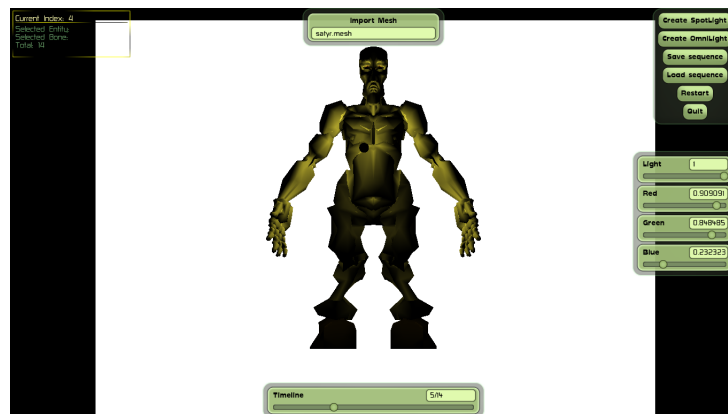


Figure A.6: Experimenting with lighting effects - 2

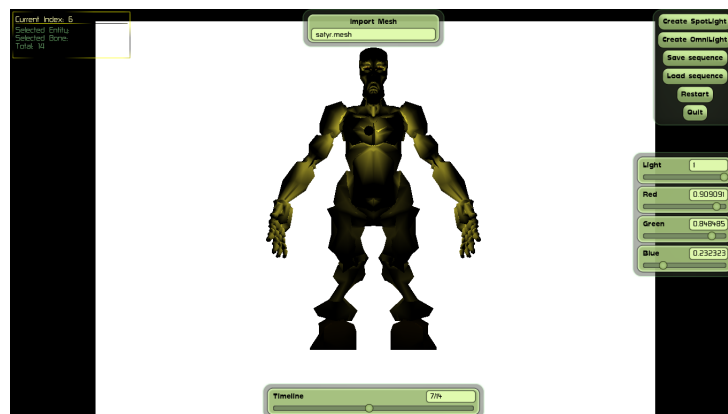


Figure A.7: Experimenting with lighting effects - 3

However, there was an issue with light selection. It was difficult for them to understand the distance between the visual representation of the light source and the virtual paper. An indication of perspective was deemed necessary for this action, however, this would be difficult to accomplish given that the workspace must remain 2-D. I noticed that the animators, due to

the fact that they were not familiar with working in 3-D, disregarded the three dimensionality of the sphere's motion and were trying to select the light without moving the sphere, and thus the haptic device, inwards or outwards. I had observed the same activity with the puppet stop-motion animators. Yet, since the focus of this study was 2-D animation, I decided to disregard the virtual environment and consider the workspace as it actually is, a two dimensional display. This led me to think of a solution to the selection issue using the ray casting metaphor, which was mentioned in Section 3.5.1.

A ray is a virtual, and possibly invisible, beam that extended from the manipulandum's representation inwards. In my proposed design, when the sphere moved, the objects which were behind it on the axis of the ray were scanned. If the object was a light source, the ray selected it by highlighting it and did not move it from its place to the sphere's position but followed a path parallel to the sphere's motion. With this design, the complexity of the virtual environment is reduced and the light selection is simplified. This method of light selection can be extended to the puppet stop-motion haptic workspace.

Character motion

Further reflection on the side of the animators indicated that the presence of the spotlights revealed the three dimensionality of the character and in combination with the ability to feel the character haptically, it re-introduced successfully the 3-D information which is absent in common 2-D animation software. The use of 3-D models for re-introducing the information of the characters' 3-D structure has been suggested, though not implemented, by Patterson J. W. and Willis P. J. (1994). Their suggestion was specific to overcoming issues of automatic in-betweening which do not apply in our case. However, they noted that the use of 3-D models introduces a new problem as animators are 'asked to interact with a 2-D representation of the 3-D model with tools which are only naturally meaningful in the 2-D environment' (Patterson J. W. and Willis P. J., 1994, p.837). In the virtual paper workspace, this issue is eliminated because the models can be manipulated directly with the 3-D input provided by the haptic device. The animators remarked that the direct 3-D manipulation of the character let them rapidly create consistent motion over time. They did not need to animate all the different shapes that formed the character or use hierarchical display models, a hierarchy of individually drawn shapes so that their transformations are more easily computed (e.g. a face comprising of the nose, eyes, lips etc.), since this was directly achievable by the direct manipulation of the character's 3-D structure.

One drawback of the virtual paper was the absence of precision in the motion of the character. The animators emphasized that precise drawing was possible with the haptic device provided that an arm support was present. Arm support would help with drawing and also with the fatigue that is caused by continuous gesture (discussed also in Section 3.6.2).

One solution to the issue of fatigue could be to place the stylus on the real desk and map one physical area to the storyboard area on the screen. Then, the animators would be able to move the images around the 2-D desk surface with small movements having their arm supported on the desk. Because the two planes of action would be perpendicular to each other, new manipulation metaphor would be needed to be designed.

I also considered important the absence of collision detection between the characters and the virtual paper. In my design, the character did not collide with the virtual paper neither graphically nor haptically. From my experience with the results of the previous design studies in which stop-motion animators enactively created a haptic map for navigation, force feedback could constrain the motion of the character on the 2-D plane and make its manipulation more precise.

Another issue was the lack of support for a wide range of motions that 2-D characters do which supersede reality such as the stretching of an arm. In relation to this, Patterson J. W. and Willis P. J. (1994) caution that kinematics-only systems impede the production of convincing solutions for the characters' motion and they suggest that dynamics-based systems which calculate natural forces are more efficient for 2-D animation. In the virtual paper, this issue can be resolved by creating 3-D models which are deformable bodies, however, attention must be drawn to the compromises in the rendering quality of either physics or graphics when they are computed in parallel. I cannot discuss this case in detail since the haptic workspace was built only for rigid bodies, however the effectiveness of the 3-D input so far indicates that it could be a beneficial addition to the workspace design.

In the virtual paper design there was no process for capturing frames because my focus was on exploring how the 2-D animators worked with the 3-D enactive interface. One obvious way to capture the frames would be to project the three dimensional information of the characters and the lighting onto the paper and save it as an image. The ability to display three dimensional information in 2-D resembles the technique of rotoscoping, which involves tracing the outline of actors' shapes in live action onto individual drawings. Rotoscoping used a projection system called rotoscope, consisting of a frosted glass panel onto which the recorded live-action film images were projected and traced over by an animator. The difference with the virtual paper is that rotoscoping is real time motion capture, whereas the virtual paper is offline and the three dimensional information is created by the animators.

Animating the camera

In both designs the animators strongly suggested that they should be able to animate the viewer's camera.

For the virtual storyboard, they suggested that a useful tool would be a recording camera that moves from drawing to drawing capturing and storing each image as a frame. They

found the application useful for rapidly pre-visualizing sequences of frames. In the virtual paper, in which the camera was fixed looking at the virtual paper, the animators proposed that the camera could zoom in and out of specific parts of the virtual paper in order to simulate decrease and increase of the size of the objects on it. This method for capturing images offers the ability to simulate the change of the character's size and is widely used in 2-D animation digital software such as Adobe Flash™.

An issue the animators identified with the virtual storyboard application, is that having all drawings in full size present in the space was not efficient if the drawings are large in number, which is the norm in hand-drawn animation. This would need a different setup to manage them all. They also regarded the 3-D environment as unnecessary and rather confusing as all drawings could be present in a 2-D space such as the one in the virtual paper application. When I designed the virtual storyboards, I had imagined the action of covering one board with the consecutive image using the haptic device for rapidly visualizing the continuation of motion in the content of the two images. The animators did not suggest that and did not think of it as a useful action when I suggested it, especially with the issue of fatigue being a detriment to precise movement.

Appendix B

List of papers, talks and publications

B.0.1 Papers and publications

Dima M., Wright M., Lee J. 2011. "A haptically-augmented interface for digital character animation", Poster, SIGGRAPH Asia 2011, Hong Kong, China

Dima M., Lee J., Wright M. 2010. "Exploration of direct bi-manual interaction in digitally mediated stop-motion animation", Proceedings of NordiCHI 2010, Reykjavik, Iceland

Dima M., Lee J., Wright M. 2010. "Hapty : a Haptically Augmented Animation tool", Extended abstracts, CREATE 2010, Edinburgh, UK

Dima M., Lee J., Wright M. 2009. "Designing a creative interface for character animation: Embodying the qualities of hand practice in the digital process", Doctoral Consortium, British HCI 2009, Cambridge, UK

Dima M., Ulattil A., Cao X., Lee J., Wright M. 2009. "Designing a haptically extended interface for digitally animating 3D articulated characters". Proceedings of EVA London 2009

Biggs S., Dima M., Ekeus H., Hawksley S., Timmons W., Wright M. 2009. "The H in HCI: Enhancing perception of interaction through the performative", Proceedings of HCI International 2009, Lecture Notes In Computer Science; Vol. 5622, Springer-Verlag

Dima M., Arvind D.K., Lee J., Wright M. 2008. "Haptically extended augmented prototyping", Proceedings of International Symposium for Mixed and Augmented Reality 2008

B.0.2 Invited Talks

"Using gestural interfaces to augment hand practice into the digital. A case study in Animation", *Prokalo lecture Series, School of Architecture, University of Edinburgh*

"Exploring the Design of novel systems that bring creative hands-on practices in digital environments: A case study in Animation", *TU Berlin - Deutsche Telekom Labs*

"Using touch to transfer craft in the digital workspace", *ECA Research Seminars, Edinburgh College of Art*

"Towards more intuitive human-computer interactions: A haptically extended interactive interface for animating 3D articulated characters in virtual environments", *Ph.D. presentations, School of Architecture, University of Edinburgh*

Exploration of direct bi-manual interaction in digitally mediated stop-motion animation

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ABSTRACT

In this paper we present the development of a digital system prototype for character animation, with the primary focus on enabling direct bi-manual interaction through the employment of haptic sense and gestural control. The aim of the research is to explore the design of digital animation systems that build upon and augment the rich tacit knowledge embodied in the traditional creative practice of stop-motion animation. A team of highly skilled stop-motion animators participated in the design process of the prototype system evaluating and reflecting upon the key aspects of the design. We describe our design approach and the methodology employed in two design key studies framed around the concepts of direct tactile manipulation and two-handed interaction. We identify the components that enabled immediacy and enhanced engagement with the new system. The outcomes of the studies illustrate the system's potential for enabling immersive physical interaction in a digital animation setting.

Author Keywords

Animation, tacit knowledge, haptic I/O, embodied interaction

ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation] User Interfaces – Input devices and strategies, Interaction styles, Haptic I/O, User-centred design

INTRODUCTION

Practitioners trained to work with digital media have access to a wide range of digital software which ease the production process, yet, little change has been made regarding the physical ways to interact with the digital workspace [5],[6]. Although in the research domain there is growing interest in exploring physical interfaces as a means

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NordiCHI 2010, October 16–20, 2010, Reykjavik, Iceland.
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of interaction, in the mass-market the Window/Icon/Menu/Pointer (WIMP) and keyboard have been, in most cases, the predominant interfaces through which digital software are accessed. Arguably, those interfaces fail to communicate the richness and complexity of human gesture [12] and consequently, embodied skills cannot be accommodated properly in a digital setting. Hence, the tacit skills of traditionally trained practitioners cannot be utilized efficiently in digital workspaces.

We illustrate this issue in the dichotomy between traditional physical Stop-motion and digital Computer Graphics aided animation and further explore it as a case-study. Our design-led research explores the application of intuitive interfaces and creative mapping for transferring the rich tacit skills of traditional Stop-motion practice in a digital setting.



Figure 1. A stop-motion animator adjusting the head of a chrysalis character

Stop-motion is one of the earliest animation techniques. A physical object, usually an articulated character, is moved through different postures and photographed in each one of them. The photographs are then combined and played back in a fast sequence thus creating the illusion of movement. Today the process is being enhanced with digital cameras and digital recording software for the arrangement and playback of a sequence. The technique can be used, amongst others, for rigid or deformable objects such as clay. Animators who work with stop-motion develop a particular set of skills which unfold around unencumbered two-handed tactile interaction with the physical models (Figure 1).

We focus on exploring the development of a hybrid system that connects the physical and digital animation practice, drawing on the concept of direct bi-manual¹ interaction which prevails in the traditional practice. In the following paragraphs we will describe the methodology that was used to develop our prototype. We will further present the results of the key-studies and the overall outcomes of the user tests, identifying significant points that need to be taken into account in future designs of such applications.

RELATED WORK

We have decided to employ physical interfaces as research has showed that, by being more apt to human motor-sensory and kinesthetic abilities, they create an enriched interaction space [5], [9], [12]. In their initial discussions with stop-motion animators, as described in the methodology section, they identified the lack of touch in a digital environment and the immense complexity of commercial animation packages to be salient drawbacks for working in a digital space. Following this comment, we employed, from the wide range of physical interfaces, haptic technology for the dominant hand gestures due to its ability to operate in 3-D space and simulate the sense of touch.

Haptic technology

Haptic devices allow the user to feel the surface of the virtual models by exertion of forces and vibrations to the user via motors. In addition, they are dynamically reconfigurable since parameters like the weight of an object, the stiffness of its surface and the material it is made of can be easily adjusted. A number of research projects make use of haptic devices to edit geometric paths of pre-animated virtual characters and adapt their motion in real time [1], [3]. These projects have explored the application of haptic technology in a limited area of digital animation. However, they have not considered the deeper implications of designing haptically-augmented systems which build upon the skills embedded in traditional stop-motion.

Tangible Interfaces

In order to investigate bimanual action, we followed Guiard's kinematic chain dictum of asymmetric division of labour in skilled bimanual action [4], and assigned tangible interfaces to the non-dominant hand which were used to perform secondary actions. Research projects which have explored the use of tangible interfaces for animation have, in contrast to our set-up, mainly employed them as the *central* gestural input to control locomotion of digital characters. Oore et al [9] presented a physical interface for low-level control of a digital character where the input device consisted of two motion trackers embedded in two bamboo rods. Tangible Handimation employed three Wii Remotes to control parts of a character. The goal of the project was to *'explore more expressive interaction, with*

the hopes of making use of tacit knowledge animators have that do not easily map to current computer interfaces' [11]. Monkey 2 [7] was a tangible input device comprised of individual pieces that could be combined to form a skeleton. The product, which is now discontinued, was used to perform instrumented puppetry.

METHODOLOGY

Throughout the whole process, we have collaborated with a team of three stop-motion animators. Two were final year animation students at Edinburgh College of Art, and the third was working as stop-motion technician at the same College. All three were specialized in modeling and animating physical objects and characters, both human and non-human. Through a collaborative process, we followed an analysis-composition-synthesis design model.

Analysis – Composition – synthesis model

We observed the animators during studio practice over a period of time and conducted a series of in-situ discussions in order to gain in-depth knowledge and analyse the bi-manual tactile interaction between the animator and the animated character. The outcomes of this contextual investigation were combined to construct a series of design key studies. These studies aimed to explore user's perception of the new, digital workspace by framing direct bi-manual interaction as the central element under investigation. All initial investigations and evaluation sessions were recorded in video to capture bodily motions and gestures as they unfolded in time.

Constructing design key studies

Two main key-studies were defined based on two important physical elements of stop-motion: The direct tactile manipulation of a puppet and the bi-manual interaction. For every study a system prototype was built, where functionality was restricted to the main element under investigation. Each study included a series of design iterations aimed at refining the initial prototype by developing the software and adjusting the hardware. The reason behind restricting the functionality of the system prototypes to each particular element under investigation was that we sought to focus on in-depth evaluation of each element separately. In the end, all elements were combined to a final prototype and further tests were carried out.

Evaluation

Intensive 'hands-on' experimentation facilitated our understanding of the requirements of a group of people with a certain expertise which is primarily exercised than verbalised or even sketched down on paper. Moreover, our system employs physical interfaces which need to be used and 'felt' before the exact design of their use is determined. By involving our end-users in an iterative and interactive 'hands-on' experience, we create an open-ended evaluation space apt to revealing unexpected, emergent aspects of their practice and challenges for our design. Video recordings provided insightful complimentary clues.

¹ Using or requiring the use of both the dominant and non-dominant hand

CONDUCTING THE KEY-STUDIES

The workspace (Figure 2) was a 2^{1/2}D space on the computer screen with no other graphical user interface apart from a text area that displayed the performed actions and kept track of the Key-frames² timeline. Keyboard buttons were used for the basic animation actions such as Set/Advance/Retrace a Key frame and Stop/Playback animated movie sequence. A 3-D sphere represented the haptic device in the digital space and followed its movement. The virtual scene included a customizable 3-D background and a set of virtual characters modeled as rigid bodies. A Skeleton, a hierarchical chain of bones and joints, was attached to each body and was given dynamic properties through a kinematics algorithm. There are two main kinematic algorithms, Forward (FK) and Inverse Kinematics (IK). In FK, if a bone is moved or rotated, the bones that follow it in the chain move accordingly. In IK, motion of an end bone determines the motion of the chain (i.e. if fingers are moved then motion of all joints up to the shoulder is computed *automatically*). We have initially chosen to work with FK since the animators highlighted the necessity of having total control over the character's motion. For the same reason, we did not implement interpolation³ or other form of algorithmically-driven automated motion computation between posed frames. In order to keep the virtual space simple, no physics were implemented.



Figure 2. The 3-D virtual space. The white sphere is the visual representation of the haptic device

For each of the key-studies described below, the animators were asked to create an animation of one or more of the virtual characters based on a storyline of their choice.

²A Key Frame is a rendering of a specific position of the animated entities captured at an instance of time.

³Algorithmic computation of possible postures in the frames between the Key-frames so that there is smooth transition of motion between Key-frames

Design I – Haptic sense

We employed two haptic interfaces: the Sensable's Omni™, a stylus-type, six-degrees-of-freedom (DoF) haptic device and the 3-DoF Novint Falcon device which could not provide rotation (Figure 3).



Figure 3. The setup with Novint Falcon and the Wii Remote (left) and the Sensable Omni™ (right)

Both devices were used to map the primary gestures of the dominant hand in a mimetic way as the central control input. However, due to each device's specifications, different configurations were tested for each device. For the Omni™ we exploited the three rotational degrees and we created a mapping in which the animator rotates the joints of the skeleton in order to move the bones. For the, limited to translation only, Falcon, and because we worked with FK, translation of the bone was designed to produce rotation on the corresponding joint (Figure 4). The animators were asked to use each device in turn.

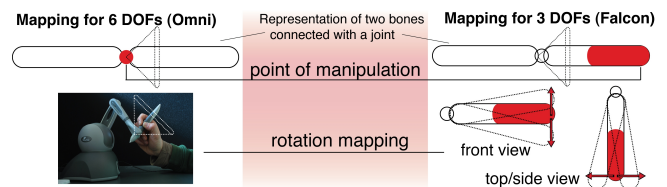


Figure 4. Mappings for bone control for each haptic device

The animators were impressed by the sense of touch and confirmed that it enhanced the interaction with the characters in the digital setting. The first problem we encountered was that the 3-D work space of the haptic device was not directly perceivable. The animators would often move the camera to get closer to the character instead of moving the visual representation of the device. To assist perception of the 3-D space, we discussed the necessity of visual cues which indicate when a character or parts of it are selected.

The 6 DoFs Omni™ stylus device was overall preferred due to the extended freedom of action it provided. The device was also regarded delicate and precise enough to perform subtle actions that deform the character, e.g for facial animation. However, the action of selecting and moving a bone, as performed with the Falcon device, instead of rotating the joints felt to them *'closer to stop-motion'*. This was an interesting realization for further development. Although FK is used in digital 3-D animation to provide

user controlled motion and our original thoughts were that it would act in the same way for stop-motion, we realized that the way stop-motion animators work is 'translated' as a combination of FK and IK. The tactile feedback augmented their engagement with the system but the fact that they could not seamlessly manipulate the different parts of the character subsided the immersiveness of the interaction.

Design II – Bimanual interaction

The interface of the non-dominant hand was used to control several cameras. Six cameras in total were placed in the virtual scene. Five were positioned in each direction, one was placed at the top and one was placed in front of the character and acted as its eyes. This last camera was designed into the system after observing during studio work that the animators often used 'first-person' viewpoint for creating parts of the animation. Each camera would become the main viewpoint by pressing a keyboard button.

Moving the camera was originally assigned to the 3-D Connexion's Space Navigator, a 3-D mouse with 6 DoFs offering control of zooming, panning, spinning, tilting and rolling. From the first evaluation sessions, it derived that the 3-D mouse did not prove to be an adequate controller for navigating in the digital space. It was regarded as a rather static device, an extended joystick. Its functionality did not support smooth navigation, limiting seamless direct engagement with the system. Further discussions regarding freedom of motion in two handed practice led to the decision of testing another gestural interface.

For this purpose we selected the Wii Remote and conducted further tests with different configurations to discover the setup that corresponded to the preferred camera movement. The Wii Remote provided more freedom of motion and more direct response to the animators' gestures. Its motion also eased the design of a seventh camera with the functionality of orbiting around the character for quickly changing the angle of view.

When we combined both interfaces, we observed that by assigning to the Wii Remote the task of translating/rotating/orbiting the camera and using the haptic interface on the dominant hand, we create an asymmetric way of working with the hands, encountered in many two-handed practices including stop-motion.

DISCUSSION

The kinematics issue showed that the design space is formed around the mapping of user's gestures to character motion. The fact that the animators were interacting with the system through a device led us to observe the difference between using a tool as opposed to directly interacting with the hands. We recognised here the possible test of other interfaces as input devices such as data gloves augmented with vibro-tactile feedback via sensor motors. However, in

order to achieve unencumbered embodied interaction with the character in the 3-D virtual space, it is important to identify first the limitations and abilities of the selected physical interface and then to carefully instrument how it will act as a mediator of the users' gesture.

The need for visual cues was a sign of the close and complimentary connection between visual and haptic perception. It is essential that future designs take into account and exploit the power of visual feedback combined with well-designed mappings to ensure continuity of artistic experience in the new setting. The above outcomes apply to how successfully the action of animating becomes embodied in the final hybrid system.

As a final remark, our method of iterative system prototyping, restricted to one study element each time and the hands-on sessions proved to be ideal for eliciting the local tacit knowledge and informing the design in a rigorous manner. Interdisciplinary collaboration with a group of creative practitioners provided a fascinating ground for engaging in HCI design by creative practice.

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