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On the Relevance of Using Virtual Humans for Motor Skills Teaching: A Case Study on Karate Gestures

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Introduction

Human motion and physical activity are more and more important in our modern society as it contributes to fight against sedentary lifestyle and obesity. It has leaded to numerous preventing campaigns and information to general public in all the modern societies. Technological revolutions have also contributed to sedentary lifestyle widespread by introducing new home interactive entertainments such as video games. The GfK study about *Les Français et l'Entertainment* (French people and entertainment) published in 2011 have shown that there are 28 millions of gamers in France which means that video games have become the first leisure activity in France for 13-19 years old people who play almost 9h per week.

However, since the beginning of 2000 new interaction devices have been introduced in video games, such as the Nintendo Wii, the Sony Move or the Microsoft Kinect. In 2011 more than 500000 units of such motion capture devices are installed in French homes. This type of devices offers a new dimension to videogames as the user can interact with his motion contrary to classical games that simply use game pads or keyboards. This revolution has completely changed the videogames market and the customers' profile. The average age of customers is 33 years old now and there are now 50% of female players. Most of the applications deal with a more natural interaction with multimedia contents but new types of applications also appeared. Hence, exergaming relies on technology that tracks body movement or reaction. The genre has been credited with upending the stereotype of gaming as a sedentary activity, and promoting an active lifestyle. However, research indicates that exergames do not actually promote a more active lifestyle ("'Exergames' Don't Cure Young Couch Potatoes". The New York Times. 2012-06-23) while they increase motivation in performing some physical activity.

Indeed exergames have been designed for entertainment and most of the applications do not aim at promoting physical activity. One of the main reasons why it does not actually promote active lifestyle is that it mainly has been created for entertainment only. As an example, becoming a champion in Nintendo Wii tennis does not really improve the users' skills when practicing tennis on a real terrain. In many applications based on technical motions, such as dancing, or practicing fitness exercises, the main goal is to reproduce the virtual coach performance. In this type of application, the user's performance is analyzed through noisy and limited sensors, which makes it difficult to learn accurate motor skills. According to the user's performance, a score is computed and high scores can open new games with new difficulties. However this process is far from participating in a real lesson with its complex psychological processes.

Many scientific domains have addressed this problem. On the one hand, many works have been carried-out to enhance the performance of immersive systems to capture the users' motions and to deliver multisensory feedbacks. On the other hand, other researchers have studied the psychological impact of using this type of technology, such as ensuring that the user is present in the virtual environment and can embody his avatar. Only few works have tried to connect these two approaches in order to improve immersive learning systems for the specific case of motor skills. Most of the scientific previous works have proposed technological revolutions to evaluate the user's performance and to provide innovative multisensory feedbacks. However these works generally focus on imitating a motion, not actually learning a motor skill.

The European SKILLS project (www.skills-ip.edu) has grouped researchers from various domains to capture, model and learn skills, and especially motor skills. It is a multidisciplinary approach to learning motor skills in various domains. The project promotes an approach which consists in identifying parameters encoding performance first, and then selecting the most relevant immersive technologies to enhance learning. In that sense, technology offers new paradigms and facilities but is not the core of the learning process. Once the parameters are identified, one of the main challenges consists in understanding the pro and cons of each technological facility. Hence, in immersive environments the user's performance is measured through sensors with their inherent inaccuracy and latency. Moreover the multisensory feedbacks are also rendered with devices that rely on simplifications, such as rendering a virtual coach, using stereoscopic glasses to render 3D scenes... Thus despite the theoretical advantages of immersive technologies, it is necessary to understand how these technical limitations practically affect learning.

In this PhD, we especially wish to evaluate the pro and cons of using virtual humans to learn motor skills in immersive environments. Virtual humans rely on more or less simplifications for both rendering and animation so that perception of the motor skills could be altered in a significant manner. It thus could affect the learning process if the user cannot perceive the details of the coach performance. The first part of this PhD thesis is thus dedicated to analyze if such a virtual coach can be used to learn complex motions such as karate forms.

Virtual humans could also be used to visualize the user's performance in real-time, thanks to avatars. Many works have been performed in virtual reality to analyze how users can embody their avatar. It has been shown that virtual mirrors help the user to embody their avatar compared to other types of visualizations such as third-person view or first-person view. In this PhD thesis we wish to analyze how avatars projected on virtual mirror can help in learning complex motor skills, such as karate forms.

This work was partially carried-out within the Biofeedback project (funded by the French government) leaded by Artefacto (www.artefacto.fr) and started in 2009. The goal of the project was to design immersive techniques to learn complex motor skills. This type of learning framework could provide coaches and teachers with methods to propose new situations and new experiences to learners. It could also provide relevant complementary lessons in motivational environments. This type of immersive environment relies on virtual humans for both visualizing examples performed by the coach and providing feedbacks about the learner's performance.

The first part of this thesis provides a state of the art about two major points: using immersive techniques in learning and introducing virtual humans in serious applications. The second part reports a study to answer the following question: is it possible to learn motor skills thanks to an animated virtual coach. The third part is dedicated to analyzing the impact of using a virtual mirror to visualize the real-time performance of the user when learning motor skills. The last part provides a general discussion and some perspectives.

Chapter 1

State of the Art

1.1 The Usage of Virtual Reality in Sports Teaching and Training

1.1.1 A Brief History of Virtual Reality: From Simulators to Virtual Environments

The main aspect of virtual reality that is extremely important to recall throughout the reading of that thesis, is its highly multidisciplinary character. Virtual reality is multidisciplinary in the technologies that are necessary for its deployment. It is also multidisciplinary in the knowledge required to understand its interaction with humans. And finally, it is multidisciplinary in its domains of application.

Even in its history, virtual reality is born of the coupling of many technologies. The main ancestors of virtual reality are probably simulators. Simulators are used for more than 50 years to train pilots (mostly airplanes, but also space shuttles, trains, and automobiles). The cockpits or cabins were mostly made of mechanical parts coupled with robotic mechanisms to simulate displacement, turbulence, crash, instruments' readings or any other reaction that would be created in a real situation by the actions of the pilot (in other word feedback mechanisms). These physical components could be coupled with videos or synthesized projections of the outside view in the cockpit windows. The aim of these simulators is to train pilots but also study their behaviors, for example, to reinforce security procedures.

Fuchs et Al., in the first volume of the "Traité de la réalité virtuelle" proposed a none exhaustive list of the domains implied in virtual reality [Fuchs2006].

In the sciences and technologies domains, virtual reality is mainly rooted in the domain of the information and communication technologies. However, it surpasses that domain and many disciplines are concomitant to the advances in virtual reality:

- Computer sciences for the development of new algorithms for the treatment of digital simulations and models and for the creation of interactive virtual environments;
- Teleoperation and robotics for the development of sensors and actuators permitting the interaction with the virtual environments;
- Mechanics, optics, and acoustics for the creation of models of the physical world.

In the domains of life and human sciences, since the human is at the center of the virtual reality systems, many domains are implied in the study of the human - virtual reality interaction. A none exhaustive list of the interested fields would include:

- Experimental psychology and behavioral sciences for the development of investigation protocols to study the perception-action loop in control environments;
- Ergonomics for the development of methods and knowledge to account for the human factor in the conception and the evaluation of virtual environments;
- Cognitive psychology for the study of the natural cognitive processes of a user performing a task immerse in a virtual environment;
- Physiology, neurosciences, etc. . . .

1.1.1.1 Virtual Reality Definition

The term "virtual reality" was first introduced by Jaron Lanier in the 1980's to describe a visual experience controlled by a computer. Since that time, it has been used to describe a large panel of applications. Many partial or wrong definitions have been employed to describe what virtual reality is. Some definitions are based on its finalities as other are mostly based on the technologies required to create it. However, two types of definition emerged from the literature, namely a technological and a conceptual definition.

1.1.1.1.1 Technological Definition

In 1962, Morton Heilig invented the "Sensorama" a cinematographic environment that had the aim to optimize the immersion in the movie by the usage of multi sensorial effects [Heilig1962]. However, it is the work of Ivan Sutherland in the 1960's that led to the first definition of virtual reality. He was the first to invent a tridimensional stereoscopic visualization device. His device was composed of stereoscopic glasses and permitted to navigate in a virtual world by turning the head. His idea was to put the user inside a tridimensional world generated by computer [Sutherland1968]. That was the first head mount display (HMD). It is only some twenty years later, in the 1980's that the first data gloves and the first virtual reality "helmets" the VIVED system developed by the NASA (Virtual Visual Environment Display) appeared and that Lanier first used the term virtual reality.

In 1992, Aukstakalnis and Blatner defined virtual reality in these terms: "virtual reality is a mean to visualize, manipulate, and interact with computer and extremely complex data" [Aukstakalnis1992]. One important notion of their definition is the interaction between man and computers. That definition evolved and in 2003 Arnaldi et Al. proposed that version (that version was also presented in subsequent version of the "Traité de la réalité virtuelle" [Fuchs2006]):

"La réalité virtuelle est un domaine scientifique et technique exploitant l'informatique et des interfaces comportementales en vue de simuler dans un monde virtuel le comportement d'entités 3D, qui sont en interaction en temps réel entre elles et avec un ou des utilisateurs en immersion pseudo-naturelle par l'intermédiaire de canaux sensori-moteurs." [Arnaldi2003]

Virtual Reality is a scientific domain and an ensemble of techniques using computers and behavioral interfaces with the objective to simulate the behavior of tridimensional entities in a virtual world. These entities are in realtime interaction with themselves and with one or more users immersed in the virtual world throughout the usage of sensor-motor channels.

That definition can be illustrated by the loop in figure 1.1 where the action of the user have repercussions on the virtual environment throughout the usage of sensors and where these action are used by the system to compute the modifications to display in the environment and to sent feedback to the user throughout the usage of actuators.

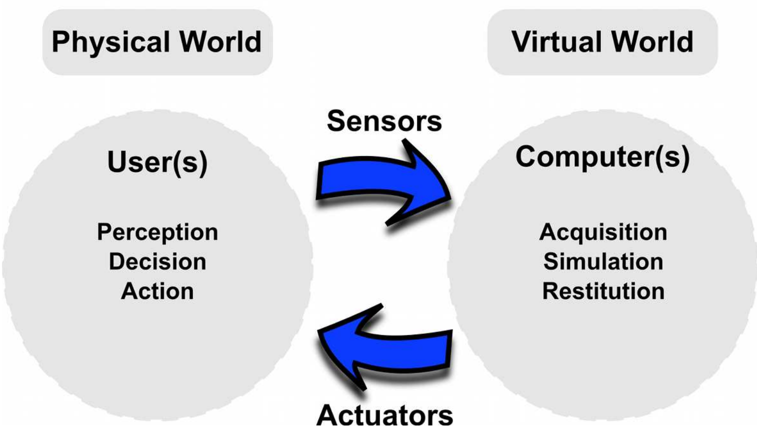


Figure 1.1 - Virtual Reality Perception-Cognition-Action Loop [Fuchs2006]

However, some factors can disturb that loop and consequently affect the user experience of the virtual world. These factors are latency and sensorimotor incoherences. Latency is the time lap between an action of the user measured throughout the sensors and the perception of its results on the virtual world. Sensorimotor incoherence are related to two factors : 1) The impossibility to simulate the physical world with high degree of fidelity for every sense. Consequently, for example, a texture might present a rough surface that for the touch will not be rough. 2) The cohabitation of two worlds. Stimulus from the physical world in which the virtual one is created continue to be received by the user and might not be coherent with what is happening in the virtual world.

1.1.1.1.2 Conceptual Definition

In the fields of psychology and philosophy, other type of definition emerged. Pragier [Pragier1995] talk about "réalisme simulé" (simulated realism) and Quéau [Quéau1993] about a feeling of immersion linked to the manipulation. Ellis, defined the concept of virtualization as "the process by which a human viewer interprets a patterned sensory impression to be an extended object in an environment other than that in which it physically exists" [Ellis1991]. Ellis further distinguish three level of virtualization:

- Virtual space: "the process by which a viewer perceives a tridimensional layout of objects in space when viewing a flat surface presenting the pictorial cues to space, that is, perspective, shading, occlusion, and texture gradients."
- Virtual image: "the perception of an object in depth in which accommodative vergence and (optionally) stereoscopic disparity cues are present."
- Virtual environment: "in this case the key added sources of information are observer-

> slaved motion parallax, depth-of-focus variation, and wide field-of-view without a prominent frame."

Ellis concluded that if these features are properly implemented, the virtual environment can "provided stimulation of major physiological reflexes such as accommodative vergence, vergence accommodation, the optokinetic reflex, and the vestibular-ocular reflex. These features when embellished by synthesized sound sources can substantially contribute to an illusion of telepresence, that is, actually being present in the synthetic environment." For Ellis, it is therefore the level of perception and comprehension that created the illusion of a virtual world, and that level is linked to the virtualization level.

Hand simply defined virtual reality as "the paradigm whereby we use a computer to interact with something "which is not real, but may be considered to be real while using it"" [Hand1996].

What emerge from all these definitions is the idea of interacting with a virtual world and to have "sensations" about that world. That degree of interaction to create these sensation needs to be assess. It is therefore necessary to develop a methodology to quantify the degree of implication and interaction of a subject in a virtual environment. Many techniques have been developed to evaluate what is commonly called "presence" and that will be defined in the next sections.

1.1.2 Immersion and Presence Factors in Virtual Environments

Immersion and presence are two terms currently used when talking about virtual reality. Even if related, these two terms should not be confused. Immersion is about the technology. Vianin defined it as the technical interface between the man and the machine not concerning psychological states of the user [Vianin1995]. Effectively, immersion concerns the interaction of the subject with the virtual environment. These interactions are possible throughout sensorial information (vision, audition, smell, kinesthetic, . . .). These interactions, necessary for the human-machine coupling are created throughout behavioral interfaces. These interfaces are divided in two categories, motor interfaces (motion capture, sensors, computer vision, . . .) and sensorial interfaces (referring to the five senses, like screen and 3D glasses, for example). Fuchs et Al. [Fuchs2006] proposed a third category concerning sensorimotor interfaces like, for example, force feedback interfaces. The quality of these interfaces will influence the sensation of immersion in the virtual environment of the subject. What differentiates immersion from presence, that will be defined next, is that in immersion the psychological affect of the subject is not involve.

On the other hand, presence can be defined as the psychological sensation of being in an environment created using immersion technologies. That sensation of presence is not equally induced for all user of a same immersive environment [Slater1993]. That definition was subject to many variations. Barfield and Weghorst [Barfield1993] talk about virtual presence and defined it as a subjective and hypothetical conscious state of being implied in a non-present environment. Steuer [Steuer1992] instead talk about "telepresence" and defined it as the experience of a presence in an environment mediated by a communication mean. In that case, presence refer to natural perception of an environment as telepresence refer the perception of a mediated environment.

The sensation of presence is not unique to virtual environments. According to Hendrix [Hendrix1994], presence can also appear when reading a book, watching a movie or a theater act. Presence is therefore not something new. However, a high degree of presence is something important to reach in virtual reality applications.

1.1.2.1 Presence Factors

Slater and Usoh [Slater1993] classified the presence factors in two categories. The first category concerns the external factor and is closely link with the immersion technology used to create the virtual environment. The second category concerns the user internal state.

1.1.2.1.1 External Factors

The external factors are related to the material used to create the virtual environment. According to Steuer [Steuer1992] there is five important points to consider:

- the quality and richness of the sensorial information transmitted by the environment;
- the coherence of the virtual environment;
- the degree of interaction between the subject and the environment;
- the fidelity of the reproduction of the subject virtual body (avatar);
- the latency of the system (as close to zero as possible) between the subject action and the reaction cause in the virtual environment.

1.1.2.1.2 Internal Factors

The internal factors are related to the internalization processes of the users. These factors consequently largely varied from one subject to another [Psotka1995]. That finding was confirmed by a study by Hodgins et Al. [Hodgins1998] analyzing the influence of geometric models on perceptions. That study showed that for some users the action felt more realistic on a textured polygonal model than on a stick figure model as other users did not perceived any difference.

The level of presence is therefore highly dependent on the individual, especially if the graphical quality of the environment is low. The presence level depends on the subject implication and on his capacity to supplement the virtual environment with his own representation of the world. However, it seems possible to study presence on a population and to draw general conclusion about the capacity of a virtual environment to induce presence.

1.1.2.2 Presence Measure Methods

Presence is a multidimensional complex phenomena and it is consequently not possible to measure it using only one kind of measures. Furthermore, subjective measures are not always reliable and pose a validity problem [Barfield1993]. The notion of presence itself is not perfectly defined. However, many methodologies to measure it have been created, and Hendrix divided these into objective and subjective measures [Hendrix1994].

1.1.2.2.1 Objective Measures

Regarding the objective measures, Barfield and Weghorts [Barfield1993] outlined some categories:

- Physiologic indicators: muscular tension, cardiovascular and ocular response, skin conduction, . . .
- Physiometric indicators: cortical responses, pupil diameter, . . .
- Performance indicators: precision, speed, . . . [Slater1996]
- Conflict resolution indicators: the capacity of the subject to adapt to the conflictual situations generated by the presence of two environments, the physical world and the virtual environment.
- Subject disorientation degree indicators: time to re-adapt to the physical world.

1.1.2.2.2 Subjective Measures

Subjective measures mostly rely on questionnaires to evaluate the degree of presence of an individual in a virtual environment [Witmer1998, Usoh2000, Slater1999]. Questionnaires alone cannot measure all factors influencing presence, it is therefore important to combine subjective and objective measures [Hendrix1994]. Furthermore, Slater et Al. have point out the difficulty of formalizing questions to assess presence of the virtual experience of a participants [Slater2007] [Slater2004].

1.1.2.3 Presence and Performance

The study of the relationship between presence and performance has major impact in virtual reality. Knowing the presence factors that can possibly improved the performance of a task execution in teleoperation has a direct impact on the conception of these environments. To establish the link between performance and presence, it is necessary to identify a list of behavioral interfaces that improved the performance of a specific task [Draper1996]. The problem is not to know if presence influences the performance, but to determine the combination of media required to induce a reaction similar to that that would be induced in real life situation [Slater1996]. If that combination is known it is be possible to train individual in virtual reality to prepare them to be performant in real life situations. For example, to ameliorate the efficiency of a surgeon in the operation room [Freysinger2002]. However, that is not an absolute rule. In some cases, a high level of presence might induce a dependance to the virtual environment to perform the task. Situations were transfer from one environment to another are required should consequently be carefully study. Sections 1.1.6.3 presents more details about that.

However, establishing the level of performance in virtual environments, gives information about the level of presence. Consequently, if an individual correctly performed a task in virtual reality, that implies that his presence and implication level were sufficient [Slater1999]. In fact, the definition of presence (being there) implies "being able to act there" [Sanchez-Vives2005].

Furthermore, performance and presence can also be related in another manner. The efficiency of a simulation can be evaluated by its degree of fidelity [Stroffregen2002]. That degree of fidelity being defined by the difference between the subject behavior in the virtual environment and the real world situation. System fidelity can therefore be divided in two categories: the fidelity of the experience, and the fidelity of the action performed in the virtual environment. The first category refers to the notion of presence. The second category is a measure of the functional fidelity. Functional fidelity is considered high if action performed in the virtual environment is close to that that would be performed in the real world [Morice2008].

The notion of performance is extremely important in the domain of sports. Bideau et Al. [Bideau2003, Bideau2004a] and later Vignais et Al. [Vignais2009a, Vignais2010] have studied the reaction of handball goalkeeper to virtual throwers in order to establish if the level of performance was the same in virtual reality than in a real situation. They were able to establish that the level of performance, and consequently of presence, was sufficient to use virtual reality as a study tool for the visual information retrieval activity of an handball goalkeeper.

1.1.2.4 Body Ownership

Body ownership can be seen as special cases of presence, where the presence to evaluate is that of the subject in a virtual human present in the virtual environment. That virtual human is a projection of the subject in the virtual environment and can be seen either in first person view, normally throughout the usage of and HMD where one can look at himself (a virtual self), or in third person view, often by being represented in the virtual environment throughout the usage of a mirror or shadow metaphor.

Body ownership is a known phenomena outside the virtual reality context and is often illustrated by the rubber hand illusion [Tsakiris2005]. An illusion where a subject places his arms on a table, one of his arm is hidden and replaced by a rubber arm. The subject sees the rubber hand being touch by a feather while his real arm is also touched by a feather. After a certain time, if the rubber arm is threaten, the subject demonstrates the same physiological and physical reactions as if his real arm was threaten.

The same experiment has been done in virtual reality with a virtual arm [Sanchez-Vives2010, Yuan2010]. Moreover, it has also been demonstrated on the whole body in an experiment where male subjects see themselves in first person view in the body of a female character [Slater2010] and in third person view throughout the usage of a virtual mirror [González-Franco2010]. The protocols used in the first study is similar to that of the rubber hand illusion. In the case of the mirror experiment, synchronous and asynchronous response of the mirrored avatar to the subject action are used as a stimulus for the body ownership illusion to operate. In both case, the virtual body is then threatened to induce a reaction.

In these experiment, ownership is assessed using the same method as for other type of presence, namely throughout physiological measures, questionnaires, and interviews. The illusion of body or limbs ownership in virtual reality is used, for example, in the treatment of chronic pain [Hoffman2000] and for phantom limbs treatment [Murray2007, Mercier2009].

1.1.3 Simulation of Virtual Humans

The most frequently used method of teaching in sports is teaching by demonstration [Desmurget2006]. That method implies a human model on which the learner take the necessary information to build his own representation of an action or gesture. The information the learner retrieves are mostly visual information obtained by the observation of the model combined with audio information provided by the discourse and the sounds (breathing, clapping, hitting, sounds due to displacement, etc. . . .) accompanying the demonstration. In the case of a virtual learning environment the model is a virtual human. The level of fidelity of the rendering of that information is therefore crucial. However, the actual technologies do not permit to model all the variables implied in human actions. Simplifications and choices must consequently be made with the risk of degrading and even altering the rendering of the information required by the learner.

1.1.3.1 Human Body Representation

The human body in motion is a complex system composed of multiple elements. When performing a motion, a human is not passively "replaying" a sequence of movements, but he his constantly perceiving information throughout his senses, interpreting that information in his brain, and sending back information throughout his nerves to control a complex apparatus of muscles that act on bones having effects on joints, tendons, soft tissues, skin, hair, etc... and on the clothes and accessories worn by that human being. Although sciences and technologies have advanced in many domains of virtual humans animation a perfect reproduction of all these is impossible.

Although recent studies approached the problem of the modeling of the musculoskeletal system [Vigouroux2005, Bonnefoy2008], that remains a complex problem. Instead a more classic approach developed by Chadwick et al. [Chadwick1989] consisted in dividing that structure in three distinct layers: bones, muscles, and skin. The skeleton is defined in a hierarchical structure of bones related in a parent-sibling relationship. The muscles are attached to the bones and actuated these and the skin moves accordingly. Layers of clothes can also be animated in a similar manner. However, that thesis used a simpler model considering only a hierarchical bones' structure. The skin and clothes of the avatar are directly attached to these bones and follow the bones movement. No further deformations are applied to that skin layer.

In that representation, bones are organized in a tree where each joint is a node and each bone is an arc (see figure 1.2). The pelvis of the avatar is usually the root of that tree. That hierarchical structure is described by the H-Anim standard (http://www.h-anim.org). That skeleton is a simplification of the human skeleton. It only contains a limited amount of the 206 bones composing the body. For example, the human spine is composed of 24 vertebrae, but is usually modeled using a small number of segments. Each limbs are represented by only one bone and the rotation point of these bones is assumed to be at the center of the joints. The joints usually possess three degree of freedom. The skeleton is animated by applying rotation to the joints.

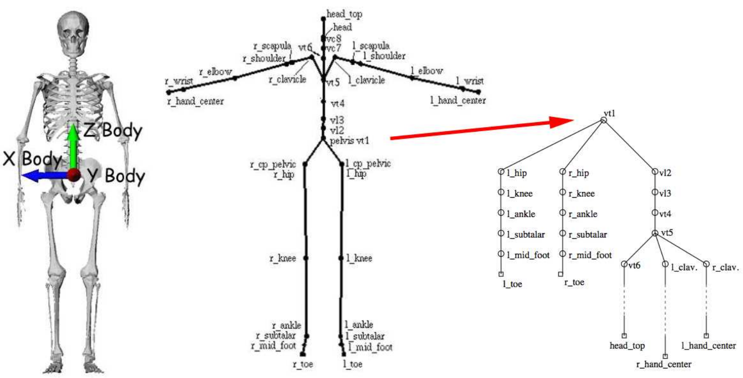
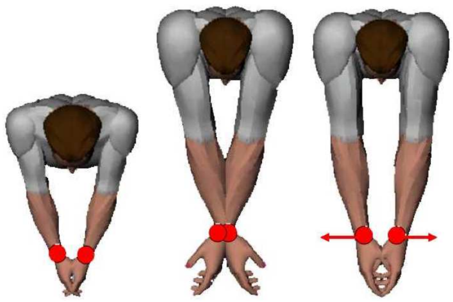


Figure 1.2 - Hierarchical representation of the skeleton. Left: representation of the bones. Center: simplified skeleton. Right: hierarchy of the simplified skeleton with the root at the pelvis joint.

1.1.3.2 Morphological Adaptation

The disadvantage of using a representation based on joint angle transformations is that it is morphology dependent. Two skeletons with the same bone hierarchy but with different bone lengths animated with the same set of rotations will not necessarily present the same naturalness of motion. A classical example is hand clapping. When the same joint angles are applied to short arms or long arms, as illustrated in figure 1.3(a) and 1.3(b), in one case the two hands clap together and in the other case, they go throughout each other. That can be resolved by applying motion adaptation techniques, as illustrated in the resolved case of figure 1.3(c).



(a) (b) (c)

Figure 1.3 - Morphological Adaptation for a Clapping Gesture

To resolve the problem of applying animations on different morphologies and even different hierarchies of skeleton, different techniques exist. For example, Ménardais [Ménardais2003] proposed to store the animation information in a morphology independent structure. That technique was further developed by Kulpa et al. in a software solution named MKM [Kulpa2005a, Kulpa2005b, Multon2009]. Other techniques implied to define set of constraints. These constraints can be of different types:

- Physical: for example, the arm cannot traverse the body or cannot pass throughout an object or another avatar, someone walking have to keep contact with the floor, someone has to keep its gravity center in certain positions to maintain equilibrium, etc...;
- Biomechanical: certain joints of the body have restricted flexibility, they cannot go further certain angles, certain type of motion are impossible for a human, etc...;
- Specific: other constraints can be add to preserve the naturalness of the motion, for example, it might be more natural to type on a computer keyboard with the arms reposing on the table rather than with the arms floating in the air even if that is feasible.

These constraints are normally resolved using inverse kinematics. Inverse kinematics has been largely used in robotics [Klein1983, Klein1995], for example, for the automatic displacement of industrial robots where efficiency is more important than naturalness, but also more recently to articulate humanoids or animal like robots. These techniques have been largely studied, optimized and combined with other animation techniques in the field of computer animation. An excellent review of these techniques can be found in [Kulpa2005a].

In that thesis, the morphology adaptation problem was resolved using Motion Builder. Motion Builder uses a combination of techniques such as the definition of constraints. Precisely what algorithms are used is unknown, however, what is important to know is that in the process of transferring the original motion to the avatar to animate it, operations are performed to match the motion coming from one morphology to another. These operations are another source of potential information lost and introduction of noise. The next section explains how the original motion is obtained.

1.1.3.3 Motion Representation

As mentioned previously, human motion is a complex phenomenon implying many mechanisms and responding to many laws. Exactly like the body need a simplified representation, motion has to be modeled in order to be stored and used to animate virtual human. Different representations of motion exist. The next sections presented some of these representations.

1.1.3.3.1 Frame By Frame Representation

At the end of the 19th century, studies by Marey [Marey1894] using chronophotography (pictures of postures of a motion in time) permitted to decompose motion in sequence. That decomposition further permitted to formally described human motion. Figure 1.4 illustrates a sequence of photographies where some limbs of the body are accentuated by a white strip apposed on a black suit. These strips are photographed over time during the execution of the motion. That work certainly inspired Johansson [Johansson1973] in is point light display idea that is presented later in that chapter (refer to subsection 1.1.4.1). Since the invention of cinema by some precursors like the Lumière [Rittaud-Hutinet1995], it is well known that by capturing and replaying images at a sufficient frequency permitted to recreate the illusion of motion for the human eye. That is also true for the animation of avatars. However, in that case, the replay frequency can vary in function of the complexity of the environment to compute in realtime and the computation power available. The description of motion in a sequence of postures equally spaced in time and applied on an avatar is consequently not always sufficient.

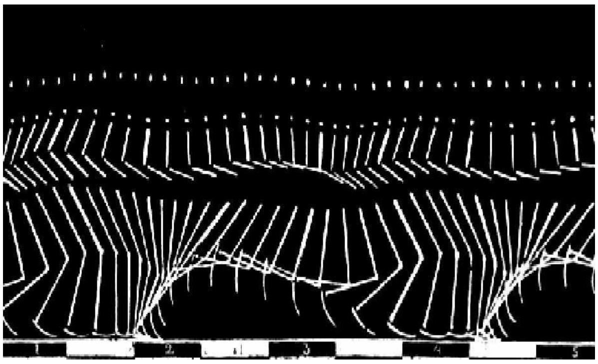


Figure 1.4 - An example of Marey's Chronophotography of Human Motion

1.1.3.3.2 Key-Framed Based Representation

One solution to the problem of having to describe postures at fix time-step is to define only key postures and to use interpolation to obtain intermediate postures. The selection of key postures is often done manually and therefore relies on the competencies of the animator and on trials and errors. However, Assa et Al. [Assa2005] proposed a method to select these key postures based on position, rotation, angular and cartesian velocity of each joints. The results obtained with that technique highly depend on the interpolation method used. Furthermore, reduced amount of key postures often create an unnatural effect of smoothness due to the lack of high frequencies variation to which humans are highly sensitive.

1.1.3.3.3 Signal Processing

At the contrary of the key-framed method, it is possible to use signal processing techniques to preserve the dynamic components of the joint angular trajectories. In these techniques, motion is decomposed in the form of Fourier series [Unuma1991] or Wavelets [Bruderlin1995]. Even if a selection of a restricted number of parameters has to be done, these methods have the advantage to encode the high frequency information like emotions or style. Unuma et Al. [Unuma1991, Unuma1993, Unuma1995] used Fourier series to describe angular trajectories of locomotion sequences and modified these in the frequency domain, for example to transform "normal" walking in "tired" walking. Other authors proposed to blend locomotion sequences in a control space using the Fourier representation [Pettré2006]. However, it is not simple to modify motion or to isolate its characteristics in the frequency space. Furthermore, these methods are mostly efficient for periodic motion.

In that thesis, the main method used for the animations is the frame by frame method. However, the hands opening and closing are animated using the key-frame method. The following sections present how the motion required for the animations is generated.

1.1.3.4 Motion Production

The most intuitive way to obtain natural human motion is to capture it directly from humans in motion. The first "motion capture" systems based on chronophotography such as the systems developed by Marey [Marey1894] and Muybridge [Muybridge2010] were used to study motion and isolated some of the factors responsible for motor performance. Nowadays, motion capture systems are able to capture tridimensional motion at high frequency. However, these systems capture the external result of the motion from markers or sensors placed on the human skin. Some systems exist to capture the motion of the bones and of other layers of the human structure but their usage is limited due to their invasive and dangerous character (a review of some of these can be found in [Fohanno2011]).

1.1.3.4.1 Motion Capture Systems

Menache et Al. [Menache1999] proposed to classify motion capture system in three categories:

- outside-in systems: These systems use external receptors (non-attached to human skin) to collect the data. The data are collected from sources placed on the human body in motion. Two categories of systems respond to that characteristic, namely optoelectronic systems based on cameras (receptors) and on passive markers (sources). The Vicon system of the Oxford Metrics society and the Optitrack system of the Natural Point society used in that thesis are in that category. Illustration of the markers and cameras can be found in figure 2.7, 4.1 and 4.2. Computer vision systems not relying on markers are also in that category. Recent systems based on the Microsoft Kinect would, for example, be outside-in systems.

- inside-out systems: These systems use receptors placed directly on the human body to collect information transmitted by external sources. Electromagnetic systems like Ascension Technology Corporation's Flock of the Birds and Motion Star are in that category. In these systems, each receptor gives its position and its orientation with regards to the emitting source placed in the scene.

- inside-in systems: These systems have both the emitters and the receptors placed on the human body. They are mechanical capture systems. They are normally composed of combinations of accelerometers and gyroscopes, for example. They capture variation in accelerations and rotations.

All these systems permit to record human motion with a certain degree of precision. However, as mention previously, they measure motion from the external body as the animation are performed on the skeleton. Furthermore, they capture motion for the human body in all its complexity while the animation process is performed on a simplification of it. Every of these systems are subject to different type of data lost and to the introduction of artifacts. For example, optoelectronic systems are subject to markers occlusion and to movement of the markers due to deformation of the soft tissues and the skin during the motion (a detail review of these problems can be found in [Fohanno2011]). These problems need to be addressed in the data treatment.

1.1.3.4.2 Motion Capture Data Treatment

Since with these systems motion is captured from the external part of the body, it is necessary to transform the coordinates of the external markers to joint centers as used in the animation skeletons. Many authors [Silaghi1998, Boulic2000] proposed to compute the joint center in the local coordinate system of the segment it describes. That supposed that there exist a fix distance between the marker and the joint. O'Brien et Al. [O'Brien2000] proposed to use a function that relate the vectors of the local coordinates of the marker to that of the limb.

Many methods were proposed for the correction of the occlusion problem in the optoelectronic systems. Some of these estimate the position of the missing markers using the position of the visible one by creating a postural skeleton [Boulic1998, Herda2000, Herda2001]. Other methods use statistical prediction to identify obvious marker's position or orientation errors [Bodenheimer1997].

Finally, once the markers of a particular capture have been transform into a joint center, that model need to be adapted to the animation skeleton that is most of the time of a different morphology than that of the capture. That is done using inverse kinematics and the method presented in section 1.1.3.2

1.1.3.5 Section Conclusions

In conclusion, even if motion capture remains the most efficient way to insure a certain degree of naturalness to the motion, the original motion is subject to a considerable amount of modifications, degradations, and simplifications over the course of the process from its execution by a human to its application on a virtual human.

The first alteration concerns the precision of the capture system. Ehara et Al. [Ehara1995, Ehara1997] evaluated the precision of optoelectronic systems like the Vicon to measure the position of the markers to be of the range of the millimeter. However, as Fohanno [Fohanno2011] noted, markers are subject to displacement due to soft tissue and skin motion of the range of 40 millimeters. Furthermore, these degrees of precision can largely vary in function of the experimental setup.

The second alteration concerns the transformation of marker positions to the skeleton to animate. The topology of the skeleton differs from that of the human. For example, as mentioned previously, the spine is represented with considerably less degrees of freedom, from 24 vertebrae it is reduced to 3 to 6 joints in most cases. It was also mentioned that in the case of many limbs, the human body is composed of more than one bone and that the rotation point is not at the center, although for the virtual skeleton, only one bone is used and the rotation point is placed at the center. To transfer to the virtual skeleton therefore introduces many approximations and can altered the original motion. However, motion capture systems preserve velocity and acceleration information.

Finally, it is impossible to capture all the variables of the motion. For example, it is difficult to capture precise motion like that of the hands, foot and toes, or facial expression at the same time as global motion. In some case, the markers might constrain the motion of the performer. For example, in our case, it was impossible to capture the hand opening and closing without disturbing the performer. These therefore had to be animated manually, introducing other sources of noise in the original motion.

1.1.4 Interacting with Virtual Humans

The previous sections presented how virtual humans are generated and animated. It is also necessary to understand how they are perceived by the user. Furthermore, that perception is certainly linked to the presence sensation defined previously.

1.1.4.1 Perception of Virtual Humans

In the actual state of things, it is impossible to produce virtual environments that would reproduce all aspects of the physical world with high fidelity. Moreover, as Mori [Mori1970] showed with the uncanny valley theory in the field of robotics and as it was later also demonstrated in other fields, it might not be desirable to go further a certain degree of fidelity if "perfect fidelity" is not possible. Consequently, a choice must be made on the degree of fidelity of each aspects of a virtual environment. Elements more relevant to the aim of the virtual environment should be favored.

Works by Johansson [Johansson1973] showed that minimal information is required by the human visual system to identify biological motion. Johansson developed a particular method named point light display (PLD) that consists in placing luminous markers on specific articulations and body parts and register the motion of these markers in a dark scene. The video sequence showing only the luminous point is then used to study the perception of the motion. The same idea can also be used with computer generated motions. That technique has been used in many studies to determine the minimal level of information required to recognize an action. Studies have shown that from PLD applied to walking, it is possible to recognize the sex of an unknown individual [Kozlowski1977, Barclay1978, Runeson1994, Hill2001, Troje2002, Pollick2002] and even to identify a known person from its gait [Cutting1977, Beardsworth1981, Stevenage1999, Hill2000, Jokisch2006]. Other studies have shown that it is also possible to recognize emotions from PLD of different types of actions [Walk1984, Dittrich1996, Pollick2001]. Furthermore, some studies suggested that it is easier to recognize a walker from PLD than from a low quality video [Ahlström1997]. The hypothesis being that the PLD contains the important information that is otherwise blur in the low quality video.

Moreover, PLD have been used also in sports, for example, to analyze the anticipatory capacity of athletes on precise kinematic indicators. It was used in squash [Abernathy1987], and tennis [Ward2002] to determine the difference between anticipatory skills among novices and experts. That methodology has been used also to analyze game schema in basketball [Didierjean2005] and soccer [Williams1995, Williams2000, Ward2003]. Williams et al. studies suggested that experts performed better and more rapidly than novices on a game schema recognition task in PLD [Williams2006]. More recently, Vignais et al. [Vignais2009a, Vignais2010] developed a protocol to evaluate the influence of the graphical detail level in the induction of a kinematic response of an handball goalkeeper confronted to the throw of a virtual player. These studies showed that the level of graphical detail can be degraded up to PLD without influencing the behaviors of the athletes as long as the ball dimension was not degraded.

However, all these studies concentrated on the recognition of motion already known by the subjects. Different experiments with different levels of graphical quality have effectively shown that the performance level and speed augmented with the knowledge of the observed motion and that in these cases, the subjects might even be indifferent to the graphical level [Hodgins1998]. Nevertheless, the level of details required by a subject to built a representation of a new motion based on that type of models is unknown.

1.1.5 Sports in Virtual Reality: A Study Tool

Virtual reality is used as a study tool in sports to palliate to some of the limitations of field study and videos which for many years were extensively used [Bideau2003]. Effectively, virtual reality permits:

1. Reproducibility of the sequences [Tarr2002];
2. A complete control of the environment and of the virtual characters [Bideau2004b];
3. A stereoscopic point of view that has been shown to have a major influence on the interception task [Masyn2004]
4. An egocentric point of view that is impossible with video [Masyn2004, Sherifdan1992]

Furthermore Bideau et Al. [Bideau2003, Bideau2004a] and later Vignais et Al. [Vignais2009a, Vignais2010] have established that the level of presence in these environment was sufficient for the performance fidelity to be high enough to study a performance in virtual reality as a performance in the real world situation. Consequently, many authors seems to consider virtual reality as a relevant method to study perception in sports [Capin1997, Bideau2003, Craig2006, Bideau2010, Watson2010].

Consequently, virtual reality was used to study the perception and action loop of athletes in various disciplines. Examples are found in handball [Bideau2004b, Vignais2009b, Bideau2010] where it was used to study the goalkeeper visual information retrieval. It was also used in football [Craig2006] to study the perception of different ball effects on the goalkeeper. Furthermore, it was used in baseball [Ranganathan2007] and in rugby [Brault2009, Watson2010] to analyzed the decisional skills of the players.

However, in that context, virtual reality as been used to induce a behavior already known by the participant and in no way to teach new skills. The distinction is important since, as it was mentioned previously, the ability to perceive a situation in virtual reality is influenced by the previous knowledge of that situation [Hodgins1998].

1.1.6 Teaching and Training Motor Skills in Virtual Environments

There exists different level of usage of physical activities and motor skills in virtual environments. That goes from the pure entertainment game to the serious game trying to teach a skill that will be later reinvest in a real life situation. Furthermore, these different interfaces addressed a different public. A personal trainer game aim at teaching a level sufficient to train alone at home. A training accelerator instead, is aimed at ameliorating a precise aspect of the performance and might be designed for beginner but also for high level athletes. A serious game, might aim at teaching the necessary skills to pursue a training in a sport club, or again it might be aim for athletes. The following sections defines the different types of motor skills teaching and training environments and gives some examples of existing applications.

1.1.6.1 Video Games

The idea of using motion or physical activities to control video games is not new. Already, back in the 1980's, ideas derived from professional training simulators and the newly born and, at the time for the media, "highly speculative and futurist" field of virtual reality research, made their way to arcade consoles and professional fitness equipments with high expectations to also hit the market of personal home entertainment systems and fitness equipments. The clear goal was to combat the bad reputation of video games as a sedentary activity, at a time where obesity and especially juvenile obesity was becoming a major sanity problem in many developed countries.

Autodesk pioneer in that domain with the HighCycle, an exercise bike that permitted to ride in a virtual landscape, and the Virtual Racquetball, a system that track the position and orientation of a racquet to hit a virtual ball. The game was played by two players visualizing throughout an early head mount display. Atari, also equipped an exercise bike and released several games for it in a project call Puffer (1982). Nintendo, attempted to commercialize a floor pad called the Power Pad in the late 1980's. However, most of these first attempts were commercial failures due to production costs too high for the home entertainment market. In the 1990's, the industry consequently mostly concentrate on the development of high-end gym equipment. That period saw the development of many exercise bikes, foot pedal, and rower equipped with game interfaces. That market did not either succeed, since health clubs were not so incline to adopt new technologies. One exception, is the Computrainer, a training and motivating assistant for stationary bikes that was release in 1986 to work with the Nintendo NES and that still exist today using Microsoft Windows compatible softwares.

The industry had to wait for Konami's Dance Dance Revolution to be released in 1988 for the interest for active games to hit the great public. The years 2000 have seen the Sony's

EyeToy:kinetic in 2005 to control games using computer vision. The Nintendo Wii was release in 2006 and permitted to control game using acceleration detection with the Wii Remote and foot pressure using the Wii Balance Board. The Microsoft Kinect later appeared at the end of the year 2010 and permitted to control game using computer vision with a depth.

Some of the games available on the Nintendo Wii and the Microsoft Kinect are designed for personal training. In most cases it is unknown if scientific evaluations of their relevance for physical activities or sports have been performed nor if scientific studies of their interaction and feedback metaphors have been performed. A none exhaustive list of the personal training games on these platforms includes: Dance Central, Zumba Fitness Rush, UFC Personal Trainer, Nike + Kinect Training, Dance Workout, my Fitness Coach, your Shape, Wii Yoga, Wii Fit and various other dance and fitness titles.

1.1.6.2 Exertion Interfaces

Mueller et Al. first described exertion interfaces in the human-computer interaction domain in 2002, defining it "as an interface that deliberately requires intense physical effort" [Mueller2002, Mueller2003]. Sinclair introduced the term "exergame" as a contraction of exertion and game in 2007 [Sinclair2007]. The same year, a dedicated, and since annual, CHI workshop was created for exertion interfaces research [Mueller2007].

With that broaden definition, exertion interfaces cover a wild range of technologies from screen-based applications controlled by body motion to embodied systems including robots, pervasive and mobile applications, simulators coupled with virtual components, and HMD or projected virtual reality. They also cover numerous types of application domains from pure entertainment to serious games for learning, training or rehabilitating, with the only common aim of making the users perform physical exercises in a motivating environment.

During the 2008 CHI workshop, the highly multidisciplinary character of exergame was noted, and participants demanded that for the field to progress, multidisciplinary teams be created [Mueller2008]. It was noted that exergaming could positively contribute to global fitness and health but that HCI researchers, that at the time were the main actors in field, did not possessed the necessary background to assess and analyze that potential.

Mueller et Al. see the future of exergame in combination with personal trainer robots [Mueller2012]. However, actually, exergames have been developed for interactive and network racquet [Molet1999, Ishii1999, Brunnett2006, Mueller2006b], hockey [Mueller2006a] , boxing [Höysniemi2004, Sidharta2005], martial arts [Hämäläinen2005], dance [Usui2006, Yang2006], in similar ways as the games offered by the game industry and mentioned in the previous section.

1.1.6.3 Enactive Training Accelerators

Another type of usage of virtual that as been explored in the sport domain is that of the training accelerators. Training accelerators were defined by Bardy et al. [Bardy2010] in the context of the european SKILLS project. Gopher defined these as follow: "Training platforms are engineering systems developed to enable the acquisition of targeted skills and direct their development under guided instruction and training. The term accelerator is used to refer to variables that are introduced and implemented to facilitate, assist and improve learning [Gopher2012]."

Furthermore, Gopher [Gopher2012] proposes three key constructs for evaluating training accelerators: relevance, facilitation, and transferability. Relevance is the system capacity to provide a relevant experience for the development of a skill on a particular task. Facilitation refers to the inclusion of elements in the training environment that facilitate and guide the acquisition of a skill. Finally, transferability refers to the capacity to reinvest a skill acquired in a training system outside that training system.

Gopher [Gopher2012] further outline the problem of "dependance" to the training system, and therefore outlines the importance of testing the acquired skill outside the training environment. Effectively, in these type of environments high degree of presence may come with the risk for the user to adapt its performance to the training environment. A measure of presence, or action fidelity like that developed by Bideau et Al. [Bideau2003, Bideau2004a] and later Vignais et Al. [Vignais2009a, Vignais2010] is consequently extremely important. In the similar manner, Gopher [Gopher2012] mentions that the feedback should be chosen appropriately not to disturb the task performance. In conclusion, in that type of environment, a balance between presence and the sense of the physical world in which the task will later be applied should be found. A high level of presence may even induce a negative transfer if it creates dependance to the training environment.

Example of training accelerators applied to sportive situations are the two rowing simulators developed by two teams [Zitzewitz2008, Ruffaldi2011b, Ruffaldi2011a, Wellner2012] and the virtual juggler [Zelic2012]. Training accelerators are designed to improve the performance of their users. They differ from learning environments in that they do not teach but permit to train an aspect of a skill. For example, the rowing simulators are used to help athletes develop their synchronization with a partner skill.

1.1.6.4 Teaching by demonstration Using Virtual Humans

Some studies have tried to assess the question of learning motor skills in virtual reality. Two of these studies were on the mimicking of taï chi forms performed by a virtual instructor. First, a study by Chua et al. in 2003 [Chua2003] immersed subjects in a virtual environment throughout the usage of an HMD. Five different types of feedback were tested, but the study was unable to find any difference in the performance of the taï chi forms among the different feedback groups. Second, a study by Patel et al. [Patel2006] compared video and virtual reality teaching by demonstration. Patel et al. concluded that virtual reality was superior to video for a taï chi learning by imitation task. However, their results are questionable on many aspects : 1) they did not perform pre-tests and mentioned that the virtual group was already superior at the first step of their training process 2) their evaluators were not taï chi experts but experiment investigators trained to grade taï chi forms 3) they computed their statistics on the average established by their two evaluators even if they mention that the evaluator inter-reliability was low.

Hachimura et Al. [Hachimura2004, Hachimura2005] proposed to use mix reality to teach japanese dance. The user wear a HMD where he sees the virtual instructor performing the dance. The user then tries to mimic the instructor performance. Hachimura et Al. tested different point of view to observe the instructor and different rendering of the virtual instructor. Furthermore, similarly to Chua et Al. [Chua2003], they tested different feedback modes. However, they limited their tests to usability tests and never performed any performance tests.

Nakamura et Al. [Nakamura2005b, Nakamura2005a] also worked on japanese dance, that time with an instructor display on a wide computer flat screen attached to a robot. That way, the user can dance its way with the robot. Vibro-motor where used to tell the learner when to start and stop dance segments. Comparison between a teaching method on video and that with the robot were performed. The robot showed to be more efficient than the video to teach the dance displacement. The authors explained that distance of the displacement are more difficult to evaluate on video than with a moving robot. The vibro-motor seem to have improved the learner rhythm. However, the performance tests were performed during the learning in the virtual environment and no initial level was established. The learning period was really short, every participant used every modes of the virtual environment only twice. Questionnaires tests showed a negative perception of the vibro-motor system by the users.

Anyhow, we can argue that in all of these cases, the task is not really a learning task but simply a mimicking task. To our knowledge, no study has tried to answer the question of learning complex motor skills from demonstration by a virtual human in a complete lesson setup (explanation, demonstration, drills, full gesture repetitions) over more than one hour of training. Moreover, studies who attempted a reduced task lack an evaluation protocol comprising an evaluating the performance before the training and after a retention period at the end of the training, according to Joy and Garcia [II2000] these are essential to talk about an improvement. Furthermore, no study have explored the learning process from the participants point of view.

Another interesting project can be mentioned here even if it is not completely a virtual teaching environment. Kwon and Gross [Kwon2005] developed a system combining video recording, accelerometer capture, gestures recognition, and some augmented feedback on the video. Their idea is to permit to a trainer to record gestures a learner should train on. Their usability tests were performed on martial art upper body gestures (punch and block). The gestures were recorded in video and with accelerometers by the trainer. The learner could then replay these gestures and tried to mimic these. The learner was also wearing accelerometers. In that case, the accelerometer were on the writs. The system recognize the gesture performed by the learner and display information on the video about the acceleration of the wrist in order for the learner to have feedback. Their system is at an early stage and they performed usability tests only, but the idea of having a system for a trainer to prepare material for a learner is very interesting.

Motivations and Objectives

The usage of simulators and more recently virtual reality in training and teaching has often been dictated by the necessity of creating safe training environments. For example, "crashable" flight and driving simulators [Nählinder2009, Pasetto2008], "unkillable" patients for medical and emergency intervention trainers [Haluck2000, Kilmon2010, Schoor2006, Simpson2002, Vincent2008] and "unharming" fires and explosions for fireman and hazard materials manipulation trainers [Morin2004, Schaafstal2002]. In these cases, using simulators or virtual environments is an obligation and the question of their relevance over a physical situation does not exist since training in the real world is not an option. However, their exist known phenomena of adaptation when passing from the simulators to the physical world [Nählinder2002]. These adaptations should be taken into account in a complete training cycle where simulations are teaching and training tools. Although very few studies are dedicated to that topic, recent advances in neurosciences, behavioral and cognitive sciences made possible a better comprehension of these phenomena on the psychological, physiological and behavioral point of view.

The recent advances in computer graphics, gaming and immersion technologies has created a new category of games. These games are more realistic and plausible and moreover permit physical interactions of the users with the game. A branch of these games is called exergames; games that require the user to deliberately make intense physical effort to interact with the game [Mueller2002, Mueller2003]. As a response to the world wide obesity crisis, the game industry as invested the exergame field with mitigate results. Exergames could help a sedentary person attain the amount of recommended daily exercise only on certain circumstances [O'Loughlin2012]. Since 2007, the CHI conference has created an annual workshop dedicated to the multidisciplinary study of making exergame interfaces more efficient for physical exercising [Mueller2007]. Authors like Sinclair et Al. have made a list of recommendations for the design of exergames [Sinclair2007]. However, these games are mostly "sports like" games. They aim at making people move and not at teaching physical abilities or motor skills. Sometime, the type of gestures they proposed are even injury prone.

As a consequence of the parallel development of the simulators and virtual reality trainers, and of the games technologies, a new branch of teaching and training environments was created with the appellation of serious games. Serious games are used in many fields of education from the visualization and manipulation of complex molecules to historic reconstructions [Youngblut1998].

Some studies even suggest that managerial skills could be acquired by playing. The army and the private industry use virtual simulations to train decisional skills in complex simulated situations [Kenny2007, Loftin2004]. These games are mostly situation games, they aim at the acquisition of theoretical knowledge or at the development of intellectual abilities of the users, very few are dedicated to motor skills.

Virtual reality is also used has a therapeutical tool in physical and neuronal rehabilitation and in psychology [Hodges2001, Holden2005, Schultheis2001]. It permits the observation and the study of pathological behaviors in complex but controlled and secure laboratory environments [Klinger2006]. Moreover, in some particular cases, it can be used to treat these pathologies. That is the case, for example, in the treatment of anxiety and phobia where the patient can be progressively immersed in an anxiogenic situation. Virtual reality is also used in physical rehabilitation, for example, of post-stroke patients [Cameirão2010, Lozano2005], paralysis [Chen2007], ambulation problems [Lamontagne2007, Yang2008]. Some studies even used it for the treatment of chronic pain. The case of physical rehabilitation is linked to motor skills, but to our knowledge, virtual reality or serious games are used in that context as tools to assist the patients in the realization of the repetitive and otherwise annoying and exhausting exercises prescribed by the therapist. They are not aim at teaching or training but at motivating the patient throughout the therapy by contextualizing or animating the exercises.

In sport sciences, virtual reality has been used mainly as a study tool. In 2003, Bideau et al. [Bideau2003, Bideau2004a] established that virtual reality can be used to create controllable, standardized, and reproducible environments to study the behavior of trained athletes. Furthermore, Vignais showed [Vignais2009a, Vignais2010] that the level of graphical detail used in these environments can even be degraded up to a certain degree without influencing the behaviors of the athletes induced in reaction to the reproduction of a real game or training situation. Consequently, virtual reality was used to study the perception and action loop of athletes in various disciplines. Examples are found in handball [Bideau2004b, Vignais2009b, Bideau2010], football [Craig2006], baseball [Ranganathan2007] and rugby [Brault2009, Watson2010]. However, in that context, virtual reality as been used to induce a behavior already known by the participant and in no way to teach new skills.

Another type of usage of virtual that as been explored in the sport domain is that of the training accelerators. Training accelerators were defined by Bardy et al. [Bardy2010] in the context of the european SKILLS project. They are tools aim at training an athlete on a specific ability or skill. Example of training accelerators are the two rowing simulators developed by two teams [Zitzewitz2008, Ruffaldi2011b, Ruffaldi2011a, Wellner2012] and the virtual juggler [Zelic2012]. Training accelerators are designed to improve the performance of their users. They differ from learning environments in that they do not teach but permit to train an aspect of a skill. For example, the rowing simulators are used to help athletes develop their synchronization with a partner skill.

The particular type of teaching that thesis is interested in is teaching by demonstration. According to Desmurget [Desmurget2006], even if teaching by demonstration is certainly the most common type of teaching used in sports, very few studies refer to it. Teaching by demonstration, or from the learner point of view learning by imitation, is defined by the action of mimicking with the goal of reproducing a gesture performed by someone else. That person, the demonstrator, can be physically present or mediated throughout the usage of video or computerized reproduction. In psychology, learning by imitation is based on the theory developed by Bandura [Bandura1986] saying that a visual model permits the learner to develop a symbolic representation of the task. Once acquired, that representation provided the necessary support to build an efficient behavioral response. That idea is also developed in neurosciences [Paillard1986].

Although virtual reality usage is in expansion, very few studies attempt to understand the behaviors of the users and the usage they make of the virtual environment when confront to a learning task. In the field of computer sciences, studies related to the usage of virtual reality in teaching and training are mostly limited to usability studies. The response of the users to the technological tools deployed to immerse them in these virtual environments has received particular attention throughout the study of immersion, engagement and presence [Riva2003]. However, even if important on the global experience of the virtual reality users, these factors alone are not sufficient to analyze the usage they make of the information provided by the learning environment and to evaluate if they can learn from it [Gopher2012].

Some studies have tried to assess the question of learning motor skills in virtual reality. Two of them are worth mentioning. Both studies were on the mimicking of taï chi forms performed by a virtual instructor. First, a study by Chua et al. in 2003 [Chua2003] immersed subjects in a virtual environment throughout the usage of an HMD. Five different types of feedback were tested, but the study was unable to find any difference in the performance of the taï chi forms among the different feedback groups. Second, a study by Patel et al. [Patel2006] compared video and virtual reality teaching by demonstration. Patel et al. concluded that virtual reality was superior to video for a taï chi learning by imitation task. However, their results are questionable on many aspects : 1) they did not perform pre-tests and mentioned that the virtual group was already superior at the first step of their training process 2) their evaluators were not taï chi experts but experiment investigators trained to grade taï chi forms 3) they computed their statistics on the average established by their two evaluators even if they mention that the evaluator inter-reliability was low.

Anyhow, we can argue that in both of these cases, the task is not really a learning task but simply a mimicking task. To our knowledge, no study has tried to answer the question of learning complex motor skills from demonstration by a virtual human in a complete lesson setup (explanation, demonstration, drills, full gesture repetitions) over more than one hour of training. Moreover, studies who attempted a reduced task lack an evaluation protocol comprising an evaluating the performance before the training and after a retention period at the end of the training, according to Joy and Garcia [II2000] these are essential to talk about an improvement. Furthermore, no study have explored the learning process from the participants point of view.

The main question of that thesis is on the relevance of using virtual humans to teach complex motor skills. The first study explores the question of the feasibility of learning by imitation of a virtual human by comparing the improvement of the performance on three karate gestures for three groups, namely a traditional class, a video-based group and a virtual reality group. The second study investigates the influence on the learning task of having a self representation in the virtual environment. The participants have a feedback of their movements represented on a mirrored cylindrical gray avatar. The impact of that avatar on the learning task of the participants is assessed by two means. Performance evaluations are performed and give an external perspective on the learning. Evocation interview are also performed to get an insight of the learning task from the participants point of view. Finally, these two studies are completed by a third one investigating the possibility to have an automatic performance evaluator in order to reduce grading discrepancies generated by humans graders. Such a tool would be required to have an objective performance evaluation of all the participants in order to compare the four learning environments presented in that thesis and eventual further iteration of these environments.

Chapter 2

General Methodology

2.1 Building a Virtual Environment to Evaluate the Relevance of Using Virtual Human for Teaching Motor Skills

Learning a morphokinetic gesture is a complex task requiring to put in place motor, cognitive, affective and sensorimotor processes. In order to learn a new motor skill, one should first understand it, visualize and build its internal representation, and then, repeat it throughout many hours of practice. A typical manner to learn motor skills is to follow the examples and advices of an expert of that skill. It is what is called learning by observation.

In order to determine if learners can acquire proper motor skills in a given environment, one should first determine if they can pick-up all the necessary information from it. That is particularly important in the case of virtual reality where the teacher is a model-based animation. Therefore, to evaluate the relevance of using virtual human to teach motor skills, we first need to build such a learning environment. That implies a balance between technological, pedagogical and methodological choices.

The next sections of that chapter, explain how a common lesson was built to be used indifferently in all the learning environments used for the studies presented in that thesis. Karate is briefly introduced to explain the choice of karate gestures with the emphasize on the fact that the goal of the studies in no way to teach karate. The chosen gestures are described together with the teaching method used in the studies. The structure of the experiments and of the lesson are described on the technological, and the pedagogical point of view. The different technology used for the virtual environments are also explained. Finally, statistical information about the participants of the studies are presented.

2.1.1 The Choice of the Gestures

An important choice is that of the gestures. On one hand, gestures should be complex enough that expert evaluators can easily discriminate experts from beginners. On the other hand, they should be simple enough that absolute novices can apprehend them and progress in their performance in a short learning period. The chosen gestures should also have clear performance criteria that permit: 1) the learner to clearly know what he is required to do 2) the evaluators to uniformly grade the performance of the different participants of the experimentation.

Taking into account these considerations, karate gestures were good candidates for our studies. Moreover, this choice was reinforced by the availability of a karate expert to assist us and by the market studies effectuated by the Artefacto society in the context of the Biofeedback project. These studies identified martial arts and aerobic dances as good candidates when designing games or serious games aim at the general public. They permit a design that can offer a good balance between effectiveness and attractiveness as discuss in section **??**.

2.1.1.1 Karate: A Martial Art

The japanese kanji "kara" mean empty and the kanji "te" means hand. The word karate is often follow by another kanji, "do" meaning the way. Therefore, karatedo literally means "the way of the empty hand". In that case, "empty" has two different and complementary meanings. It means that karate is an ensemble of bare hand techniques; fighting techniques without any arms. But it also mean "void" in the buddhist sense. In that interpretation, karate means: a way based on the repetitive practice of these hand techniques to access enough "letting go" to be in perfect control of oneself.

Modern karate was introduce in Japan in 1922 by sensei Gichin Funakoshi during a sport demonstration. That martial derived from the Okinawa island martial art practice rapidly developed to satisfy the rise of japanese nationalism. Karate later developed all around the world, partly due to the popularity of martial arts' movies. Karate is actually practiced by more than 100 millions persons in many degrees of these two definitions, namely as a martial art, as a sport, as a combat sport, or as a self defense training. However, what should be called karate and what is actually called "traditional karate" should only be the discipline which emphasize both aspect of the etymologic sense of the word.

2.1.1.2 Three Isolated Basic Gestures

For the purpose of our experiment, we chose three basic karate gestures. It is important to note that the purpose of our experiments is to study the teaching of complex motor skills in different learning environments and in no way to teach karate. Therefore, these three gestures should be considered for themself only and in complete isolation of karate. The three techniques were taught with respect to the performance criteria of the Shotokan school under the Japan Karate Association (JKA). The founder (shomen) of this branch in France is Kasé sensei who arrived in the mid-1960's.

The participants of our experiments were asked to train on these three gestures, namely, one frontal punch (tsuki) at the torso level (chudan), one frontal kick (mae geri) and one defense using the forearm in an external to internal motion that could be used to stop a torso level attack (soto uke). All three gestures were performed in a natural static standing position (hachiji dachi) in series of ten repetitions. Each of the gestures was chosen for their specific difficulties or skills. Next sections will described precisely the performance criteria of these three gestures.

2.1.1.2.1 Tsuki: A Frontal Punch

The tsuki is a frontal punch (figure 2.1). It can be performed at various heights. It can aim at the sternum (chudan) or at the face (jodan). For the purpose of our experiments, one of the performance criteria was to aim at the sternum at a height above the plexus and below the shoulders, therefore at the chudan level.

The tsuki requires the synchronization of the two arms. While one retires in armed position (hikite) the other one punches synchronously. When performed by experts, it can in fact be noted that it is the hips motion initiated from the ground in synchrony with the retraction of one arm in hikite that give the energy to the punching arm. Both arms should in fact be perfectly relaxed, no force should come from the upper body muscles. In theory, all the force comes from the hips rotation and the contraction of the abdominal muscles in synchrony with the breathing.

Both the retracting arm and the punching arm should move in a perfectly linear trajectory. Both wrists should rotate homogeneously during the linear trajectory of the arm in order to have completed a 180° rotation at the very end of the gesture. During all the gesture, the fists should be closed and perfectly aligned in the prolongation of the forearm.

At the departure and arrival of the gesture, one arm should be in hikite position while the other should be in tsuki position. That means that one forearm is retracted with the fists pointing up, placed about 15 centimeters over the hips along the body, with the elbow pointing in the back as if it could hide behind the body. The other arm is stretch (but not overstretch) linearly with the fits pointing down and align with the sternum. Both shoulders should be perfectly relaxed. Feet should be placed parallel to one other, in the alignment of the shoulders. The legs should not be completely stretched, but perfectly relaxed. The back should be straight and relaxed.

Detailed performance criteria used by the instructor in the lesson and by the experts to grade the performance of the tsuki can be found in table 7.5 of appendix section 7.2.2.

2.1.1.2.2 Mae geri: A Frontal Kick

The mae geri is a frontal kick requiring balance in order to alternate both legs. The motion is in five phases (figure 2.2). First, the knee should be elevated over the belt. Then, the leg should be extended in a rapid whipped motion. Finally, the leg should be retracted quickly to the first position before returning to the standing position.

The mae geri can also be performed at different heights: gedan (legs), chunan, and jodan. In our experiments, the height of the mae geri was not a performance criteria. The gesture starts in standing position. Both feet should be placed parallel to one other, in the alignment of the shoulders. The legs should not be completely stretched, but perfectly relaxed with the knees softly bent. The back should be straight and relaxed. The knee of the kicking leg is then raised as high as possible over the belt with the foot still parallel to the ground with the toes raised to point up. It is the abdominal muscles that should lift the knee, one should therefore feels a contraction of these muscles and a small retroversion of the hips. The contraction should be felt as if it was initiated from the ground of the standing leg. The back and the head should stay straight. It is the knee and hips that should group together and not the upper body. The leg is

Figure 2.1 - Three different moments of the realization of a tsuki

then thrown in complete extension (but not overextension) with the foot pointing and the toes raised in order to hit an invisible target with the part of the foot just under the toes in the region of the metatarsal arch, a part called the koshi in japanese. In our experiment, the target can be at any height but should be centered with respect to the person executing the mae geri. After hitting that invisible target, the leg should be retracted in the previous grouped position. The extension-retraction movement should be regular but rapid like if the leg was whipped. During all the motion, the knee should stay at the same height, the back should stay straight, the arms and upper body should be relax, the standing leg should not move and stay softly bent and the standing foot should be perfectly flat on the ground at any time. After the leg retraction, the kicking foot should slowly go in standing position. All this motion should be done in perfect control of the leg and foot by the usage of the abdominal muscles. Relaxation of all the other muscles is what permits equilibrium.

Detailed performance criteria used by the teacher in the lesson and by the experts to grade the performance of the mae geri can be found in table 7.7 of appendix section 7.2.4.

2.1.1.2.3 Soto uke: A Frontal Defense

The soto uke is certainly the most difficult of the three gestures in that it requires a lot of coordination. Most subjects failed to understand it at the initial evaluation and took more than one lessons to get a gross idea of it. One arm starts at the ear level and sweeps in front of the torso in order to clear the area and push to the side an eventual tsuki punch. At the same time, the other arm retracts in armed position. As for the tsuki, there is a rotation of both wrists. This circular motion is illustrated in figure 2.3.

The soto uke is the defense response to a tsuki attack. It can somehow be seen as a counter tsuki and it shares a lot of its characteristics. The standing position is the same and as it is the case for the tsuki, the motion is initiated from the ground by the rotation of the hips and the retraction of one arm in hikite position. When practicing the soto uke individually in series of

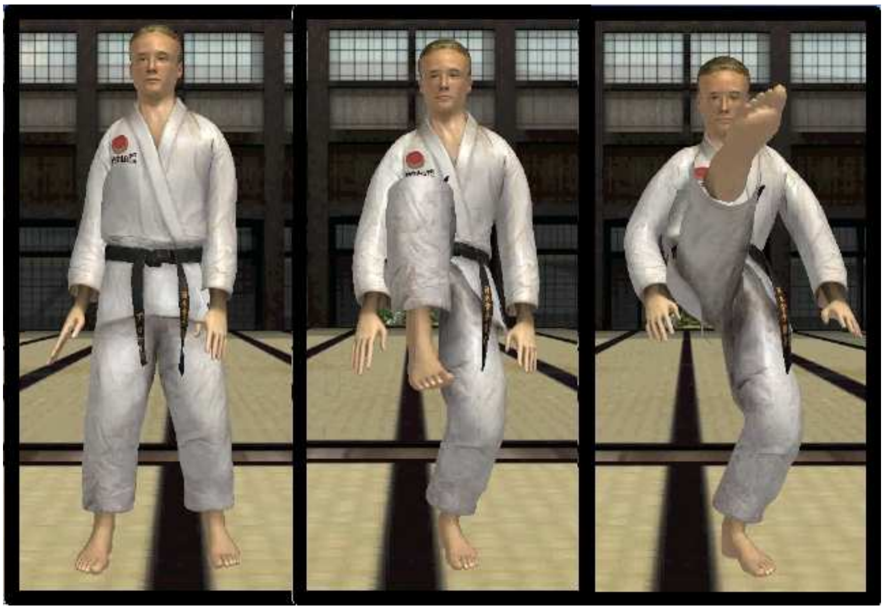


Figure 2.2 - Three different moments of the realization of a mae geri

repetitions, the retracting arm starts in tsuki position and the other arm starts with the closed fist at the ear level with the palm pointing up. The elbow is aligned with the shoulder and is trying to point back. When the opposite arm retract, the fist and elbow move in a circular motion. The whipping wrist effectuates the same rotation motion as the retracting arm. The whipping arm stops in front of the sternum, the fist at the height of the shoulder and pointing toward the body, the arm and forearm forming a 90° angle. The hips and the shoulders end at 45° angle like if the retracting arm had pull them to the back. That way, the whipping arm push a tsuki coming from a frontal opponent to the side and the opponent's fist pass to the side of the defender body.

When practicing the soto uke in series of repetitions, the karateka should go back from the defending position to the start position. The whipping arm is extended in tsuki position and the fist rotate to point down while the arm in hikite goes to the ear in a circular motion. The next soto uke can then be initiated.

Detailed performance criteria used by the teacher in the lesson and by the experts to grade the performance of the soto uke can be found in table 7.9 of appendix section 7.2.6.

2.1.2 The Design of the lesson

As illustrated in figure 2.4, the experiment lasted 5 weeks, the first and the fifth week are dedicated to evaluations of the participants of the studies. Evaluation will be described in section 3.2.2 of the first study and section 4.2.2 of the second study respectively as they present different characteristics from one experiment to the other. The other three weeks are dedicated to the training at the rhythm of one hour of training per week. The same lesson was used during the three weeks. The design of the lesson is explained in the following sections.

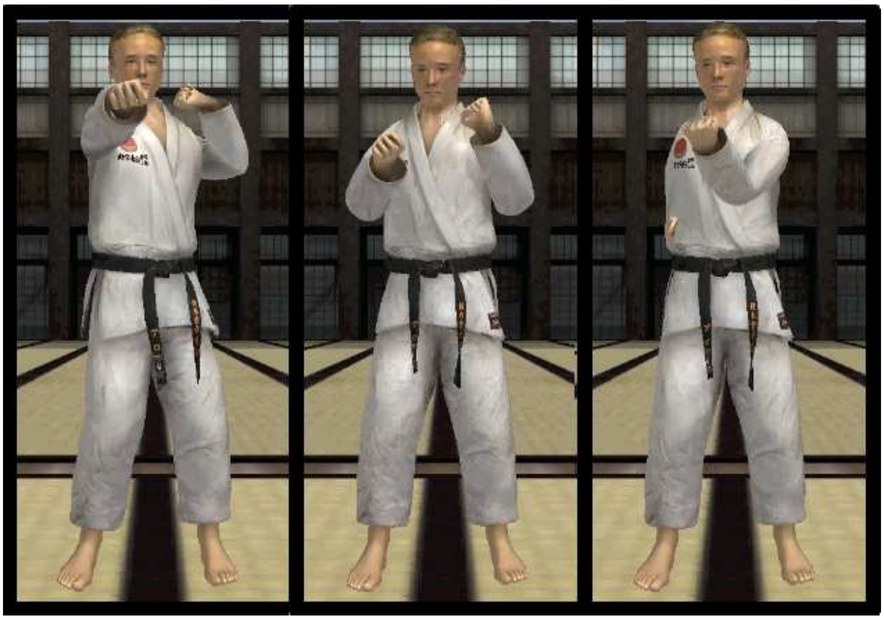


Figure 2.3 - Three different moments of the realization of a soto uke

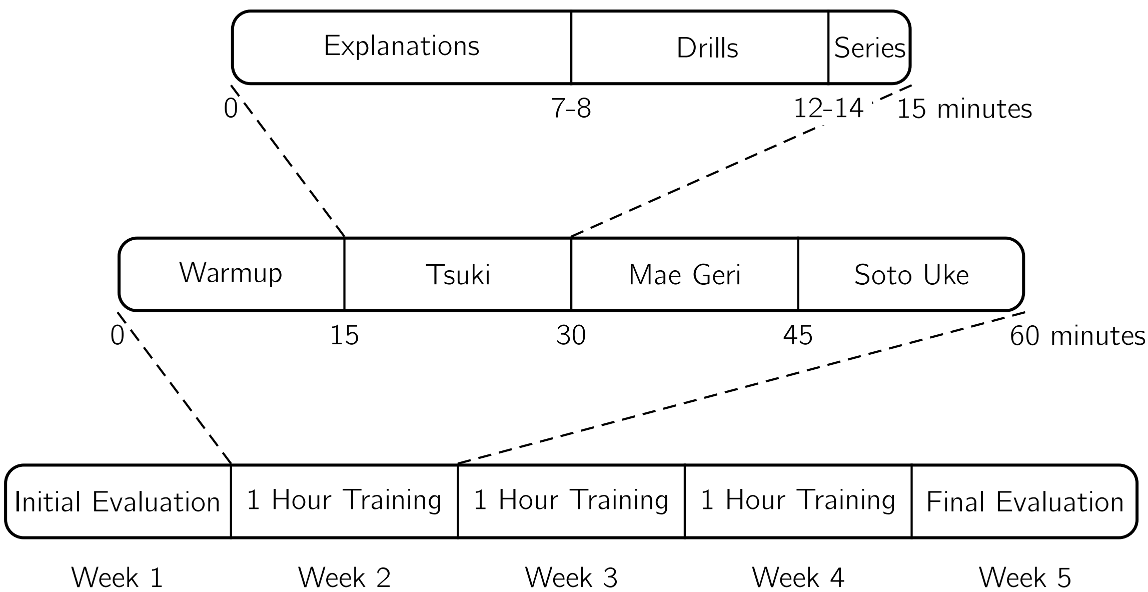


Figure 2.4 - Participants' Training Timeline

2.1.2.1 The Choice of the Teaching Method

We based the design of our lesson on what would be a part of a traditional karate class. This part is called kihon, it is an individual repetition in unison with the leader of the lesson (a sensei or a sempai; a higher grade student) of a technique or of a drill designed to teach a technique. Repetition of basic techniques is crucial in traditional karate and even higher grade participants performed many repetitions at every training, because in the karate philosophy, it is only through repetition that one can approach perfection and complete self-control in the performance of the gestures. That teaching method, where an instructor demonstrate and explain on his body how to perform a gesture is the most commonly used method in sport. It is called teaching by demonstration.

2.1.2.2 The Different Moments of the Lesson

The lesson lasts 1 hour and is divided in 2 main periods. In a first time, all participants of the different experiments performed a 15 minutes standardized warmup. After that warmup, each of the three gestures were studied for 15 minutes. These 15 minutes were divided in 3 periods, namely a period dedicated to explanations of the performance criteria of the gesture, a set of drills to progressively acquired the gesture techniques, and finally, several repetitions of the gesture.

2.1.2.2.1 Video Warmup

The warmup lasts 15 minutes and is performed in front of a video of the trainer for all experimental learning environments. The trainer was explicitly asked to create a warmup based on warmups traditionally used in karate training. He was also asked not to include any drills or specific preparations for any of the three gestures that will later be taught in order not to bias the experiments. Consequently, the warmup was composed of exercises to warm the muscles and to accelerate the heart beat, and of flexions, extensions and rotations of the main articulations used in the three gestures.

2.1.2.2.2 Lesson

Gestures' Explanations

The first part of the training of each of the three gestures is dedicated to the explanation and illustration of the performance criteria. That part lasted approximatively 7 to 8 minutes depending on the gesture. During that part, the trainer verbally explained the performance criteria of the gesture and illustrated it by demonstrations on his body.

Gestures Divided in Drills

Each of the gestures is divided in simple drills in order to learn it in pedagogical steps. For example, the tsuki and the soto uke are first performed one arm at the time, and then synchronously in 2 phases before being performed in their integrity. The mae geri, is divided in phases. First, the trainer teaches how to lift the knee over the belt. Then, from the bended knee, he teaches how to kick and then how to retract and step down. Each leg is trained separately. Alternating between the two legs is teach only at the end when series of the complete mae geri gesture are performed. The drills part lasts approximatively 5 to 6 minutes depending on the gesture.

Performance of the Complete Gestures

Each of the three gestures training ended with two series of ten repetitions of the complete gesture at two different paces. The gestures are first perform slowly and then at maximum speed. It is important to note that in our experiments, the pace of the performance of the gestures is not a performance criteria. During the evaluations, each participant of the studies is encouraged to perform the gesture at his own pace. Two paces are proposed in the training for the participant to test his capacities of following the trainer. This last part lasts approximatively 1 to 2 minutes depending on the gesture.

2.1.3 The Design of the Virtual Environment

2.1.3.1 Virtual Dojo

The virtual dojo was designed in 3D Studio Max by a professional graphic designer and is based on an imaginary dojo. It is used to contextualize the karate lesson. As explained in section 1.1.2, decor in virtual environments are important immersion factors, to give the users a sense of dimensions, distances and proportions. The graphist created all the necessary files for a direct integration in the XVR platform that was used to generate the virtual learning environment.

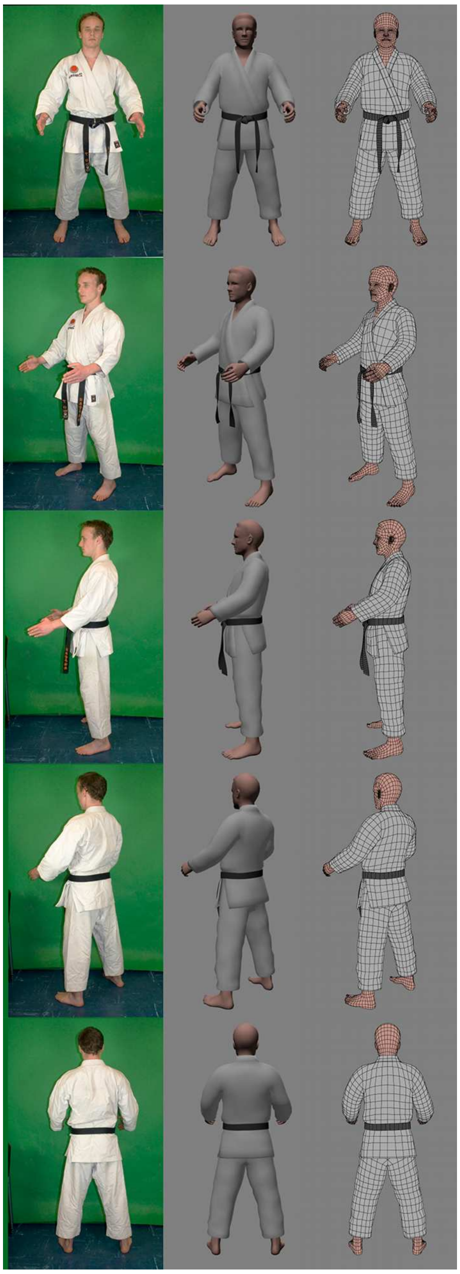
2.1.3.2 Virtual Trainer

2.1.3.2.1 Graphical Design

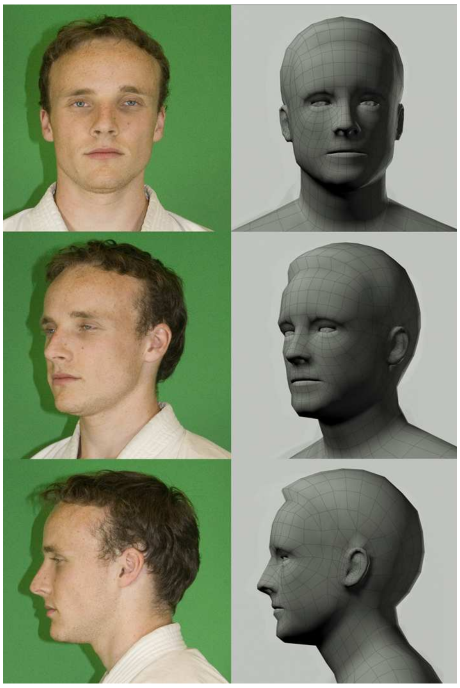
The instructor avatar was designed in 3D Studio Max by a professional graphic designer from pictures of the human instructor (see figure 2.5) using the H-anim norm for biped (http://www.h-anim.org). We deliberately made the choice of representing the human instructor with a high degree of fidelity instead of using a cartoon like avatar. This choice is motivated by two main reasons:

1. In the first study, we wanted the virtual environment to be a tridimensional stereoscopic and egocentric animation movie of the video lesson. The main objective being to study the influence of the virtual human in the learning performance of the participants.

2. We wanted to position our virtual environment in the category of serious games and not games.



(a) Virtual trainer: details of the Body



(b) Virtual trainer: details of the Head

Figure 2.5 - Virtual trainer built from photos of the real trainer: (a) details of the body (b) details of the head

2.1.3.2.2 Motion Capture

We used motion capture to animate the virtual instructor since with regards to the literature discussed in section 1.1.4, we considered motion fidelity as the most important characteristic of a virtual human used to teach complex motor skills. Motion capture was performed using 12 Vicon MX (Oxford Metrics, Oxford, UK) high resolution cameras capturing at 120 frames per second at a 4 megapixels resolution. The Vicon system is a passive optoelectronic system with camera capturing reflection of the infrared light projected on reflective markers by a ring of infrared LED surrounding the objective of each of the cameras and synchronized with the camera speed.

The instructor was equipped with 49 reflective markers placed on articular centers as displayed in figure 2.6. The marker placements correspond to the ISB norm defined by Wu et al. [Wu2002, Wu2005]. The LHND, RHND (left and right hand) and LWRI and RWRI (left and right internal wrists) are not usually used, they were added for our specific needs. The karate gestures we wanted to capture comprised many rotations of the wrist and the addition of these markers facilitates the reconstruction of the motion by helping to distinguish the internal and external side of the wrist. No marker was placed on the fingers since that would interfere with correct closing of the fist during the gesture. Consequently, opening and closing of the fist were not captured and later had to be manually animated.

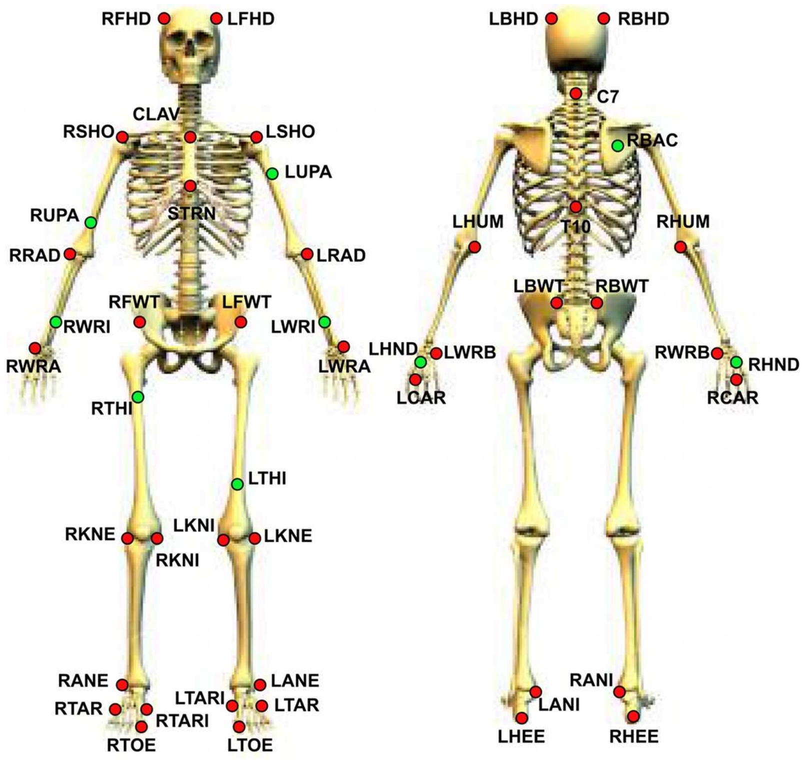


Figure 2.6 - Vicon Markers Placement

Optoelectronic systems like the Vicon permit to track motion with a precision of the millimeter order but with the potential problem of the lost of markers due to visual occlusion by other part of the body. This implies that the captured motions have to be reconstructed. That was performed using the Vicon IQ 2.5 software. Lost of markers for duration smaller than 120 frames (one second) were reconstructed using spline interpolation. For longer lost or when the spline reconstruction failed to give the expected result, the IQ's kinematic fit method was used on lost of duration less than 1000 frames (8,33 seconds). Finally, in the extremely rare cases were both these methods failed, a rigid body reconstruction was used. If, however, the result was not satisfying, the data was rejected and another capture was used. This reconstruction permits to produce C3D motion files. These files were then used to map the physical instructor gesture onto the virtual instructor to animate it.

2.1.3.2.3 Motion Retargeting on the Virtual Instructor

Once the motion capture files have been reconstructed, the motion had to be map onto the avatar. That was done using Motion Builder 2010 32 bits. The C3D files generated at the previous step were imported into Motion Builder. Markers positions were then converted to bone positions using a constrained actor plugin developed by the M2S laboratory. The constrained actor plugin is used to retarget the C3D markers positions to an amorphological skeleton. Subsequently, the avatar developed in 3D Studio Max was imported in Motion Builder in FBX format. Bones of the actor were mapped to the avatar bones using the Motion Builder character animation process. Fingers closing and opening into a fist were animated manually from the synchronization of the motion capture and the video images. All the animations were revised from comparison with the video images and from the comments of the instructor in order to minimize any artifacts that could have been introduced during the animation process. Finally, the animations were reimported in 3D Studio Max and exported for their usage in XVR using the Halca plugin. Halca being a characters animation library interface for the XVR platform developed by the EVEN lab [Spanlang2009].

2.1.3.2.4 The Virtual Instructor Voice

The voice of the human instructor and the sound resulting from the gestures were recorded both for the video and the virtual setup using the microphone of the video recorder. For the virtual environments, the sound recording was extracted from the video image and converted to MP3 format. It was edited so that the sound and animations would started synchronously. The playback of both the animations and the sounds is managed by XVR.

2.1.3.3 Technological Environment

The virtual learning environment was developed using the VRMedia XVR software platform (http://www.vrmedia.it) together with the Halca avatar animation library developed by the Event Lab [Spanlang2009]. The XVR platform managed all the inputs and outputs necessary for the immersion and the interactions and generated the virtual environment in realtime accordingly.

In input, it received the head position of the participants in order to modify the view point of the projected environment to create the illusion of an egocentric vision. Later, in the second experiment, full body information was received in input in order to animate an avatar representing the participant. The XVR software managed the tridimensional generation of the virtual dojo and of the virtual instructor and the synchronization of the playback of the animations of the virtual instructor and the corresponding sound files. In the second experiment, it also managed the realtime animation of the mirrored avatar of the participant. The XVR software is responsible for sending in output the integrality of the virtual learning environment comprising all these components at a pace of 120Hz alternating with an image for each eyes to create the stereoscopic vision illusion. This is the necessary information required for the tridimensional stereoscopic projection sent by the video projector and perceived by the participant through the usage of stereoscopic glasses. Figure 2.7 illustrates that cycle with all its technological components.

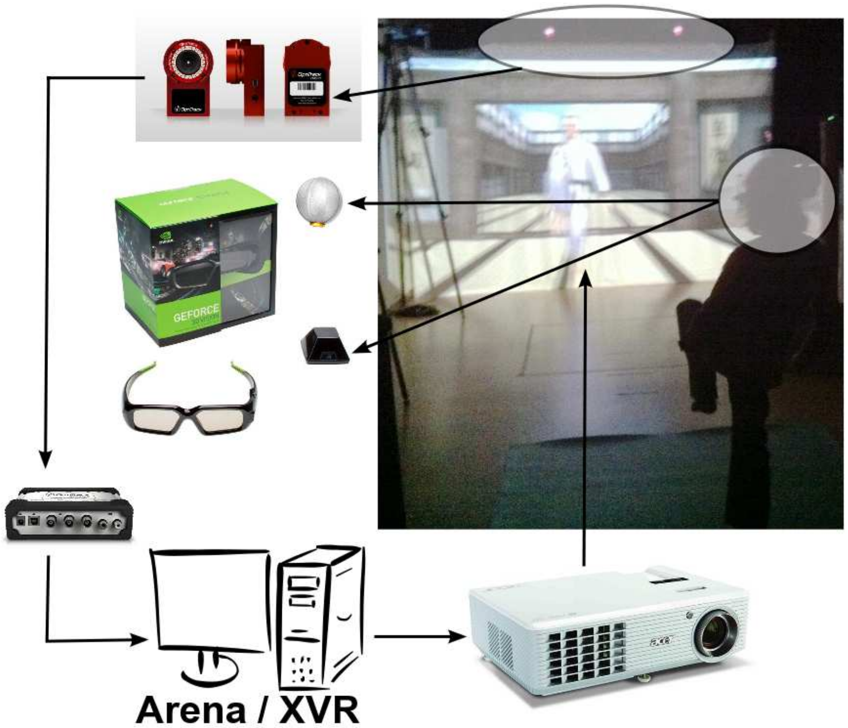


Figure 2.7 - The Technological Setup

2.1.3.3.1 Projected Virtual Environment

The virtual environment created by XVR was projected on a three meters high projection screen by a high frequency video projector (Acer H5360). The video projector was placed on the ceiling at six meters of distance of the screen. Dimensions of the virtual environment were adjusted so that the virtual instructor was displayed in real size. The participants were placed in front of the screen. A two by two meters carpet was used for the participant to have a tactile and visual delimitation of the capture zone. The participants were therefore aloud to move two meters sideways and from 4 meters to six meters far from the screen. The video projector projected images at 120 Hz alternating images for the right and the left eyes.

2.1.3.3.2 Artificial Stereoscopic Vision

The illusion of stereoscopic vision was created by the combination of the projection of these alternating images at a rate of 120 images per seconds and its synchronization with the active shutter LCD glasses wore by the participants. For our experiments, we used the NVidia GeForce wireless 3D glasses. These are active glasses, meaning that they synchronize with the computer video card to occlude the eye opposite to the one the projected image is sent for. We had to use radio frequency (bluetooth) to synchronize the glasses since the infrared from the Optitrack cameras was interfering with the infrared synchronization system of the glasses. The stereoscopic vision created that way is artificial and does not precisely correspond to the natural stereoscopic vision of every participants. In fact, XVR creates each eye image using two virtual cameras placed in the scene at the computed position of the physical eyes of the participants. That placement is computed from the estimated position of the head, that will be discussed in the next section for the first experiment and that is computed from the full body tracking in the second experiment. From that placement, the two cameras are positioned side by side with a distance corresponding to an average natural eye to eye distance. That artificial stereoscopic vision together with the artificial egocentric vision presented in the next section is sufficient for most participants to create the illusion of natural vision, however as discussed in section 1.1.2 some participants might perceived it negatively.

2.1.3.3.3 Head Tracking For Egocentric Vision

Head tracking was performed by placing four reflective markers on the stereo glasses and tracking these using ten Optitrack V100:R2 cameras placed around the participant in the projection room. These markers were identified in the Natural Point's Arena software by creating a rigid body. The barycenter position and orientation of that rigid body was sent to XVR using the UDP protocol. XVR treated that information to modify the view point of the scene in order to create the illusion of an egocentric vision. Detailed about the Natural Point's Optitrack cameras, the Arena software and their interaction with XVR will be discussed more extensively in the context of the second experiment in section 4.2.1 where they will be used not only to track the head but the full body of the participants.

2.1.4 Studies Participants' Profiles

For the purpose of our study, we recruited 41 sports sciences students (28 men and 13 women) aged between 18 and 28 years old and practicing more than 2 hours of sport per week. The recruitment was done by announcing the experiments on the information website of the sports sciences faculty. All subjects responded freely to the advertising and were free to quit the experiment at any time. The only condition to participate to the experiment was to be aloud to practice karate like sports. Sports sciences students already need medical authorization to practice sports in their study program. Another condition was not to have practiced karate or a similar martial art before. This was assessed on the consent form participants had to fill and confirmed by the initial evaluation performed the week before the training started. Table 2.1.4 details the group repartition.

Study Group	Number of Subjects		Age	Sport Practice
	Men	Women	Avg Years	Avg Hour/Week
Traditional	6	5	20.1 +/- 0.3	5.35 +/- 2.8
Video	7	5	21.0 +/- 2.5	5.64 +/- 4.2
Virtual Environment without Feedback	8	0	22.6 +/- 2.8	5.29 +/- 2.0
Virtual with Mirror Feedback	7	3	23.5 +/- 2.3	7.2 +/- 3.2
Global	28	13	21.5 +/- 2.4	5.9 +/- 3.1

Table 2.1 - Participants' Profiles

Chapter 3

Teaching with Virtual Humans: A Comparative Study of Teaching in Traditional, Video, and Virtual Environments

3.1 Introduction

In this study, we want to answer the question of the feasibility of learning complex motor skills from the imitation of a virtual human. As detailed in section 2.1.1 of the general methodology, karate gestures are good representatives of complex motor skills. On one hand, they are complex enough to necessitate learning and permit a clear distinction between novices, trained novices and experts. On the other hand, they are precisely codified and therefore permitted a standardized and uniformed evaluation of their performance. We consequently used the teaching of three basic karate gestures as our study case.

Many factors influence the learning processes of an individual, making all learning situations unique [Lave1988]. Some of these factors are internal and depend on the individual himself. Factors such as the personal background and anterior learning experiences influence the learning of new skills. Other factors such as the familiarity with the learning environment, the motivation and also the mood of the individual at the moment where the skill is taught can influence the quality of the learning. However, the control we have on these factors is fairly limited and we can even hardly measure these. We have to rely on many participants to attenuate these individual effects and observe tendencies.

Another type of factors that influence the quality of learning are external factors. These factors include the different variants of the learning environment such as the type, the characteristics and qualities of the media used for teaching, and the presence of other learners. These are factors we can isolate and control in order to study a specific learning environment.

3.2 Methodology

3.2.1 Three Different Learning Environments

The characteristics of the learning environments we want to isolate are these specific to the usage of a virtual instructor. Starting from a traditional karate learning environment we individuated the characteristics that differ from the conditions found in a virtual environment with a virtual instructor. We used an intermediate video environment to further isolate these characteristics.

Some of the main differences concern the media. In a traditional karate class the instructor is physically in front of the participant. Consequently, the participants can see him in a natural manner. In the case of our virtual environment, the instructor is in front of the participant but by the intermediate of a real scale projection. To isolate the projection factor from the virtual human factor, we therefore used an intermediate situation where a video recording of the real teacher is projected in real scale. That also serves to isolate the group factor and all adaptation and interaction factors, since in the video case as in the virtual environment case, the lesson is static and the participants trained individually. Table 3.2.1 summarizes the characteristics of the different learning environments.

	Traditional	**Video**	**Virtual**
Lesson Type	group	individual	individual
Vision	stereoscopic	monoscopic	stereoscopic
View Point	egocentric	allocentric	egocentric
Instructor	human	video of human	virtual human
Adaptation	to the group pace	no adaptation	no adaptation
Interaction	with the participants	no interaction	no interaction

Table 3.1 - Characteristics of the Three Learning Environments

However, what differentiates the video setup from the virtual human setup are the factors concerning the vision and the viewpoint, contrary to the natural vision situation of the traditional environment, the video setup is monoscopic and allocentric. On the other hand, the virtual environment presents artificial stereoscopic vision and egocentric viewpoint. It can be argued that it would have been preferable to also isolate the artificial stereoscopic vision and egocentric viewpoint in order to really individuate the virtual human from the other factors. It was not possible at the moment of our experiment, but as these technologies become more accessible, it would be advisable to perform the experiment with a group training in front a stereoscopic and egocentric video recording of the instructor. Although, it will probably be impossible to have the same artificial vision setup for both the video and the virtual environment. More details about the vision technology and setup used in our experiment can be found in section 2.1.3.3.2 and 2.1.3.3.3.

3.2.1.1 Learning in a Traditional Class with an Instructor

For the purpose of our experiment, we created an atypical traditional class scenario where the instructor was asked to teach in front of the class like if there was a barrier between him and the group that prohibits physical interaction with the participants. He was also asked to rigorously respect the lesson plan and pace and not to adapt its content to the participants. The participants were not allowed to interact in any way with the instructor or with each others and had to stay on "their side of the class". As in the case of the recorded lesson used in the video and virtual setting, the same lesson was taught for the three trainings. Even if eliminating any adaptation or interaction is humanly impossible, we tried to reduce these to the minimum since they are not the subject of this study. Consequently, the instructor was informed of the importance of these aspects for the outcomes of the study and he discipline himself to respect the constrains of the experimental setup.

The traditional group environment, obviously permit natural stereoscopic vision and egocentric viewpoint on a physical human instructor. Although limited to a small zone by our requirements to mimic what would be the condition in the two next environments, the participants were aloud to move to change their view on the instructor. What differentiates the traditional environment from the two others is the possibility to retrieve information from the observation of the other participants and the possible, even if limited, interactions and adaptations of the instructor. Consequently, the traditional group only serves as a ground base to observe what would be a normal progression after three weeks of a one hour training (45 minutes on the specific gestures) in the most common learning environment.

In that environment, both the participants and the instructor trained bare foot and wore traditional karate suit (gi). The lesson was taking place in a martial arts room as it can be seen in figure 3.1.

Figure 3.1 - A traditional karate class with an instructor

3.2.1.2 Learning from a Video of the Instructor

Video recording is another media that is commonly used to teach sports. It permits the participant to train at home individually. However, for our experiment, the training was in a laboratory setup and each participant had a fix schedule. That permitted to ensure that every participant effectively performed their training in the same environmental conditions. The video lesson was prerecorded. The instructor respected the same lesson scenario he used for the group lesson and explained and demonstrated the gestures as if the participants were in front of him. The same lesson was used for the three training periods.

The video was projected in real scale dimension. The participant was in front of the projection and was aloud to move freely in the projection room. The participants wore comfortable sport clothes and trained with bare foot as it is the case in karate. However, the instructor was recorded wearing shorts only, since, during the recording session, he was equipped with the markers for the motion capture that occurred simultaneously. The video setup is displayed in figure 3.2.

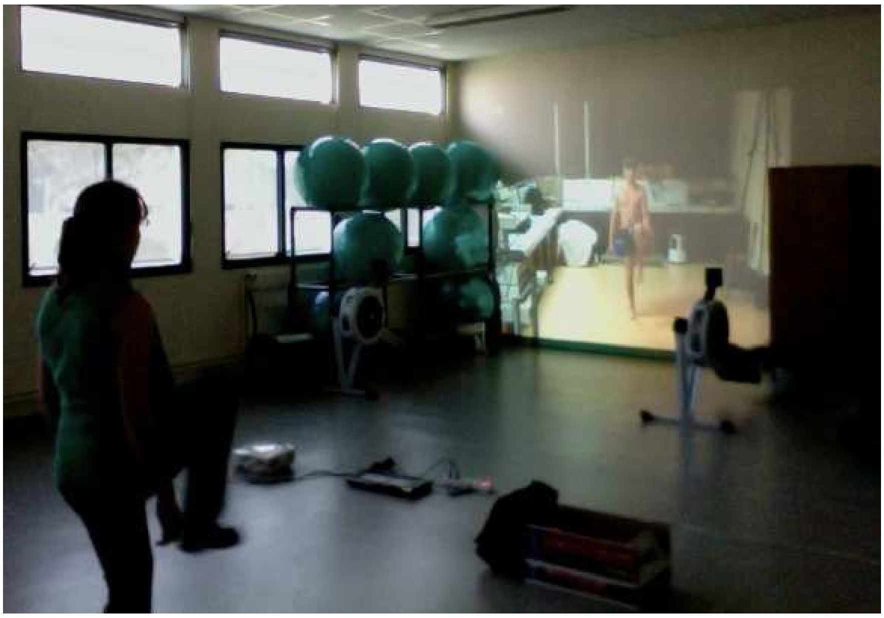


Figure 3.2 - A karate lesson in with a pre-recorded video instructor

3.2.1.3 Learning from a Virtual Human Representation of an Instructor

The virtual reality participants trained in a projected immersive environment where a virtual instructor was performing a prerecorded lesson as illustrated in figure 3.3 and explained in section 2.1.3.3. The prerecorded lesson was strictly the same as the video lesson since they were recorded simultaneously with both technologies. The virtual lesson was recorded by motion capture using the Vicon system as explained in section 2.1.3.2.2. The sound used in the virtual lesson was that recorded by the video camera. In the virtual environment, the motion of the head of the learner was tracked to adapt his viewpoint in order to provide the participant with a viewpoint as similar to his natural egocentric viewpoint as explained in section 2.1.3.3.3. Artificial stereovision was used to perceive the tridimensional environment. The participant was in front of the projection and was aloud to move freely in the small zone corresponding to the capture zone. Going out of that zone would provoke the lost of the head tracking. However, that zone corresponds to the personal zone participants of the traditional training used. The same space usage was observed in the video training group. The three chosen gestures do not require large displacement and the zone was clearly delimited by a carpet. Therefore, lost of head tracking only occurred rarely among all participants and trainings.

The virtual environment was reduced to its simplest expression in order to evaluate the impact of the avatar only. The virtual world was a representation of a japanese dojo as explained in section 2.1.3.1 and the instructor was a representation of the real instructor himself built from photos, as explained in section 2.1.3.2.1 and illustrated in figure 2.5.

The instructor was presented wearing a karate suit in a dojo in order to contextualize the virtual environment. However, the participants trained bare foot and wore comfortable sport clothes. It might be argued that the karate suit in the traditional and virtual environment might have occluded some details of the body parts implied in the gestures and that it is a bias compared with the video setup. However, it was technologically impossible to do otherwise and recording separately the video and virtual lesson in order to have the instructor wearing the karate suit in the video would have introduced a more important bias since the two lessons would not have been strictly identical. That bias however exist between the traditional environment and the two others. Optimal conditions would have been to be able to record the video and virtual training directly during the traditional one and to create the virtual dojo from pictures of the martial arts room and to project both environment in that same room.

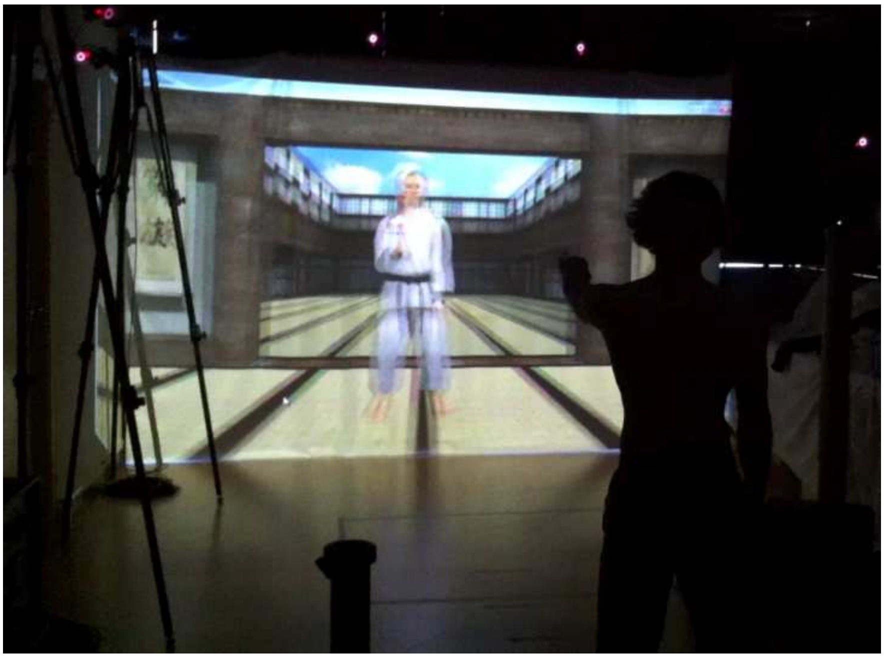


Figure 3.3 - A karate lesson with a virtual human representation of an instructor

3.2.2 Evaluation by an Expert

In order to determine the impact of the different environments on the learning, we need a way to establish initial and final level of performance. Evaluation by experts is the most common type of evaluation in individual sports where the performance of a set of skills, gestures or routines at an established level of competency permits the passage to another degree. It is also common in competitions where judges attribute a grade to a performance according to a precise list of performance criteria [Dosseville2011]. It was therefore natural to use it as our prime evaluation method.

Since we want to observe a progression, it was necessary to perform two evaluations. The first one to establish the initial level of the participants and the last one to establish their level after training. The objective of these evaluation, particularly the last one are to evaluate the improvement on the performance of the gesture, it is therefore important that these evaluations are performed outside of the learning environment and that they are not accompanied by the instructor in any way [II2000].

For this study, the evaluator was the karate instructor. Mostly like it would be done in a traditional class, he used the evaluation grids (see appendix 7.1) he himself designed to grade all the participants. The instructor is a recognized expert of his domain, he has more than ten years of deliberate practice of karate, he performed in international competitions and his ability to teach karate is recognized by both the French Karate Federation (FFK) and the International Japanese Karate Association (JKA).

3.2.2.1 Initial Evaluation

At the beginning of the study, the starting level of the participants was assessed by performing a simple test. Each of the three karate gestures was presented individually once on a video sequence of ten repetitions performed by the instructor. The participants then had to try to reproduce these by performing two sequences of ten repetitions of each gesture. These sequences were recorded on standard video. One series was performed with the participants facing the camera, the other series was performed with the participants showing their left profile to the camera. This initial evaluation served two purposes. First, it ensures that none of the participants already know the gestures and, second it establishes the starting level of the participants. The starting level was evaluated by a the instructor who attributed a score to each participant by watching their performances on video.

3.2.2.2 Final Evaluation

In the week following the last training, the participants were evaluated in a similar manner as at the beginning. As it was the case for the initial evaluation, the participants were evaluated outside of their learning environment. For the final evaluation, the experimenter only called the name of each gesture, the gestures were not recalled to the participants in any manner. Participants had to remember each of the gestures by their japanese name and show their learning by performing 2 series of ten repetitions of the called gesture. These repetitions were captured on video, one series facing front and another showing the left profile. Videos were then evaluated by the instructor.

3.3 Results

In order to evaluate the performance of the learning environments we statistically analyzed the evolution of the scores between the first and the second evaluation for the three groups. In a first time, we performed a two-ways ANOVA (group and evaluation) with repetition. No statistical difference ($p < 0.05$) was found between the groups for the initial and final evaluations for the tsuki (table 3.2) and the soto uke (table 3.4). However, the VR group had a significantly different score with respect to the traditional group for the mae geri ($p = 0.006$) at the initial evaluation (table 3.3). That can be explained by the fact that one of the learners of that group already score high at the initial evaluation compared to the other learners. Despite that limitation, the statistical test confirms that all the groups were similarly beginners for all the three gestures.

Moreover, the same test demonstrated that there was a significant difference between the scores of the initial and final evaluation ($p < 0.001$). It clearly demonstrates that all groups have improved their performance on the three gestures as can be shown in the set of figures 3.4.

Finally, a one-way ANOVA (groups) was used to see if the improvement (difference between the final and the initial evaluation) occurred in the same manner in all three groups. There was no significant difference between the groups in improvement for tsuki ($p = 0.887$), mae geri ($p = 0.074$) and soto uke ($p = 0.217$). That means that there is no significant effect of the experimental set-up on the score improvement.

In conclusion, these results tend to show that the virtual teacher was as efficient as the physical or video teacher to deliver relevant information. Learners were equally able to improve their performance throughout learning indifferently of the learning environment they used. Therefore, virtual reality can be used as a learning tool for that kind of complex motions.

	Traditional	Video	Virtual
Traditional		0.654	0.737
Video	0.332		0.454
Virtual	0.946	0.412	

Initial

Final

Table 3.2 - Inter-group p value for initial and final evaluation of the tsuki

	Traditional	Video	Virtual
Traditional		0.191	0.006
Video	0.526		0.091
Virtual	0.763	0.377	

Initial

Final

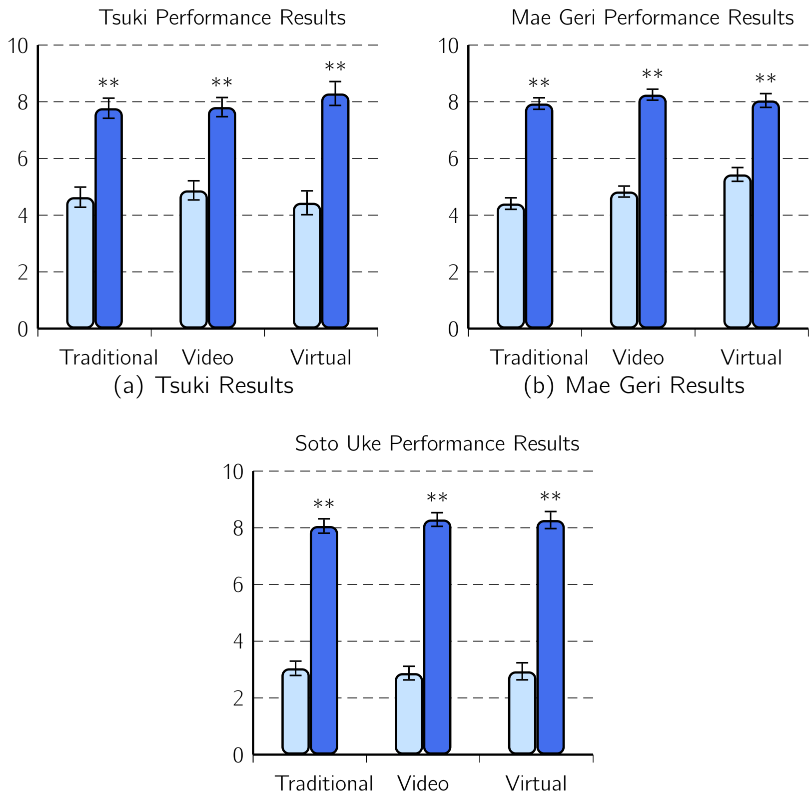
Table 3.3 - Inter-group p value for initial and final evaluation of the mae geri

	Traditional	Video	Virtual
Traditional		0.663	0.804
Video	0.961		0.884
Virtual	0.629	0.592	

Initial

Final

Table 3.4 - Inter-group p value for initial and final evaluation of the soto uke



(a) Tsuki Results
(b) Mae Geri Results
(c) Soto Uke Results

Figure 3.4 - First Study Evaluation by an Expert Results

3.4 Conclusion

The question of that study was to determine the feasibility of learning complex motor skills from the imitation of a virtual human. To answer that question, thirty-one novices were evaluated on the performance of three karate gestures they had to learn from the imitation of an instructor. That instructor was either a physical human, a video representation of that same human or a virtual human representation built from the motion capture of the physical instructor.

The participants of the three group followed the same karate lesson at the pace of one hour of training per week. Every participant was evaluated twice, once prior to the training to assess their initial level, and once one week after the last training to assess their final level. Both evaluation were performed outside of the learning environment in an identical manner for every participants independently of their group. The initial and final performance were recorded on video and graded by the expert instructor. Grade out of ten were attributed for every performance.

Results demonstrated that all participants were novices and had a similar initial level with the one exception between the traditional and the virtual group on the mae geri gesture. Similarly, results showed that all the participants improved their performance as a result of the training. No significant difference was observed in the final level and in the improvement of the participant among the three groups. Consequently, the results of that study permitted to conclude that learning from the imitation of a virtual human is possible. Furthermore, in the limit of the precision of the evaluation method used in that study, learning by imitation of a virtual human is equivalent to learning by imitation of a video reproduction of a human, and even to learning from imitation of a physical human.

Chapter 4

Teaching with Virtual Humans: Dealing with A Self Representation in the Virtual Environment

4.1 Introduction

The results of the first study permitted to conclude that according to one expert's grading of the three groups pre-training and post-training evaluations, all groups were absolute novices on the three gestures before the training and gained an equivalent amount of knowledges and capacity to perform the gestures after three weeks of one hour hebdomadal training. These results only permitted to conclude that, in our experimental setup, the media did not influence the global external performance observed by a human expert. Consequently, we can think that the learning environment with a virtual human provided the necessary information for an individual to attain a level of competencies on the three gestures equivalent to the level attain by other individuals learning from a video or a traditional environment.

However, these results provide no information about the specificities of the knowledge of the gesture. The global performance might be equivalent, but different groups might have progress differently on diverse performance criteria. Furthermore, external measures of the performance does not provide any information about the internal states of the learners. Two learners might performed at an equivalent degree of competencies but be at two different states in their appropriation of the gesture, that might largely influence their future progress on the learned skill. External performance neither gives information about the motivation of the learners. Learners willingness to further ameliorate their performance can potentially influence their learning process.

Consequently, in that second study, we proposed to refine the evaluation methods. In a first time, we established a precise list of performance criteria. In the first study, the expert used a simple grid (see section 7.1) on which he took notes and gave a final grade out of ten. In that study, each of the performance criteria was graded on a Likert scale from 1 (not at all) to 7 (perfectly) and a global note was attributed on the same scale (see section 7.2 for detailed grids). Moreover, we asked a second expert to grade the same performances. We wanted to ensure that different experts will arrive to similar conclusions. Finally, we performed evocation interviews after the first and last training in order to gain insights of the participants internal states.

We applied these new evaluation methods on two different virtual learning environments. The first one is the virtual environment described in the first study. The second virtual environment is augmented with a virtual "mirror" displaying the participant motion in realtime. This new virtual learning environment is described in section 4.2.1. The subsequent section (4.2.2) further detailed the new evaluation methods. The results of the different evaluation methods are presented individually in section 4.3 and discussed in interrelation in section 4.4.

4.2 Methodology

In this study as in the first one, the task of all the participants was the same: follow a lesson given by an instructor about three karate gestures. That had to be done during three hebdomadal one hour sessions of training. The lesson was the same for all participants and for the three weeks, it is the lesson described in section 2.1.2 and illustrated in figure 2.4. Two different virtual environments were used, one is the virtual environment described in section 2.1.3 and the second one is the virtual environment augmented by a mirror that displays the action of the participants in the form of a gray mirrored avatar. That environment will be described in the following sections. The participants using the second environment therefore had the possibility to regulate their action by observing their mirrored avatar. The only thing in the training protocol that differs from the first experiment, is that the mirror group had an habituation period of 5 minutes at the beginning of the first training where they discover their mirror avatar and were invited to play with it to realize that it was moving in response to their action.

The aim of that second study was twofold. First, we wanted to evaluate if the different learning environments had an influence on the after training performance of the gestures, as it was the case in the first study, but also on a detailed list of performance criteria describing each of the three gestures. That was done by having two karate experts grading the participants performance. As it was the case for the first study, the grading was performed from video recordings of the pre and post performances of the participants. Second, we wanted to understand the participants engagement in the task and the influence of the learning environment on that engagement. That was done using the evocation interview as described in section 4.2.2.2.

4.2.1 Mirror Feedback

We chose the mirror metaphor because realtime visual feedback of the users' motion in diverse form of shadows, avatars representing the user, or mirrors is frequently used in recent exergames **??**. Furthermore, as discussed in section 1.1.4 mirrors have been largely studied as immersion and presence factors in virtual environments [González-Franco2010, Knox2009, Hämäläinen2004]. Mirrors are also common tools, used in some sports to facilitate the learning of postures and gestures. In that study, we therefore wanted to assess if and how the participants learning in the virtual environment would used the mirror, how they would perceived it, and if that would influenced their performance of the gestures after the three weeks of training.

4.2.1.1 Real-Time Full Body Motion Tracking and Mapping

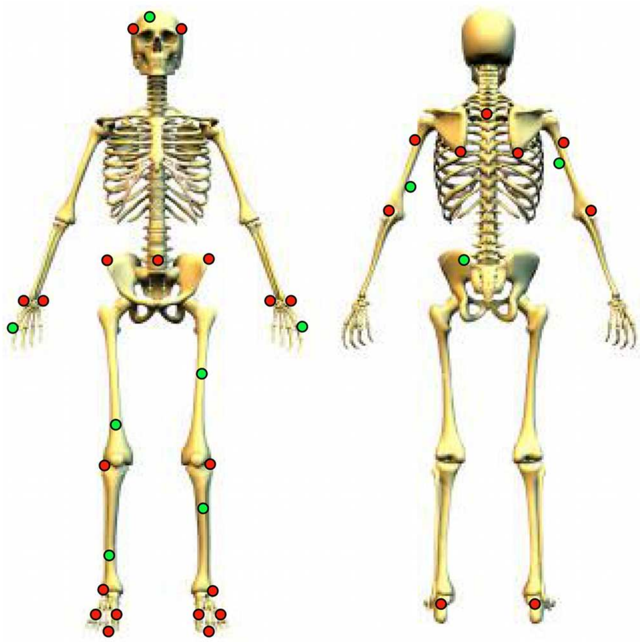
In order to provide the users with realtime feedback of their motion, we needed to capture and map these in realtime. We chose to use optoelectronic motion capture for its degree of precision and accuracy because the quality of the reproduction of the motion of the users is the most important factor in the context of learning motor skills. Tridimensional stereoscopic realtime video reproduction like that used in Patel et Al. [Patel2006] could arguably be more realistic but it was not a technology available to us. Furthermore, other systems based on computer vision like the Microsoft Kinect do not permit to render precisely the tridimensional motion of the users.

We could have used the Vicon system like it was the case for the motion capture of the instructor, but we preferred to use the Natural Point's Optitrack system which is also precise to the millimeter. It is lighter in term of cost and usage for realtime applications. The data was captured in realtime by a ten v100:R2 cameras installation. The cameras captured the reflective markers in the scene at a speed of 100 frames per second with a resolution of 640 x 480 using Arena 1.7.0 software. The markers placement respect the 38 markers placement presented in the video tutorials available on Natural Point website (http://www.naturalpoint.com/optitrack//products/arena/tutorials.html) and is illustrated in figure 4.1. We used the reflective markers fasten with wig adhesive directly on the skin when possible or otherwise on the participants clothes. Hands markers were placed directly on the skin, we didn't used the Optitrack handsets. The markers were placed on the participants after the warmup. An Arena skeleton was created for each participant at each training session after the markers placement during the calibration step. The skeletons therefore precisely correspond to the participants' morphology.

The data captured by Arena was sent to XVR using the UDP protocol. Arena acted as a UDP server sending data to a unicast IP and port address. XVR received the data throughout a client application developed at the Event Lab Barcelona and based on the Natural Point NatNet 2.2 SDK. The client application transmitted the data to XVR in the form of translation vectors and rotation quaternions.

The mirrored avatars were created at the beginning of each training session by asking Arena to send the skeleton information. The mirrored avatars were built in realtime from that information. The created skeleton has 24 bones. Each of the bones was drawn using cylindrical shapes of the dimensions of the corresponding Arena's bones and were therefore corresponding to each participant's morphology. Articulations were represented by spheres. The foot and hands of the participants were represented by flat rectangular shapes in order to be able to observe their rotation. The head was represented by a sphere. We chose to represent the participant avatar using shapes only in order to be able to map the motion precisely to the bones. Adapting motion from different participants to an avatar with a fix morphology or inversely adapting a graphically complex avatar to different morphologies are complex and actually not completely solved problems. In this study, we deliberately chose motion fidelity over graphical fidelity because it is important that the feedback received by the participant precisely correspond to his motion.

Figure 4.2 displays the animation loop of the mirror version of the virtual learning environment.



(a) Theoretical Placement

(b) Effective Placement on a Participant

Figure 4.1 - Optitrack's Arena 38 Markers Placement

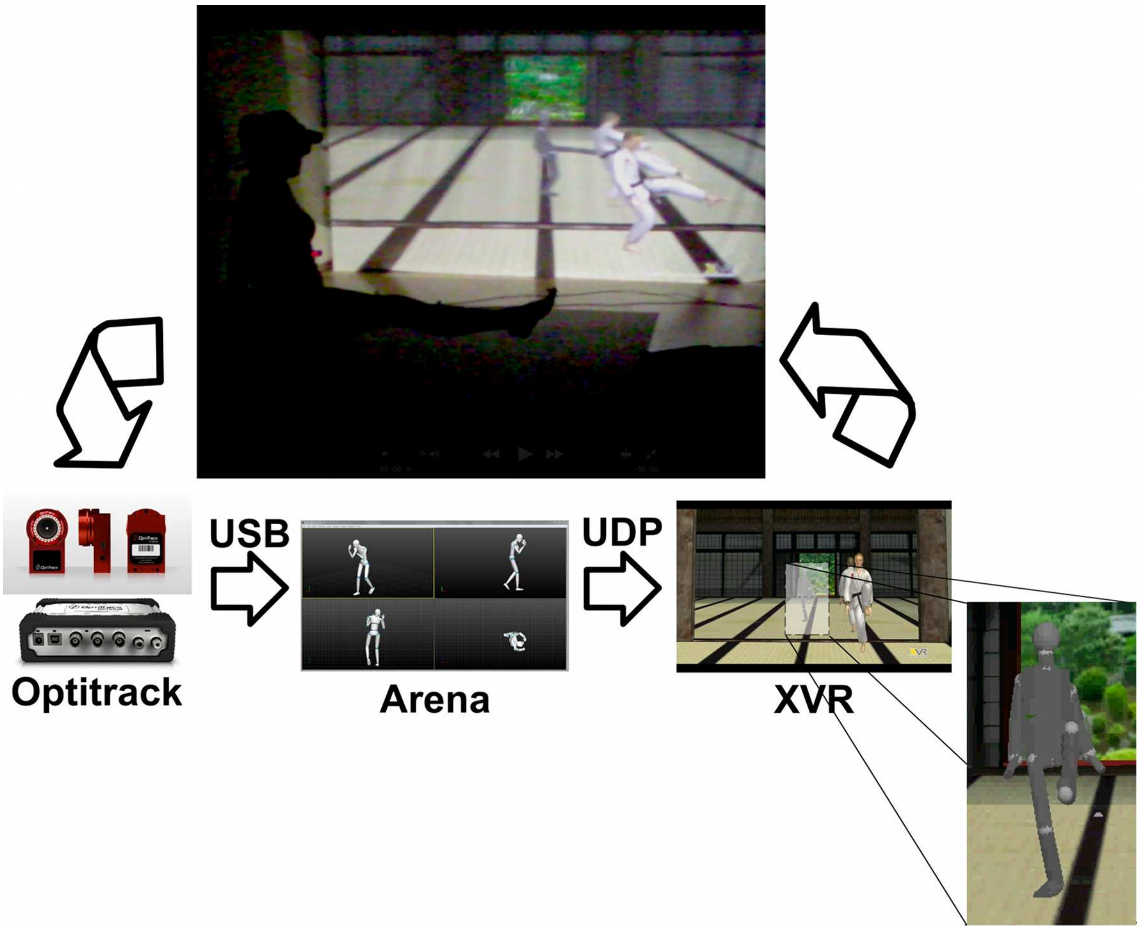


Figure 4.2 - Second Study Schematic Loop

Information about the reflective markers placed on the participants was captured by the Optitrack system. That information was send to the Arena software that uses the markers spacial position to animate the skeleton created for each participant. That skeleton information was sent to XVR that uses it to animate the participant mirrored avatar in the virtual environment. That avatar was displayed in the environment in the mirror that was at the back of the instructor. The virtual environment was projected on a screen in front of the participant. The instructor was in real size dimension. The participant sees the environment in tridimensional stereoscopic egocentric vision throughout the usage of stereoscopic glasses and head positioning. That technological setup is the same that was used in the first experiment and was explained in more details in section 2.1.3.3.

4.2.2 New Evaluation Methods

4.2.2.1 Refinement of the Expert's Evaluation Grid

In this study we wanted to detail how the evaluator graded each participant. This had two main objectives:

1. It permited to have a more detailed portrait of the performance. Therefore, it outlined aspects of the learning that could differ from a learning environment to another. An hypothesis might be that learners in the virtual environment augmented with a mirror, will performed better on postural criteria since they have a visual feedback on which to adjust their posture.

2. It permited to establish a precise list of criteria that could later be used to create an automatic grading system. If feasible, an automatic grading system might be really useful since it will not be sensible to inter-evaluators and even intra-evaluators variation. Discrepancies among evaluators and even between two gradings of the same evaluator are well documented phenomena.

With the concourse of the expert instructor, we established a detailed list of performance criteria for each of the three gestures. These performance criteria are closely related to the instructions the instructor gave about each gesture in the explanation part of the lesson. They are a formalization of the criteria he intuitively used when grading the performance of the first study.

We divided these lists in categories of criteria. Some of the criteria are postural and concern the starting and ending part of the gesture only or different phases of the gesture, other postural elements should be respected during all the duration of the gesture. Finally, some of the criteria are linked to the execution of the gesture or to the repositioning between two executions of the gesture since in our setup, gestures are evaluated in series of ten repetitions.

"Gesture while" performance criteria concern elements like the standing stance, the feet position on the ground, the relaxation of the upper body and of the shoulders, the trunk posture and the alignment of the fists with the forearm. They are related to the global posture that should be kept during the gesture execution. Starting and ending performance criteria together with phases performance criteria are related to posture and position of different limbs of the body at specific moments of the gestures. It could be, for example, the arrival of a punching gesture with the arm straight and stretch with the fist looking down, centered at the sternum at a specific height. Finally, execution performance criteria are related to the kinematic of the gesture, the gesture in motion. They are criteria like the arm or leg trajectory, the execution speed, the synchronization of the different limbs, the rotation of the wrist and the motion of the hips. The synchronization of the breathing with the execution of the movement, was listed but both evaluators agreed that it was not possible to grade this criteria from a video recording of the performance. The detailed lists of performance criteria for each of the three gestures are presented in appendix section 7.2.

4.2.2.1.1 Multi-Evaluators Comparison

However, evaluation by experts, as any human activity, is subject to bias due to the human nature. The same evaluator can grade differently the same performance at two different moments of time, and will probably not grade the last performance he evaluated the same way he had grade the first. A common practice in that case is to have many evaluators randomly grade the same performances and to observe tendencies.

We think that a minimum of three to five evaluators would have been ideal but due to the small pull of karate experts available and the time required by the task (each evaluator took 12 to 15 hours of his spare time to grade the ensemble of performances), we were able to have two only. We wanted the evaluators to be of the same school as the instructor to ensure that the performance criteria would be understood and grade the same way. Patel et Al. [Patel2006] also had two evaluators grading performances in their study, but they were not experts and were trained to grade performance only for the purpose of their experiment. We think it is extremely important that evaluators be experts of the domain since they are used throughout many years of practice to recognize subtleties in the performance of the gestures to evaluate.

Both of our evaluators are experts of the domain. At the moment of the study, they had more than 7 years of deliberate practice of karate and had attained the black belt level. They were both karate instructor recognized by their peers and by the JKA and both had already performed in international level competitions.

Each evaluator received the ensemble of performances together with the evaluation grids. The performances were organized by gestures and by evaluation. There was one video of each participant for each of the gestures. The video comprised a series of ten repetitions in front view and a series of ten repetitions in side view as explained in section 3.2.2.1. The evaluators were free to replay the video as many times as they need to grade each performance criteria and the global performance. Each of the evaluator received the video prepared in a different random order mixing the two groups (with and without mirror). The evaluators didn't knew which participants were in which groups. Evaluators performed the grading at their own pace during their spare time.

4.2.2.1.2 Validity of the Grading Scale

In order to assess the validity of the grading scale, we also asked both evaluators to grade the performance of five JKA black belt level karatekas. According to the JKA standards, a karateka can attained the black belt level only if he mastered the basic techniques. These basic techniques evidently include the three gestures used in our experiments. The black belt level is usually attained after many years of deliberate practice. The black belt is acquired by attaining an evaluation performed in front of one or more sensei (karate master) and other black belt karateka of the dojo. All the karateka that were evaluated to represent the "expert" level of our grading scale had more than x years of practice of karate, were aged between x and x years old and had already participated in international level competitions. The results of that comparison are discussed in section 4.3.1.4.

4.2.2.2 Evocation Interview

The purpose of the evocation interviews is to describe the learning activity from the point of view of the participants. To describe the activity, we are interested in the manner the participant imitated the gesture presented by the virtual instructor and eventually progressively build its internal representation in an appropriation process. The evocation interview are used to identify the intentional and the perceptual elements of the movement of the participant throughout his description of the manner he performed the gesture and throughout the meaning he give to his activity.

The interview is an accompaniment of the participants in the evocation of a lived experience [Vermersch2003]. The objective is to have the participants talk about their cognitive and motor acts, their goals in the action, the elements (visual, auditive, tactile and kinesthetic) they used in the action and the internal states (emotion, judgment, evaluation) they built in the course of the trainings. In the participants discourses, we tried to identify an evolution in the realization of the task. If learning occurred, the gesture description should be personalized in part or in integrity. In order to correspond to the participants perception of the actions, the description should evolve from a description based on the instructor words and formulations to a description in the participant words. The control mode of the motion should also evolve from a visual information retrieval in the environment to a proprioceptive control of the gesture based on sensation.

Finally, another objective of the interviews is to identify the role of the virtual learning environment in the participants' learning task. The answers provided by the participants will lead our reflections on the virtual environment characteristics and their constrains on the learning task.

4.2.2.2.1 Interviews Methodology

The Interviews Context

The interviews were performed immediately after the first and third training session. Each interview lasted between twenty minutes and one hour. The interviews were recorded with the agreement of the participants. All the interviews were transcribed in extenso with the pauses, silences and sounds permitting to identify the gestures accompanying the discourse.

The Leading of the Interviews

The principle of the evocation interviews is to have the participants freely speak of the experience they just lived. Therefore, the interview leader should not direct the conversation, but accompany the participants to talk about specific aspects of their experience:

- have them describe the learning task associated to seach of the three gestures;
- Orient them to go further the instructor description of the gestures and have them described their own perceptions and sensations of the gesture by using their own words;
- At the third session, have them describe their impression of progress in the performance

of the gestures, but also explore the internalization process inherent to the learning task;

- have them talk about the virtual environment and the capacitating elements of the environment.

The Two Parts of the Interviews

The interviews are divided in two parts. The first part concerns the description of the learning task. The role of the interview at that point is to guide the participant in his description of his activity. From that first description, the second part of the interview consist in having the participant refine his discourse by contextualizing his learning task and explaining the manner he learned in that context. The goal is to know how the virtual environment and the constrains of the study where resources or not for the learning.

Interviews' Transcription Treatment

The main objective of the interview treatment is to identify the learning task description and its structure.

In a first time, elements of the discourse related to the learning task and its context should be isolated and arranged in a table. The elements related to the actions are ordered in the left column and the comments accompanying and eventually justifying these actions are ordered in the right column. That way, the left column represents the learning chronology and its regulation. While the right column gives insights on the justification of the actions, the actions' goals and the reasons and justifications of the regulations choices.

Usage of the Left Part of the Table

In the treatment of the left column, it is assumed that the language and words used in the description of the gestures are indicators of their internalization. As an example, if the interviewer ask the following question: "can you tell me about the gesture you were doing at that moment?"

- If the participant repeats the description of the gesture with the instructor words, it can be assumed that the participant has memorized the process as explained by the instructor and that he uses his procedural memory. From that, two interrogations can be raised: 1) Is the participant able to perform the actions he has described? 2) Is the participant evoking what he really did or is he just answering the question?

- If the participant speaks at the first person using action verbs, it can be assumed that he is really talking about an action he performed or at least, he described the action has he think he had performed it.

- If the participant speaks at the first person using perception words like "I feel", it can be assumed that the participant is talking about perception he felt during the action and that he used to control and regulate his gesture.

- If the participant speaks at the first person using vocabulary related to the senses (I see, I hear), the sensorial elements he used to perform the action can be identified.

- If the participant speaks at the first person using vocabulary related to memorization like "I think", it can be assumed that he bases his discourse on the representation of the gesture he mentally built.

Usage of the Right Part of the Table

When the participant describes his action, two possibilities occur: 1) he describes what he intended in his performance of the action 2) he describes, from his point of view, what he effectively did. The participant description is often completed by comments on his actions. Some of these comments interest that research and complement the elements identified in the left part of the table. These element are organized in the right part of the table.

In a second time, a table is built for each of the three gestures of each of the participants. These table summarizes each of the categories of items collected in the content analysis. These categories are:

1. The description of the learning task from the participants point of view;
2. Their goal in the action: what the participants were trying to do during the lesson;
3. The perceived elements: what the participants observed, heard or sensed, what they used in the environment to build their action;
4. Their internal states: how the participants felt, what they thought and which decisions they took during the action.

4.3 Results

4.3.1 Evaluation by Experts Results

The following sections summarize the results of the evaluation of the performance by expert evaluators. Performance criteria are grouped in categories of criteria and represented on star diagrams. Each categories are illustrated by 3 stars. The first star represents the progression from the initial evaluation to the final evaluation of the group of participants training in the virtual environment without mirror. The second star represents the same progression for the group training in the virtual environment with the virtual mirror. The last star presents the results of the final evaluation for the two groups.

Although observing a low evaluators interreliability, Patel et Al. [Patel2006] made the choice of using the average grades of their two evaluators to discuss their results, we think it is more advisable to discuss tendencies in the evaluation rather then score themselves. For that reason, the stars displayed in the following sections present the results of the first evaluator. Detailed results with error bars and degrees of significance for the two evaluators can be found in the appendix section 7.3. The explanations of the star diagrams will be articulated on observing tendencies among the two evaluators about the progression of the participants and about the comparison of the final scores of the two groups. We will also discuss discrepancies between the two evaluators when they occured. Differences in the delta (post - pre evaluation results) among the two groups and evaluators will also be presented when it is statistically significant.

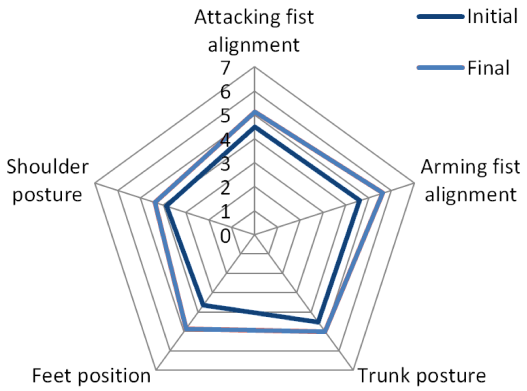
4.3.1.1 Tsuki

The first set of results presented in figure 4.3 concerns the gesture while performance criteria, that means performance criteria that should be kept during all the performance of the gesture. That mostly concerns postures, like the placement of the feet on the ground and the upper body relaxation. That also concerns the alignment of the two fists with the forearm.

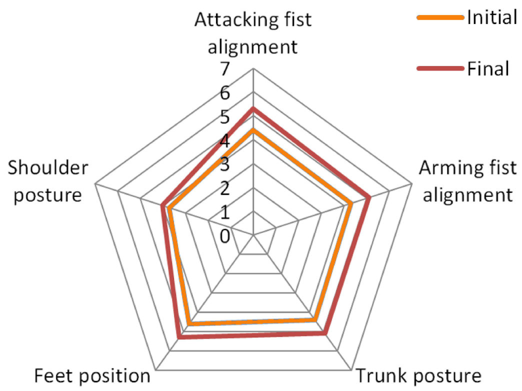
These elements are relatively easy for the punching gesture, therefore both group already started with high scores at the pre-training evaluation. Their starting level is equivalent according to both evaluators except for the feet position, that first evaluator graded lower for the without mirror group.

A progression between the pre-training and post-training evaluation can be observed for all the criteria except the shoulder posture in the case of the second evaluator. The second evaluator observed a statistically significant progression of the fists alignments and feet position for both groups. The first evaluator only observed it for the arming fist. For the feet position, the first evaluator only observed progression in the case of the without mirror group that had started to a significantly lower level than the mirror group.

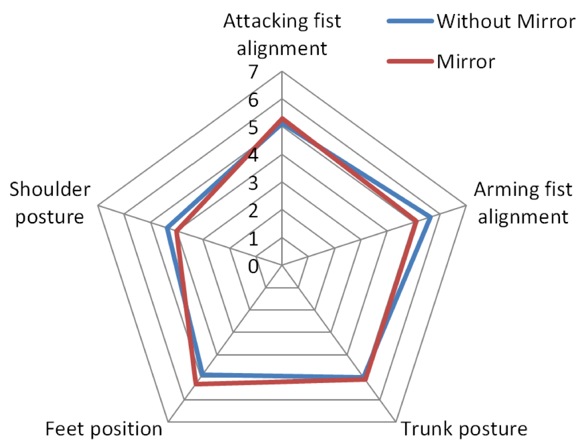
The second evaluator observed a final score significantly higher for the trunk posture in the case of the mirror group. Otherwise, both groups finished with equivalent scores. Neither of the two evaluators observed a significantly different improvement (delta of the pre and post evaluation) of the two groups on any of the performance criteria.



(a) Progression of the Without Mirror Group



(b) Progression of the Mirror Group

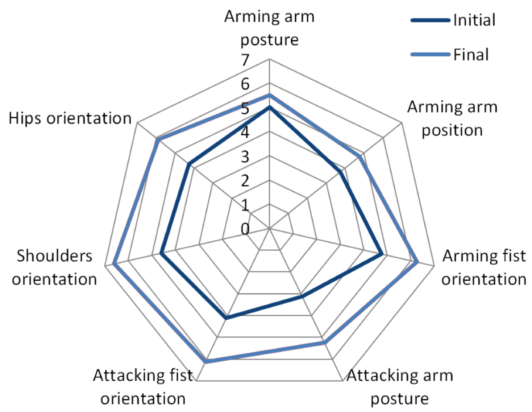


(c) Comparison of the Final Results of the 2 Groups

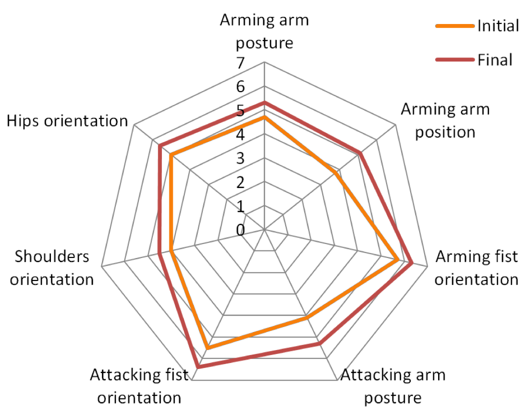
Figure 4.3 - Tsuki Gesture While Postural Performance Criteria Evaluated by Expert 1

The starting and ending postural performance criteria concern the departure and arrival posture of the gesture, the arrival of one laterality being the departure of the other in the case of the gesture repeated in series. That concerns the fists positions and orientations in space, together with both arms postures and the hips and shoulders orientations. Results for this set of criteria are illustrated in figure 4.4.

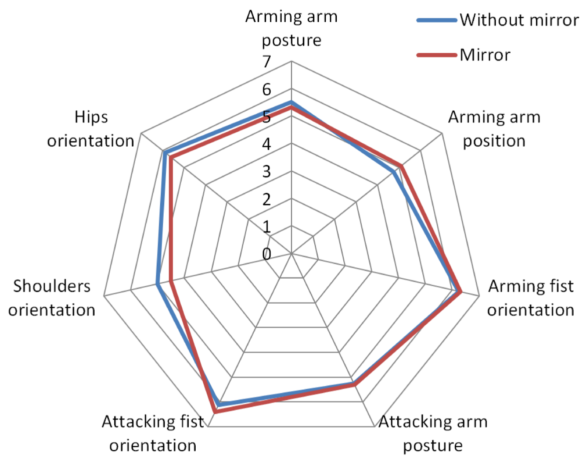
The mirror group performed slightly better at the pre-training evaluation on some of the performance criteria although this difference is significant only in the case of the arming arm posture according to the second evaluator and in the case of the attacking arm and hips orientation according to the first evaluator. Both groups progress between the pre and post evaluation on all the criteria. This progression is statistically significant for both groups in the case of the arming arm position and the attacking arm posture according to the first evaluator and in the case of the attacking arm posture and position and the shoulders orientation according to the second evaluator. The without mirror group also progress significantly on their fists and hips orientations according to the first evaluator and on their arming arm posture and position according to the second evaluator. That might be due to the fact that they had started with lower grades. In the case of hips orientation, the first evaluator grade a significant progression of the group without mirror, as the second evaluator grade a significant progression of the opposite group. However, no significant difference is observed in the improvement nor in the final scores of the two groups on all the performance criteria.



(a) Progression of the Without Mirror Group



(b) Progression of the Mirror Group



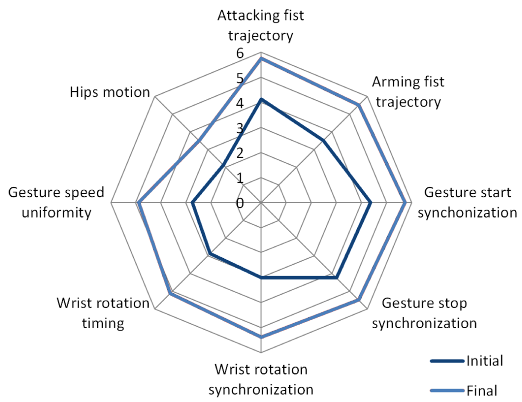
(c) Comparison of the Final Results of the 2 Groups

Figure 4.4 - Tsuki Starting and Ending Postural Performance Criteria Evaluated by Expert 1

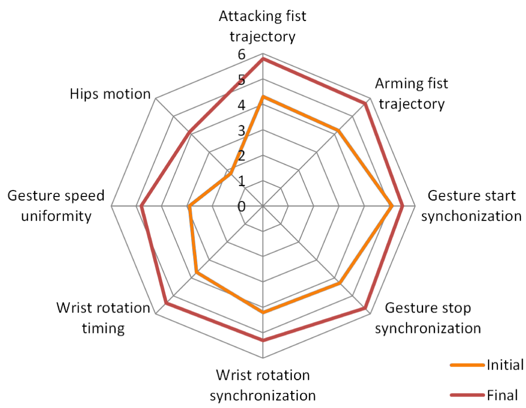
The execution performance criteria are the performance criteria related to the gesture in motion. They are all the performance criteria related to the trajectories and rotations, synchronization and speed together with hips movement. Results for this set of performance criteria are presented in figure 4.5.

Once again, the mirror group starts with a slight advantage on some criteria, but that is significant only for the trajectory of the attacking arm according to the second evaluator and for the synchronization of the wrists rotation according to the first evaluator. Both groups progress on all the criteria in a significant manner according to both evaluators, except for the mirror group on the gesture start synchronization criterium according to the first evaluatorand the without mirror group on the wrists timing and the gesture speed criteria according to the second evaluator. The second evaluator didn't notice any progression for any group on the hips motion.

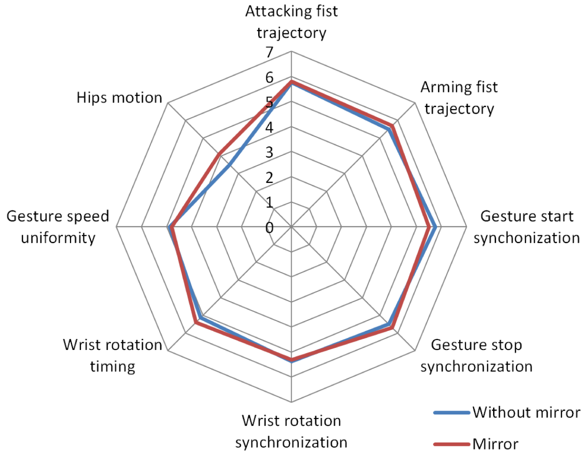
There are no significant difference on the improvement nor on the final scores of the two groups according to both evaluator. The first evaluator observed a significantly greater improvement than the second evaluator on the wrists rotation timing, the speed uniformity and the hips motion criteria. Nevertheless, that observation is similar for both group, that therefore probably denote a different way of grading these criteria.



(a) Progression of the Without Mirror Group



(b) Progression of the Mirror Group



(c) Comparison of the Final Results of the 2 Groups

Figure 4.5 - Tsuki Execution Performance Criteria Evaluated by Expert 1

Globally, both groups improved in similar ways on all the criteria and on the global score. Even if the mirror group start with a slight advantage on some criteria, that has no influence on their final results. Both evaluators agree on most criteria grading and observed the same tendencies, although the first evaluator generally grade higher. The first evaluator also observed a significantly higher improvement on the global score than the second evaluator.

From these evaluations, we cannot conclude that a group has improved more than the other, we can only assess that they were both beginners on the gesture and that they both improved their performance.

4.3.1.2 Mae Geri

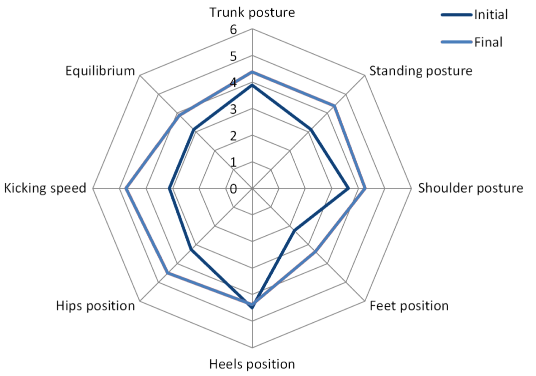
The first set of stars for the mae geri presents the gesture while postural criteria and the gesture execution criteria. As it was the case for the punching gesture, the gesture while performance criteria of the kicking gesture concern the postural criteria that should be kept during all the gesture execution, they are the upper body (trunk and shoulders) and the standing (legs and gravity center) postures together with the positions of the feet and heels on the ground. The execution criteria concern the gesture in motion, namely the kicking speed and the equilibrium.

As it can be observed in figure 4.6, the mirror group scored slightly higher both at the initial and final evaluation. However, this difference is statistically significant only in the case of the shoulders posture according to the second evaluator for the initial evaluation and for the feet position also according to the second evaluator on the final evaluation.

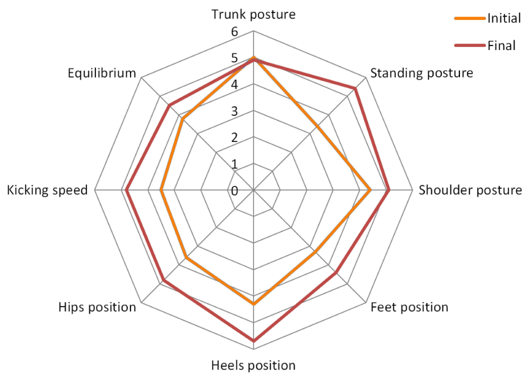
Both groups progress on all the criteria excepts the mirror group that graded high at the initial evaluation for the trunk posture and stayed at a similar level at the final evaluation. A similar situation occurred for the without mirror group on the heels position criterium. The progression is statistically significant in the case of the feet position according to both evaluators. It is also significant in the case of the standing posture, the hips posture, the equilibrium and the kicking speed according to the first evaluator and in the case of the heels position according to the second evaluator. The second evaluator also noted a significant progression of the mirror group for the standing and the trunk posture and for the kicking speed. On the other hand, he noted a progression of the without mirror group on the shoulders posture. However, there is no significant difference among the groups in the improvement on any criteria according to both evaluators. There is also no significant difference among the group for the final scores except for the foot position where the second evaluator observed a significantly higher performance of the mirror group.

Figure 4.7 presents the score of both groups for the initial and final evaluation on the criteria relative to the different phases of the kicking gesture. These performance critteria are related to intermediate moment of the gesture and are mostly positional and postural criteria. For these criteria, both groups start at equivalent level. The only significantly different scores are at the advantage of the mirror group in the case of the foot posture in the kicking phase according to the second evaluator and the foot position again in the kicking phase according to the first evaluator. Both groups significantly progress on all criteria except the without mirror group on the foot posture in the kicking phase according to the first evaluator and the mirror group on the same criteria according to the other evaluator.

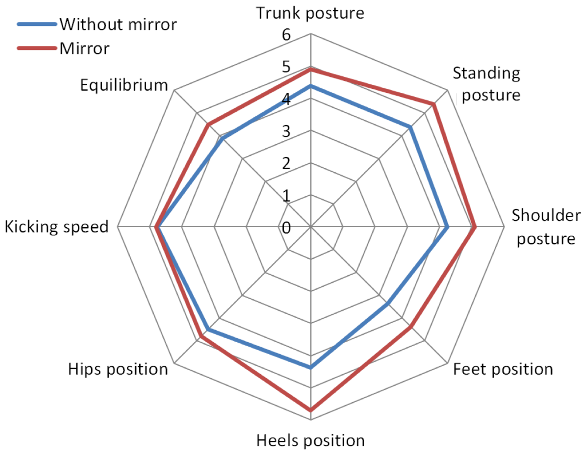
The final scores are not significantly different for any criteria except for the foot position in the kicking phase, where the mirror group score higher according to the first evaluator. However, the same evaluator had also grade higher the initial performance of the same group on that criteria. The improvement scores for all groups and evaluators are not significantly different on



(a) Progression of the Without Mirror Group

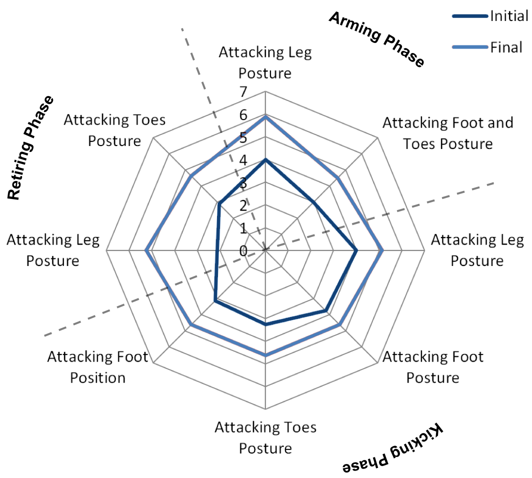


(b) Progression of the Mirror Group

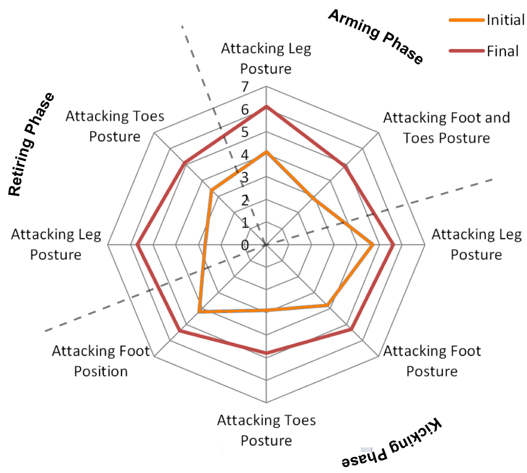


(c) Comparison of the Final Results of the 2 Groups

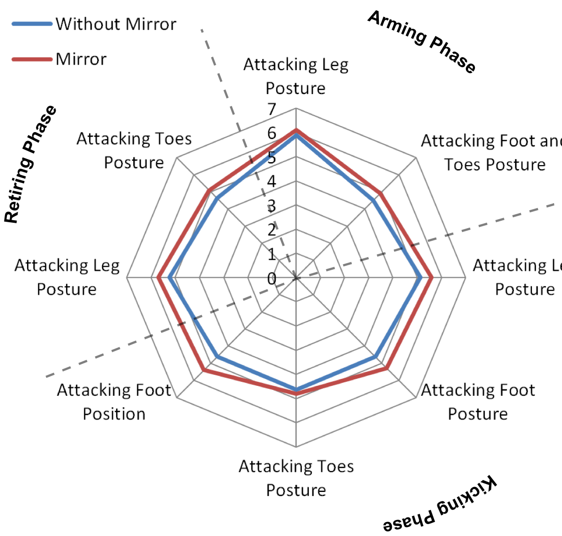
Figure 4.6 - Mae Geri Gesture While and Execution Performance Criteria Evaluated by Expert 1



(a) Progression of the Without Mirror Group



(b) Progression of the Mirror Group



(c) Comparison of the Final Results of the 2 Groups

Figure 4.7 - Mae Geri Gesture Phases Performance Criteria Evaluated by Expert 1

any criteria.

In term of their global grade, both group started at an equivalent level and both group significantly progress. There is no significant difference on both group improvement. However, the first evaluator observed that the final level of the mirror group is significantly higher than that of the without mirror group. Once again, we observed that both evaluator graded in a different manner but with similar observations. The first evaluator observed a significantly greater improvement than the second evaluator on some criteria but as it was the case for the tsuki, these observations are true for both groups so that does not favored a group against the other.

As is was the case for the tsuki, the observations of both evaluator do not permit to conclude that one group or the other has progressed more. We can only conclude that both groups were beginners and have improved their performance due to the training.

4.3.1.3 Soto Uke

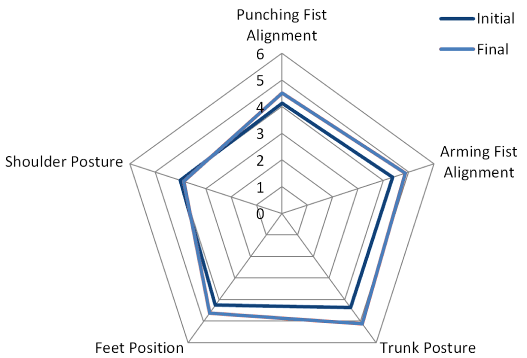
The gesture while performance criteria for the defending gesture are globally the same as for the punching gesture. As it can be observed in figure 4.8, both groups started at an equivalent level at the initial evaluation and both also finished at an equivalent level. The first evaluator only observed a significantly higher score for the mirror group on the final evaluation for the shoulders posture criteria, otherwise there is no significant difference among the scores of both groups for both evaluations.

Both groups progressed in nearly all the criteria except the without mirror group on the shoulders posture criteria. This progression is significant for both groups on both fists alignment according to both evaluators, on the feet position according to the second evaluator, and on the trunk posture according to the first evaluator. The second evaluator also noticed a significant progression of the mirror group on the trunk and shoulders posture. The first evaluator observed that significant progression of the mirror group on the shoulder posture and also noticed a progression on the mirror group feet position. However, there is no significant difference among the groups on the improvement for any of the performance criteria.

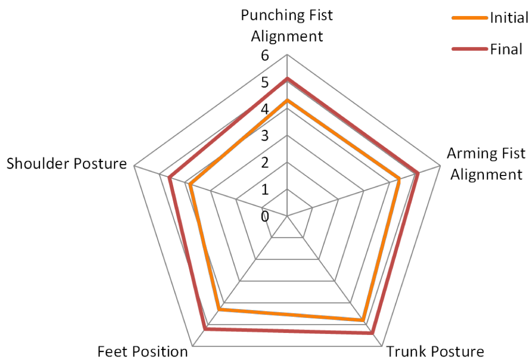
The gesture start postural performance criteria are all the criteria related to the positions and postures of the body and the different limbs at the beginning of the gesture. In the case of the defense gesture, these are not the same as the arrival criteria. When performed in series, as it is the the case in our evaluations, a repositioning phase is necessary between the end of a gesture and the start of the next one.

As it can be observed in figure 4.9, the mirror group scored higher than the without mirror group at the initial evaluation. According to the first evaluator, this difference in significant in the case of all three criteria concerning the arming arm and fist and in the case of the punching arm posture. However, the second evaluator did not observed that significant difference. The first evaluator observed a significant progression of both groups on all the criteria except the arming arm position where a none significant progression is observed. The second evaluator observed a significant progression on all the criteria except the shoulders and hips orientation where he observed practically no progression.

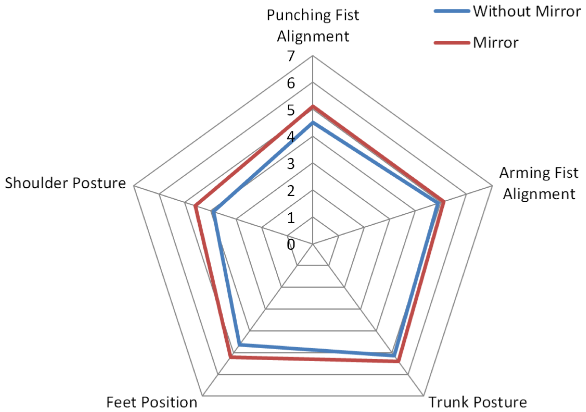
None of the two evaluators observed a significant difference in the final scores except the first evaluator on the arming fist position at the advantage of the mirror group. There is no significant difference in the observed improvements on all the criteria, except in the case of the arming arm posture and fist orientation where the first evaluator noted a significantly greater improvement of the without mirror group. However, since that group started at a significantly lower level,



(a) Progression of the Without Mirror Group



(b) Progression of the Mirror Group

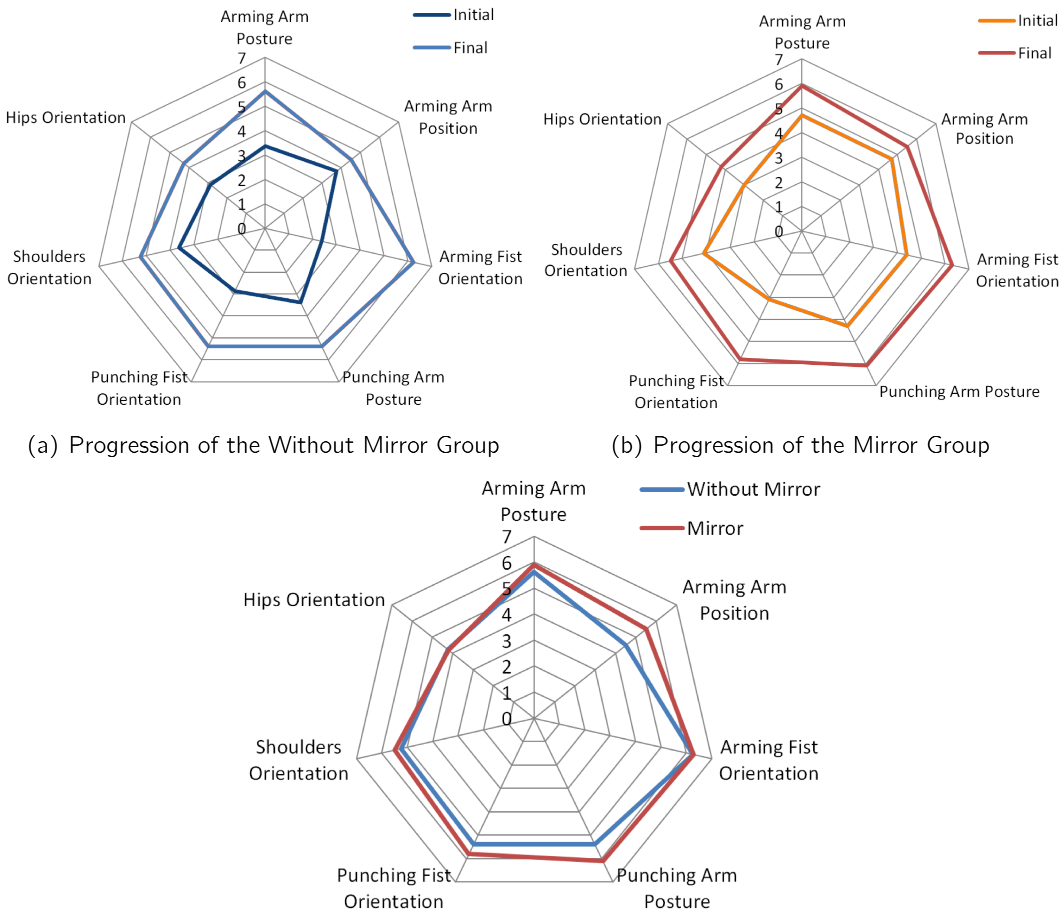


(c) Comparison of the Final Results of the 2 Groups

Figure 4.8 - Soto Uke Gesture While Postural Performance Criteria Evaluated by Expert 1

it is hard to conclude if they progress more because they had more space for amelioration or because their learning was actually more efficient.

A difference in the grading method between the two evaluators can be observed on these criteria were the first evaluator grade a significantly greater improvement than the second evaluator on four out of seven criteria (punching arm and fist criteria and shoulders and hips criteria) for both group and on two other criteria (arming arm posture and fist orientation) for the without mirror group.



(a) Progression of the Without Mirror Group

(b) Progression of the Mirror Group

(c) Comparison of the Final Results of the 2 Groups

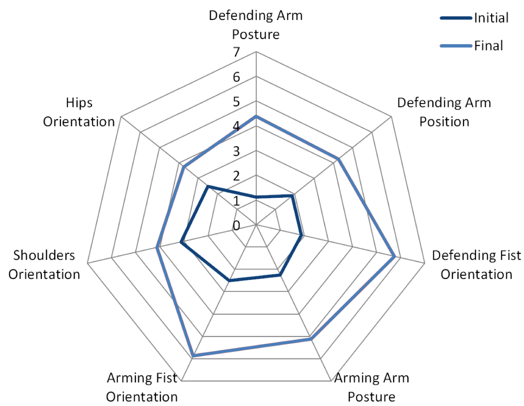
Figure 4.9 - Soto Uke Gesture Starting Postural Performance Criteria Evaluated by Expert 1

The gesture end postural performance criteria are all the criteria related to the positions and postures of the body and the different limbs at the arrival of the gesture. As it was the case and the gesture start criteria and as it can be observed in figure 4.10, the mirror group scored higher at the initial evaluation on many criteria. That difference is significant according to both evaluators in the case of the defending fist orientation and in the case of the defending arm posture and position according to the first evaluator only.

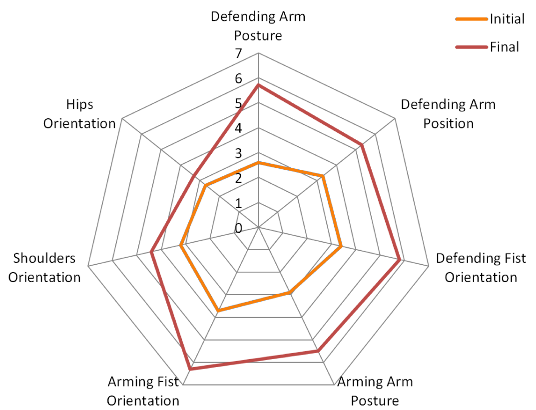
The first evaluator observed a significant progression of both groups on all the criteria except for the mirror group on the hips orientation criterium. The second evaluator observed no progression of the two groups on the hips orientation, but did observed a significant progression on all the other criteria except for the without mirror group on the defending arm position and the shoulders orientation criteria.

Both evaluators observed a significantly better performance of the mirror group for the defending arm position on the final evaluation. The first evaluator also observed that tendency on the defending arm posture, as the second evaluator observed it on the shoulders orientation. There is not significant difference on the improvement on all the criteria according to both evaluators, except on the defending fist orientation according to the first evaluator.

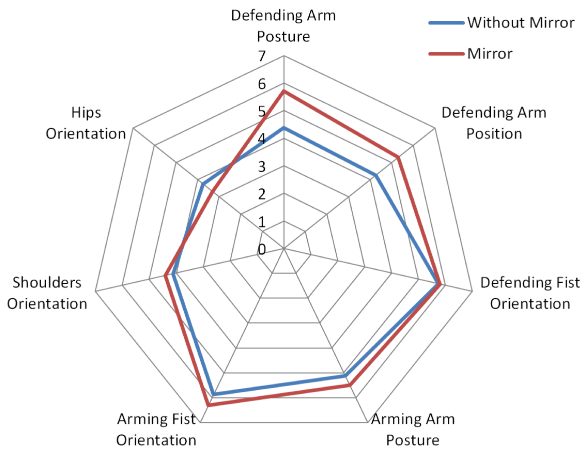
As it was the case in the gesture start criteria, a difference in the grading method between the two evaluator can be observed. The first evaluator grade significantly greater improvements five criteria out of seven (all except hips and shoulders orientation) for both groups and on another criteria for the without mirror group (hips orientation).



(a) Progression of the Without Mirror Group



(b) Progression of the Mirror Group



(c) Comparison of the Final Results of the 2 Groups

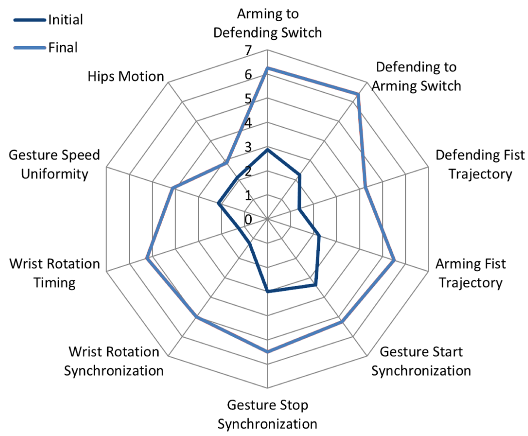
Figure 4.10 - Soto Uke Gesture Ending Postural Performance Criteria Evaluated by Expert 1

As illustrated by figure 4.11, the last stars regrouped the execution and the repositioning performance criteria. All theses criteria are related with the gesture in motion and are therefore linked to trajectories, rotations, synchronizations and speeds. Once again, a superiority of the mirror group can be observed at the initial evaluation. Both evaluators agreed on the fact that that superiority is significant in the case of the switch from defending to arming position of the arm, on the trajectory of the defending arm and on the synchronization of the beginning and ending of the translation of both arms. The first evaluator also observed it on the wrists rotation timing, as the second evaluator observed it on the switch from arming to defending position of the arm and on the synchronization of the rotation of the wrists.

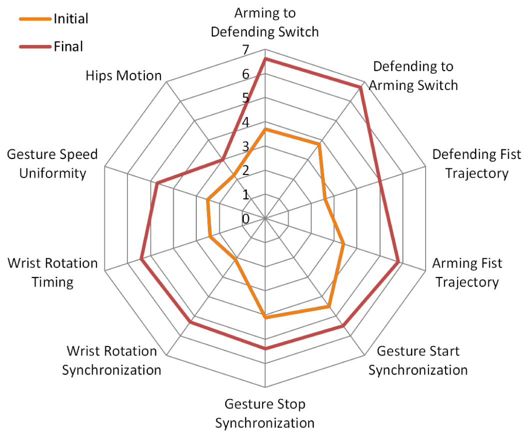
However, according to both evaluators, both groups significantly progress on all the criteria except for the hips motion where the second evaluator did not observed a significant progression of neither of the two groups. There is no significant difference on the final scores of both groups for both evaluators on all the criteria. In term of improvement, the second evaluator did not observed any significant difference among the two groups.

Otherwise, the first evaluator observed a significantly greater improvement of the without mirror group in the case of the switch from defending to arming position of the arm, the synchronization of the ending of the translation and the timing of the rotation. As previously, that observation is outbalance by the fact the the mirror group already performed better on these criteria before any training.

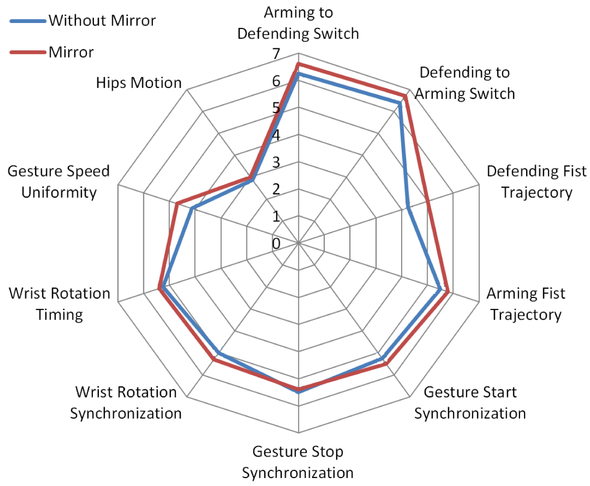
A difference in the grading method among the two evaluators can be observed. The first evaluator graded a significantly greater improvement than the second one for both groups on four out of eight criteria (both trajectories and rotation synchronization and timing) and on two other criteria, one in favor of the without mirror group (translation end synchronization) and one in favor of the mirror group (speed uniformity).



(a) Progression of the Without Mirror Group



(b) Progression of the Mirror Group



(c) Comparison of the Final Results of the 2 Groups

Figure 4.11 - Soto Uke Gesture Execution Performance Criteria Evaluated by Expert 1

In term of their final grade, the mirror group started at a significantly higher level according to both evaluators and finished at a significantly higher level according to the first evaluator. However, both groups were beginners and both progressed. Furthermore, any of the evaluators noticed a significant difference in their improvement. It is consequently impossible to conclude that one group improved more than the other.

The difference in grading method between the two evaluators appeared more clearly in the case of the soto uke. The first evaluator observed an improvement significantly greater than the second evaluator on many performance criteria (21 out of 30) including the global score. However, that difference is consistent among the two groups and therefore does not bias the conclusions made from the observation of tendencies among the evaluators.

4.3.1.4 Comparison with Experts' Scores

The way the first evaluator used the grading scale, it is always possible to distinguish experts from untrained and trained novices in term of their global scores with a significant difference of $p < 0.01$. That is also the situation between untrained novices and experts for all the performance criteria of the mae geri. However, on some performance criteria of the tsuki and the soto uke, that distinction is not possible.

For the tsuki, that concerns the orientation of the arming wrist on the start of the gesture, the synchronization of the beginning of the translation and the rotation timing in the execution of the gesture. In these case, there is no significant difference in the grading of the mirror group versus the experts already at the initial evaluation.

At the final evaluation, there exist a significant difference between the experts and the novices only in the case of the hips motion in the execution criteria set and in the case of the shoulders position and the attacking arm posture and position in the gesture end criteria set for both novice groups. There is also a significant difference in the case of the hips position and the arming arm posture between experts and the mirror group. In the whole gesture criteria set, there is always a significant difference except in the case of the foot position of the mirror group.

For the mae geri, the distinction between experts and trained novices is also significant for almost every criteria. The only exception regards the standing posture, the heels position and the foot posture in the kicking phase where there are no significant difference between the experts and the novices of the mirror group at the final evaluation.

For the soto uke, there is a significant difference between the experts and the novices at the initial evaluation in the case of all performance criteria. The only exceptions are the starting posture and position of the arming arm at the start of the gesture for both groups. For these particular cases, if we look at the detail of the evaluation of the expert performances, we noticed that that is due to the fact that some experts optimized their gesture by almost skipping the starting position, going directly from the ending position to the next defense. They consequently get low scores on these criteria.

At the final evaluation, the significant difference between the experts and the novices remains true in the case of a majority of performance criteria. Exceptions are the arming arm posture, position and orientation and the defending arm posture at the start of the gesture for both group of novices. At the end of the gesture, it becomes impossible to significantly distinguish experts from novices on the arming wrist orientation criteria for both groups and on the defending wrist orientation for the without mirror group. It is also impossible to significantly distinguish experts from novices of both groups in their final evaluation performance of the repositioning phase criteria and in the synchronization of the rotation in the execution of the gesture. As mention previously, most of these criteria are related to repositioning phase and the start of the next defense when the gesture is performed in series. In the case of novices, that phase is clear as in the case of experts, that repositioning is sometime optimized. As it will be discussed further, we can observed that the second evaluator did not grade these criteria in the same manner as the first. The first evaluator blindly applied the grid as the second evaluator considered that optimization factor in his grading.

Novices scores on the diverse performance criteria for the tsuki range from 1.80 to 5.7 with a maximum standard deviation of 2.10 for the initial evaluation and from 3.5 to 6.4 with a maximum standard deviation of 1.29 for the final evaluation. The scores of the experts for the tsuki range from 5.50 to 7.00 with a maximum standard deviation of 1.5.

For the mae geri, these scores range from 2.13 to 5.00 with a maximum standard deviation of 1.87 for the initial evaluation and from 3.38 to 6.10 with a maximum standard deviation of 2.13 for the final evaluation for the novices. The scores of the experts range from 5.75 to 7.00 with a standard deviation of 0.31.

For the soto uke these scores range from 1.13 to 4.80 with a maximum standard deviation of 2.00 for the initial evaluation and from 2.88 to 6.70 with a standard deviation of 1.33 for the final evaluation. The scores of the experts for the soto uke range from 4.75 to 7 with a maximum standard deviation of 3.00.

In the case of the second evaluator, the distinction between experts and untrained and even trained novices is clear. For all the performance criteria of the three gestures, including the global scores and on both evaluations, there was a significant difference ($p < 0.01$) between the scores of the experts and that of the novices.

Novices scores on the diverse performance criteria for the tsuki range from 1.13 to 2.10 with a maximum standard deviation of 0.75 for the initial evaluation and from 1.13 to 3.30 with a maximum standard deviation of 1.00 for the final evaluation. The scores of the experts for the tsuki range from 4.80 to 6.20 with a maximum standard deviation of 1.00.

For the mae geri, these scores range from 1.00 to 2.00 with a maximum standard deviation of 0.69 for the initial evaluation and from 1.13 to 3.00 with a maximum standard deviation of 0.99 for the final evaluation for the novices. The scores of the experts range from 5.20 to 6.00 with a standard deviation of 0.24.

For the soto uke these scores range from 1.00 to 2.00 with a maximum standard deviation of 0.70 for the initial evaluation and from 1.00 to 2.80 with a standard deviation of 0.74 for the final evaluation. The scores of the experts for the soto uke range from 5.60 to 6.00 with a maximum standard deviation of 0.71.

4.3.2 Evocation Interview Results

The evocation interviews were performed on both groups after the first and the third training session. The without mirror group comprised eight participants and the mirror group ten. From the evocation interviews it was possible to deduce that four participants of the without mirror group were familiar with video games or virtual reality as the four others were not. In the mirror group, that was the case for five of the participants. The following sections described the tendencies that can be observed globally and within each group. In these sections, individual results are presented only in the case of the learning process progression of the participants. Individual analysis tables, in the interview language (French), can be find in the appendix section 7.4 for more details. For each group, the first and third training synthesis summarized the tendencies observed on three aspect, namely, the participants engagement in the task, the learning process, and the control mode used by the participants to construct and regulate their action. The next section, the learning summary, summarized the individual learning process. The group conclusion sections discussed the tendencies in the learning process in relation with the learning environment. Finally, the interviews conclusion presented the tendencies common to both groups.

4.3.2.1 Without Mirror Group Results

4.3.2.1.1 First Training Interview Synthesis

That section presented a summary of the interviews' results after the first training for the without mirror group. Results are presented for three categories, the participants engagement in the task, the learning, and the control mode.

After the first training, only one participant seem to be fully engaged in the comprehension of the gestures (subject 7). Another participant (subject 3), seem to have tried to learn but gave up confront to the complexity of the soto uke. The others six participants seem to have performed an imitation task because they were asked to, but were annoyed by the repetitions. In the case of the tsuki because they felt the gesture was easy and does not necessitate repetitions. In the case of the two other gestures because they were not able to perform these correctly.

On the point of view of the learning, the description of the participants action was essentially based on the instructor instructions. Participants used the words and expressions of the instructor, that shows that they have memorized what they were required to do. In some cases, participants were able to give an analytic description of the different phases of the gestures. Three participants (subject 1, 7, and 8) were able to give a meaning to the tsuki and the mae geri gestures (punch and kick). However, after the first training, none of the participants were able to give a meaning to the soto uke gesture (defense).

Vision is the favored control mode used by the participants. The main activity performed by the participants in their learning task consist in the observation of the instructor and the comparison with standing poses of their imitation of the instructor. Furthermore, the participants carefully listen to the instructor instructions. During the interviews, the participants were able to precisely repeat these instruction. The instructions were, therefore, correctly memorized, but from the interviews only, we can not know if they were correctly applied. The virtual learning environment was positively perceived by the participants, but some participants judged it insufficient for an appropriated learning of the gestures.

4.3.2.1.2 Third Training Interview Synthesis

During the third training, six participants out of eight (except subjects 3 and 4) tried to understand the gestures by an active participation and implication in the realization of the exercises proposed by the virtual instructor. On the other hand, the participants differentiated themselves from the instructor. Instead, they were engaged in the construction of personal strategies (imaginary targets, synchronization of their breathing, synchronization with the instructor execution speed, . . .). They used these strategies as games to support their learning.

Regarding the control modes, all the participants used proprioceptive indicators to regulate their actions (squeeze the shoulder blades, maintain equilibrium, feel the thighs flexion, . . .). All the participants seem to be able to evaluate what they were required to do, at least for the starting and ending positions of the gestures. Participants were also able to give meaning to the tsuki and mae geri gestures that thereby became "gestures" instead of actions to mimic.

In that training session, the participants' interviews outlined a shift from a visual control mode to one based on the senses. In the first interviews, participants mentioned visually comparing their action to that of the instructor by looking in alternation at their body and at the virtual instructor. In these interviews, they mentioned using tactile, auditive and proprioceptive sensations.

The virtual environment was judged severely by the participants. They appreciate the individual character of the learning. They can train without the judgement of others. On the other hand, they feel they are missing critical informations for the regulation of their performance of the gestures.

4.3.2.1.3 Individual Learning Summary

That section summarize the individual progression of the participants in their learning process.

Subject 1

The first participant did not had the desire to learn the tsuki that he feel he already know and master at the first session. On the other hand, he is engaged in the learning of the mae geri and the soto uke. Knew knowledges emerged from his discourse regarding these gestures. The individual character of the learning satisfy him. He appreciated the liberty of performing only the repetitions he wants. However, he found the virtual environment limited. He would have appreciated feedback on his actions in the form of corrections and evaluations.

Subject 2

From the second interview, we can deduce that the second participant memorized the instructor instructions and gave meaning to the gestures. He used auditive information to control his gestures. The second participant appreciated the virtual environment that he found "funny", but he found it inappropriate for the type of gestures to learn. He felt constrain to listen to the instructor while he would have normally rely on observation.

Subject 3

From the interviews, we can deduce that the third participant observed the instructor attentively during the first training. During the third training, he has built a system of reference on the instructor that he used to validate rapidly his own positions and postures. However, he reported having difficulty to feel the sensation described by the instructor. He felt disturb by the movement of the virtual environment (artificial egocentric vision). He felt annoyed to repeat the same lesson three times. He would have like to be able to pause the lesson to observe freely the instructor.

Subject 4

From the interviews, we can deduce that the fourth participant actively questioned his imitation activity and tried to find answer in the observation of the instructor during the first session. However, in the third session he relied instead on the instructor verbal instructions to perform.

The fourth participant his used to learn that type of gestures with closed eyes using sensations. He found that technique difficult for the soto uke. That participant questioned the interest of the virtual environment and would have preferred a physical instructor.

Subject 5

The interviews of the fifth participant permitted to deduce that from the first training session to the third, he progress from a global execution of the gestures to a more detailed one in the last training session. In that third session, he searched for his own sensations instead of observing the instructor. He played an anticipation game with the instructor trying to perform the gesture before him. The fifth participant felt imprisoned in the virtual environment. He was extremely attentive to the decor. The participant would have like to be able to observe the gesture form different angles.

Subject 6

The sixth participant was disappointed by the virtual environment. He felt annoyed by the repetitions. However, he tried to build personal strategies to maintain his interest (imagine targets, focus on one body segment, ...). Despite his negative reception of the virtual environment, the sixth participant felt he had learned the gestures.

Subject 7

At the end of the first session, the seventh participant was satisfied by the fact of having a private instructor, however, at the end of the third session he was annoyed by the lack of "atmosphere" of the virtual environment. He felt that the lesson was not adapted to his needs. During the third session, the seventh participant no longer observed nor listen to the instructor, he performed the repetitions only.

Subject 8

The eighth participant criticized the virtual environment. He was strongly disappointed and questioned the interest of the environment. For him, the virtual environment has no purpose since it does not propose any interactions and feedback on his performance of the gestures. The eighth participant questioned the fact that he effectively learned something from that environment.

4.3.2.1.4 Group Conclusions

Participants 1, 4, 6 and 7 were familiar with video games or virtual environments, the other participants were discovering that type of activity. Participants 1, 4 and 6 were willing to learn, particularly the mae geri and the soto uke that they judged more complex. However, all participants used cognitive tools of their imagination to counterbalance the repetitive character of the environment. Participant 7 even questioned the interest of the virtual environment.

Participants 5 and 8 doubt to have learned even if they think to have understood the gestures. Participant 2 wanted to learn but felt obliged to modify his learning process to adapt to the learning environment (from visual to auditive information retrieval from the instructor). The third participant experimented a similar process but experience difficulties to feel sensations in his realization of the gestures. He felt disturbed by the virtual environment.

In general, the participants appreciated the individual character of the training in a virtual environment. The appreciated the possibility to train without the pressure of being watch by others or even by a real instructor. That permitted them to train at their own pace and to take initiatives. In conclusion, they appreciated the freedom offer by that kind of environment. On the other hand, they criticized the repetitive character of the lesson. They found it annoying to be alone in front of a screen without any feedback on their actions. They questioned the degree of precision of the virtual representation of the instructor.

4.3.2.2 Mirror Group Results

4.3.2.2.1 First Training Interview Synthesis

As explained in section 4.2.1, the novelty of the mirror environment is that the participants were having a feedback of their action in the form of a mirrored avatar. In the same manner used for the participants of the without mirror group, the following sections present the results for the mirror group. Results presentation is organized in four subsections. The two first summarized the interviews performed after the first and third training sessions, the next subsection presents the learning progress of the participant. Finally, the last subsection presents conclusions for the mirror group.

Globally no participant of the mirror group mentioned being annoyed after the first training session. However, only three participants mentioned using the mirrored avatar to compare their postures to that of the instructor. Nothing in their language support the idea that they identified themselves to the avatar. Participants generally talk about the avatar has a third person mimicking their actions. Only participant 10 talk of himself as part of the virtual environment in interaction with the virtual instructor.

Nevertheless, every participants seem to be engaged in the comprehension of the gestures. Understanding the gesture and mimicking the instructor is for them the goal of the activity. Five of the participants used the mirrored avatar as a source of information on their action, but also as a distraction source making the environment more pleasant.

From the learning point of view, the participants description of the action were essentially based on the instructor instructions. The participants repeated the instructor expressions showing that they memorized what they have to do. Some participants were able to do an analytic description of the different phases of each gestures, but that description remain based on the theory of the gestures.

Vision and audition are the favored control mode. The observation of the instructor is the main activity of the participants during that first training. Their attention goes from the instructor to their own body to adjust static starting and ending postures of the gestures. The participants carefully listened to the instruction and memorized these. However, during the first interviews, nothing in the participants discourse confirmed that they can effectively applied these instructions in their gestures execution. Few participants used the mirrored avatar as a supplementary tool to adjust their postures.

4.3.2.2.2 Third Training Interview Synthesis

At the difference of the without mirror group, seven participants of the mirror group were still engaged in the learning of the three karate gestures during the third training session. The participants even reported feeling satisfaction in the realization of the mae geri and the soto uke. However, three participants reported feeling bored. They found the training sessions repetitive and not varied enough to keep their attention. Every participant considered that one training session is enough to learn the tsuki.

Consequently, every participant reported having learned and mastered the tsuki. However, even after the third sessions, three of the participants continued to use the instructor expression to describe their learning. The other seven participants used a personalized vocabulary and mentioned personal learning strategies, that supposes an internalization of that gesture. However, five participants continued to use the instructor language to describe the mae geri and the soto uke. Accordingly, they reported having difficulties to perform these gestures.

The control modes used by the participants are more varied than it was the case for the without mirror group. Participants 2, 5, 7, 9 and 10 used the mirrored avatar to control their action. They observed the avatar and the mirror and modified their postures according to what they observed. Participants 3, 4, 6, and 8 did not used the avatar, they used their bodily sensation only to estimate the correctness of their postures. Participants listened to the rhythmical informations (counting and breathing of the instructor) and tried to apply its verbal instructions. Participant 1 observed his reflection on the avatar and his own body to adjust his postures.

Only one participant mentioned the impression of being fully immerse in the virtual environment. Participants 1, 2, 5, 7, 8, and 9 found the mirrored avatar useful to adjust their motion and to rapidly compare it to the instructor one (they could see both side by side on the screen). However, every participant spoke about the avatar at the third person. For participants 6, 4, and 3 the mirror is useless.

4.3.2.2.3 Individual Learning Summary

Subject 1

During the first training session, the first participant focused on the instructor instructions. His main activity was to understand and construct an internal representation of the gestures. The participant did not used his own body sensations as a comparison tool with the instructor. At the third session, the participant no longer listen to the instructor. He continued to observe the instructor for the realization of the mae geri and the soto uke, but started using his body sensations for the tsuki.

Subject 2

The second participant found it difficult to star the learning activity. He felt unease at the beginning of the training. However, already in the first training session he started to play with the mirrored avatar and used it to control his action. During the third training session, the participant mentioned being under the impression of possessing the avatar and walking it in the virtual environment. However, he did not identified the avatar has himself. The participant mentioned that being in contact with a floor similar to that of the virtual environment could have help for immersion and to found stable ground positions.

Subject 3

The third participant was engaged in the learning task. During the first training session, he tried to build a representation of the gestures to adjust his body sensations. During the third session, he focused on his sensations and start to found the realization of the gestures pleasant. The participant tried to follow the instructor rhythm in the performance of the gestures. The third participant suggested that according to him a correction system applied to the mirrored avatar would give it meaning. He would also have like to be able to manipulate the instructor in order to observe him from different view points and angles.

Subject 4

During the first training session, the fourth participant activity consist in trying to animate the mirrored avatar, "that gray character who mimic me", to recall the participant words. When the gestures speed is slow, the participant reported succeeding in the task, but failing to follow the instructor when the rhythm accelerate. During the third session, the participant focused on the instructions and used is body sensations to regulate is action in the case of the tsuki. For the mae geri and the soto uke he still recourse to the observation of the instructor. The participant reported playing with the avatar during the performance of the tsuki. The participant suggested ameliorations to the virtual environment. He proposed that being able to pause the instructor, zoom it and pivoting it would help him to observe more finely the gestures. He would have like the mirrored avatar to be more realistic and personalized. He would have like the environment to be augmented with targets.

Subject 5

The fifth participant reported having difficulties to apprehend the learning task. All three gestures were difficult for him. During the first session, he did not gave any attention to the virtual environment and did not saw the mirror. After the third session, he reported being bored and unmotivated. He did not understood the purpose of the learning environment. For him, a traditional learning environment is better. He do not think to have learn even if he fairly tried.

Subject 6

During the first training session, the sixth participant talk about the learning environment using the word video. However, he reported having used the mirrored avatar as complementary informations to the instructor. That helped him in his construction of the gesture. After the third training session, he reported having difficulties with the soto uke. He feels the environment does not provide enough informations for the construction of that gesture. He used the mirrored avatar to observe his action, but he that control method perturbed him.

Subject 7

Already during the first session, the seventh participant was focused on the information retrieval for the gestures execution. He was already searching to regulate his action based on his personal sensations. During the third session, he used the mirror to regulate his action only when he found it useful.

Subject 8

During the first training sessions, the eighth participant observed the instructor and carefully listen to the instructions. After doing so, he observed his action throughout the mirrored avatar. During the third session, he tried to feel in his own body the sensations described by the instructor. He diminished his usage of the mirrored avatar. He reported feeling uncomfortable with it.

Subject 9

Participant nine found the exercises easy at slow pace. The participant reported having started to understand the gestures during the repetitions by detaching his attention from the instructor. During the third session, the participant used the mirrored avatar for an avatar vs instructor comparison. He used that information to correct his postures but he need is own body sensations for the gestures rhythm and fluidity. The ninth participant considered the virtual environment as a game that would need amelioration to be more ludic. However, he did not think that kind of environment can be useful to learn sportive techniques.

Subject 10

The tenth participant spontaneously used the avatar to perform. He also identified the avatar has himself. He speak of the instructor has being behind him like in the mirror and not in front of him like on the screen projection. The participant reported being immersed in a game. During the third sessions, the participant reported being concentrated on the mirrored avatar but being bored of the repetitions. The participant is not sure to have learned.

4.3.2.2.4 Group Conclusions

The participants 1, 4, 8, 9, and 10 were used to virtual environments. They quickly decrypted the environment and identified the mirror. They used the mirror to adjust their coordination and to compare and adjust their actions to that of the instructor. However, the first participant compared that environment to a video environment.

The other participants were new to that type of environment. The second participant even felt sick due to the egocentric vision that "moved" too much for him. The third and seventh participant saw the mirror but used it only punctually to correct their position. Their preferred regulation mode remains their body sensations. The fifth participant expressed difficulties to understand what he was required to learn. He focused on the gestures but was always searching for new indices to help himself in the performance of the gestures. He almost unnoticed the environment. The sixth participant had difficulty to identify what the mirrored avatar represented. He was under the impression of following a video lesson.

4.3.2.3 Interviews Conclusions

4.3.2.3.1 The Role of the Indicators of the Learning Environment

Between the first and the third training, an evolution of the indicators used in the learning process for the regulation of the motion can be observed. In a first time, the focus of the participants was on the retrieval of visual and auditive informations on the instructor. Their main goal was to understand and built an internal representation of the gestures. In the case of the tsuki, that process was rapidly completed, and for most participants occurred in the first training. For the two others gestures, that process lasted during the three training sessions, and in some case was not completed even after the third training, implying that more than three training sessions would have been required for the process to take place. The second step, was to regulate the performance of the gestures. The main indicators used by the participants were the body sensations described by the instructor that they tried to perceive on their body. The mirror group also had the possibility to use the mirror and did it mostly to adjust starting and ending postures of the gestures. Furthermore, the participants had to imagine their body in motion in order to build a representation of themselves performing the gestures to replace that of the instructor. Some participants, even used imaginary tools, like visualizing targets, to regulate and direct their gestures. Finally, for the participants not feeling bored by the repetitions and consequently still actively implied in the learning process, the last step was a complete internalization of the movement to avoid the usage of external visual indicators to realize the gestures. The rhythm imposed by the instructor was, for the participants, a strong indicator of their learning. Being able to follow the instructor rhythm at fast pace was for them an indicator of success.

Moreover, it is possible to link that rhythm component with Egret et al. [Egret2003] work on the mental representation of the action in time. In addition to its formal characteristic, a motor skill can be characterized by the chronology of its organization. Some Authors suggest that there exist an abstract coding of the temporal structure of a gesture, for example in golf [Egret2003] or in piano [Meyer2003]. Their hypothesis is that the relative timing (in percent) of each portion of the skill remains constant among the variation in speed and amplitude of the gesture. Furthermore, since, for the participants, the rhythm is an important indicator in the repetitions, we can supposed that what they learned is an abstract representation of the temporal organization of the gestures and no a spatial displacement of limbs or a complex multi-limbs coordination.

4.3.2.3.2 Participants' Learning Process Management

Three categories of learners were represented in both learning groups. From these three categories, two are learners that did not managed their learning. The first category is composed by the participants learning throughout trials and errors. These learners are attentive at the content of the learning (What?) but not at the manner to learn (How?). They used personal strategies that they think are efficient to learn. For example, they mimic the instructor, used knowledges from a sport they judge similar (boxing), or "played a karate game".

A second category is composed of participants ignoring the learning activity and imagining themselves in a game or in a repetition activity. Some of these participants were even surprised to be ask about their activity during the interviews. For them, the learning activity was strictly limited to applied the instructor instructions integrally. These participants are representative of a category of person who learn by following rigorously someone else instructions.

The third category concern the participants who controlled their learning. In that category, the amount of control varies. Some participants control their actions punctually in a failure or success logic. On the opposite, other participants had an intense control activity. They constantly evaluated their action. They analyzed their manner of performing the actions and evaluated other manners. They compared the evolution of their performance in the course of the repetitions. These control were followed or not by regulations of the action.

To summarize, a minority of participants actively regulated their learning activity. However, some participants voluntarily controlled their manner to learn aiming at better learning strategies. That control is an activity per se, outside the learning activity. It implies self-conscienceless. Furthermore, a minority of participants regulate their activity during the learning process. Whenever these participants were not satisfied by their learning, they were ready to modify their learning method.

4.4 Discussion

From the results presented in section 4.3.1, it is possible to observe that it is practically impossible to conclude on the pertinence of a feedback metaphor from the observation of external performances only. For that reason, the results of the evocation interviews presented in section 4.3.2 permit a complementary interpretation of these results.

If we consider the results of the evaluation of the performance at the final evaluation only, we might be tempted to conclude at the superiority of the mirror group. That would even confirm the hypothesis that having a visual feedback is better than not having any feedback at all. That would be the conclusion of most studies including that of Patel et al. [Patel2006], since as discussed in section **??** and emphasized by Joy and Garcia [II2000] most of the studies on learning in virtual environments assume that since their subjects are novices, that implies that they all start at an equivalent level and consequently do not perform any pre-tests.

However, when we look at the initial level of our participants, we observed that that hypothesis is not true. Patel et al. [Patel2006] mentioned in their study that already at the first step of their learning process, performance evaluations showed a superiority of their virtual reality group over their video group. We might suspect that they were in fact confront to a similar scenario we observed where the initial level of one group is already superior to that of the other group before any training. Effectively, there is no such thing as a "perfect novice"! Every individual participating to an experiment arrived at the experiment with its personal background. That background includes familiarity with the technology used in the experiment, but also and specially in the case of motor skills, different abilities to apprehend a new skill. Technological background and other socio-cultural variables might be assessed with the use of questionnaires, but questionnaires can not account for different motor skills abilities. Performing pre-tests, even with the risk of causing a bias, like in our case having all the participants see a video of the gesture, are the only way to know if the initial level of the participants were effectively equivalent.

Moreover, if instead of observing the final level of the participants, we consider the improvement, namely the difference between the final and the initial level, the tendency is inverted, the mirror group seem to have improved less than the group without any feedback. That results might be surprising and even chocking considering the hypothesis that a visual feedback would be better than no feedback at all. Performance evaluations alone are not sufficient to understand that result and we have to refer to the evocation interview results to get an insight of what might have created that situation.

The first element to notice is that at the first training session very few participants mentioned having used the mirror, some participants even seem not to have noticed the mirror, that even if before the training session they had a five minutes period where they could play with it. From the analysis of their description of the task, their goal and their perception, we might hypothesis that it is too early in the learning process for the mirror to be of any use. At that point of learning, they are concentrated on the instructor, particularly on his verbal instructions and they have not yet built an internal representation of the gesture necessary for the need to regulate their action to appear.

Furthermore, what happen at the third training session is even more interesting. The evocation interviews permit to determine that both group are annoyed by all the gestures' repetitions, that is particularly true of the tsuki gesture which appear to them easy and that they feel they master. However, some participants of the mirror group "invented a second task" apart from learning the gestures by imitation of the instructor. According to these participants, at the thirds session, their task became to animate the mirrored avatar to make it performed like the instructor. Most of the participants talk about the mirrored avatar as a third person. Only one participant identify the avatar as himself, even if some participants talk about it like someone reproducing or mimicking their gestures. One participant completely quit the task of learning the gestures and played a "boxing game" with the mirrored avatar.

In addition, some participants mentioned that the fear of losing markers during the training distracted them from the performance of the task. Markers are inherent to the technological setup we used for the full body motion capture required to animate the mirrored avatar. Therefore, we chose to consider markers as a constrain related to the mirror environment. It might be argued that markers are instead a bias, that they are an external factor perturbing the immersion and the task of the participants and that in that regard they should have been isolated from the environment by the study of another basic virtual group wearing the markers. Both positions are defendable, and ideally both should have been explored.

Nevertheless, all these cumbersome aspects of the mirrored avatar, it had a positive effect on the motivation of the participants. Participants of the mirror group more willingly completed their third training session than these of the without mirror group. Therefore, it can be hypothesized that despite the fact that the mirror has a null or negative effect on the improvement of the performance on short term, its long term effect would be to motivate the participants to pursue the training. Further studies would need to be performed to know if on longer term, the mirror could become a useful source of feedback. Actually, we can only hypothesized from the performance evaluations that it might have a positive effect on some initial and final postural criteria. That is in conformity with some of the conclusions of Chua et al. [Chua2003].

Additionally, the evocation interviews outlined that the participants largely rely on sound information to construct their gestures. They based their construction on the verbal instructions of the instructor and they synchronized their execution on the instructor breathing. Some of the participants even mentioned reproducing that breathing sound in order to perform the gesture. Such a large usage of the sound information was unexpected and would need to be further investigated. Sonification of the learning environment could potentially be an interesting interaction and feedback metaphor. That metaphor as been explored by Takanata et al. [Takahata2004]. Moreover, some of the participants proposed the usage of visual elements such as targets. Effectively, the instructor sometime verbally suggest to the participants to imagine targets in order to direct their punch or kick. These "imaginary" targets could take form in a virtual environment. These suggestions would need to be explored in further iterations of the virtual environment. They could potentially help the improvement of the performance and the motivation of the participants.

4.5 Conclusion

The question of that study was to investigate the impact of a third-person representation of one self in the virtual learning environment. That representation was in the form of a mirrored gray cylindrical avatar. The question was investigated from two points of view: 1) from an external point of view using performance evaluation 2) from the point of view of the participants using evocation interview. The performance evaluation grid was improved from the first study to include, in addition to the global score, a multi-criteria evaluation on a seven point Likert scale. A second expert evaluator was recruited to grade the performance in order to confront the evaluation of the instructor and to observe concordance in the groups' tendencies.

The improvement of the evaluation grid permitted to observe tendencies that would otherwise not appear. The multi-criteria grid, for example, outlined that the initial level of the mirror group was higher than that of the without mirror group already before training. Without the multi-criteria grid, that would have appeared only in the case of the soto uke. That observation is important since it might then explain a better final performance. However, as it was the case in the first study, evaluation of the performance alone does not permit to conclude on the superiority of one environment over another in providing teaching by demonstration of the three karate gestures.

Moreover, the evocation interview highlighted the fact that lack of difference in improvement between the two environments might be due to the fairly limited usage of the mirror metaphor. Participants rarely used it in the first training session and, when using it in the third session, do not always use it as an aid to improve themselves. In fact, many participants used the mirror to distract themselves from the repetitive character of the training. The mirror, therefore, help them maintain their motivation but was rarely used as intended to regulate their actions.

However, the evocation interview permitted to pinpoint the usage the participants made of the sound information provided by the learning environment. That result was unexpected and might orient further iterations of the virtual environment toward audio feedback. Among other, participants also made suggestions to augment the environment with targets so that they can oriented their hit in punching and kicking. Without any surprise, used gamers ask for more interactions and more realism of the mirrored avatar. Participants requested the possibility to manipulate the virtual instructor, for example, turn it to observe it from other perspectives, replay portion of the explanation or exercises or skip sections they feel they master. In other word, they want to take full advantage of the individual and personalized character offered by a lesson in virtual reality. All these aspect should be taken into consideration in the design of future iterations of the virtual environment.

Chapter 5

Standardization of the Performance Evaluation: The Necessity for an Automatic Evaluator

5.1 Introduction

Evaluation by experts is the most common type of evaluation in individual sports where the performance of a set of skills, gestures or routines at an established level of competency permits the passage to another degree. It is also common in competitions where judges attribute a grade to a performance according to a precise list of performance criteria. It was therefore natural to use it as our prime evaluation method.

However, evaluation by experts, as any human activity, is subject to bias due to the human nature. The same evaluator can grade differently the same performance at two different moments of time. That can be due to external factors such as the moment of the day or year, the weather or the environment (noise, light, etc, ...). This can also be due to internal factors such as the evaluator mood, boredom, tiredness or the evaluator habituation to grade similar performances. All these factors can alter his grading. A human evaluator might also be temped to observe a progression for a same individual he recognized between the initial and the final evaluation, that even if such a progression does not exist. Many factors related to the evaluation environment and the capture method and not the performance itself might also change the evaluator perception of the performance.

The comparison between the two evaluators of the second study also outlined that different evaluators grade the same performance in sometime extremely different manner. Even if trained in the same school by the same instructors, two experts of a discipline might have different interpretations of the performance criteria and their application. Moreover, they might have a different interpretation of the grading scale. To counterbalance the large amount of factors influencing the grading by experts, the expertise of many evaluators would be required. However, we might take in consideration that grading by experts is a highly time consuming task and that the pull of experts in a precise discipline is often limited. Furthermore, the duration of that type of experiment might also be taken into account. For example, in the case of our experiment, each study lasted 5 weeks, if we consider that all groups can performed the experiment at the same moment which is rarely the case. Therefore, the complete cycle of all the experiments reported in this thesis took place over three years. It is obvious that the grading of the evaluators evolved over that period of time and that a comparison of the four environments of that thesis would be bias if based on human evaluators only.

Consequently, we used biomechanics analysis with the aim to develop an automatic grader. The following sections explain the preparation steps for an automatic evaluation of a performance, from the motion capture of that performance to its grading. Effectively, the motion capture of a performance need to be reconstruct and map on a specific format of skeleton in order to be compared to a reference. Since every individual as a specific morphology and every performance varies in timing and speed, specific preparations need to be done to compare the performance in time and space. The following sections detail the tools we used to perform these comparisons. However, these normalization might alter the precision and accuracy of the evaluation we thereby obtain. A methodology to evaluate the validity of the automatic grader is therefore presented, followed by the presentation of the results and a discussion about there interpretation and significance.

5.2 Methodology

The automatic evaluation of the performances, that should later become an automatic coach, was planned since the beginning of the project. That part was developed in the context of the Biofeedback project. For that reason, the automatic grader tools were developed in C++ in the Visual Studio 10 developing environment. The skeleton format required in entrance of the grader is BVH. That format was chosen to be independent of the motion capture technologies used in preparation. The automatic grader is aimed at being a "black box" taking in entrance BVH motions and outputting, at the present time in differed time, an analysis of that motion compared to a reference one.

5.2.0.4 Motion Capture of the Evaluations

For that reason, all the initial and final performances of all the participants of the studies presented in that thesis were captured using tridimensional motion capture. To ensure the maximal possible quality and thereby permit further analysis of the data, outside the Biofeedback project, if required, the performances were captured using the Vicon system. The evaluations were captured simultaneously in video and in 3D in the same manner it was done for the instructor motion (refer to section 2.1.3.2.2).

The reconstruction was also performed in IQ in the manner presented in section 2.1.3.2.2. As explained in sections 3.2.2.1 and 3.2.2.2 every participants was asked to perform two series of ten repetitions of each gesture. Eight repetitions of each series were used for the analysis for a total of sixteen trials, eight for each laterality. Normally, the first and the last repetitions of the series were trimmed and the core repetitions were used. However, in cases of reconstruction problems causing data rejection, they were sometime used. Due to data rejection, one subject of the mirror group was evaluated on thirteen repetitions only (7 right, 6 left) at its initial evaluation, all the other subjects were evaluated on sixteen repetitions.

5.2.0.5 Motion Retargeting of the Evaluations

The motion retargeting process of the performances is similar to that of the instructor presented in section 2.1.3.2.3. The C3D files are imported in Motion Builder 2010 32 bits and converted to an amorphological constrain actor using the M2S Lab plugin. The bones of the actor are then generate to correspond to the BVH standard using a Motion Builder Open Reality plugin also developed by the M2S laboratory. That permits to map the motion of the actor unto the skeleton. The result can then by exported in BVH and used in the automatic evaluator.

5.2.0.6 Motion Segmentation in Trials

A manual segmentation of every performance motion files as been performed. That segmentation is necessary since the automatic evaluator compares every single repetition (what we will call a trial) against a single reference trial of the instructor for each gesture and each laterality. An example file for the tsuki is provided in figure 5.1.

```
"InstructorNameTsuki2.bvh",1047,1090,"tsuki","Instructor Name","droite",,,,,,,
"InstructorNameTsuki2.bvh",2418,2487,"tsuki","Instructor Name","gauche",,,,,,,
"Subject1NameITsuki002.bvh",1615,1810,"tsuki","Subject1 Name","droite",,,,,,,
[...]
"Subject1NameITsuki001.bvh",1315,1527,"tsuki","Subject1 Name","gauche",,,,,,,
[...]
"SubjectXNameITsuki002.bvh",2598,2708,"tsuki","SubjectX Name","droite",,,,,,,
[...]
"SubjectXNameITsuki001.bvh",856,1078,"tsuki","SubjectX Name","gauche",,,,,,,
[...]
```

Figure 5.1 - Performance Segmentation File Example

The first two lines are the reference trials of the instructor. They are followed by a line for every trial of every subject. The first part is the BVH file name. It is followed by the starting and ending frame of the trial of the gesture. The next parts are the gesture name, the subject name and the laterality concerning the trial (gauche = left or droite = right). One segmentation file was built for each group and each evaluation for each of the three gestures. The segmentation files are provided in input of the automatic evaluator that use these to prepare every trial for comparison with every other trial.

5.2.0.7 The Choice of the Instructor Reference Trials

In our experiments, the participants task is to learn three gestures by imitation of the instructor. Consequently, when evaluating their performance, the model that should be used in comparison is that of the instructor. In order to choose these reference models, we analyzed the series of repetitions of the performance of the complete gesture the instructor performed at the end of gesture training session (refer to figure 2.4). These series were segmented using the same manual process used for the participants and presented in the previous section. Each series was then sent to the automatic evaluator. The output of the automatic evaluator is a matrix of the distance of every trial against the others. From that matrix, we used the mean of every trial against the others in order to find the trial minimizing the distance with the others. A central trial was found of each laterality of each gesture. These trials were used as the reference trials for the evaluation of the participants' trials.

5.2.0.8 Automatic Evaluation Based on Biomechanical Parameters

Comparing two performances is a complex problem as a motion is modeled as a high-dimensional vector with numerous parameters. Moreover each parameter, such as joint angles or positions, is strongly linked to the specific situation. For example, two different persons with different morphology performing the same performance might exhibit different joint angles and positions. That leads to a spatial variability which makes it difficult to design a relevant metric to compare two motions. Variability can also occur in time as a motion can be performed with different speeds and timing.

Hence, comparing two motions requires to reduce space and time variability. Despite that space-time signal analysis, human performance might be evaluated through more complex and high level variables, such as the punch ending position in front of the sternum, or ensuring coordination between the two wrists rotations as described in the previous subsection 4.2.2.1. That type of performance evaluation can be carried-out by experts knowing that type of knowledge. Defining an automatic system to perform similar evaluation is a challenge which is beyond the scope of that thesis. In this work we assumed that the evaluation grid filled-in by the experts enables us to analyze the performance of the subjects from the karate domain point of view.

In that part, we consequently focus on designing a metric to automatically evaluate the performance of the subject. To that end, that metric has to compute the distance between a given motion and a reference $Ref(t)$. The choice of the reference trials was explained in the previous section. $Ref(t) = \{Ref_i(t)\}_{i=1..n}$ is a state vector of n parameters, such as joints angles and position. In computer animation [Kulpa2005b] morphology-independent parameters have been introduced in order to reduce space variability due to differences of morphology between two subjects.

We therefore considered that $Ref_i(t)$ is:

- the 3D Cartesian position of each joint in the pelvis reference frame (to make the data become independent from the global rotation and position of the body). In that type of representation, two subjects with a different morphology performing the same motion have different values.

- an adimensional vector for each limb, such as the relation position of the wrist in the shoulder reference frame $Ref_{arm}(t) = \frac{Arm(t)}{length(Arm)}$ where $length(Arm)$ stands for the total length of the arm. $Ref_{arm}(t)$ is consequently a 3D vector which coordinates range from

-1 to +1 independently of the length of the arm.

- or the global position of the pelvis.

5.2.0.8.1 Dynamic Time Warping

In the same way, each user motion is represented with the same type of data $Sub(t) = \{Sub_i(t)\}_{i=1..n}$. By using morphology-independent data we decreased the influence of the morphology in the comparison between two motions. However a timing difference may remain between the two motions. A simple root mean square difference computed between two signals with different timings might lead to compare two poses that occur at two different times. Let us consider a tsuki composed of a forward followed by a backward displacement of the hand (two successive phases). If the subject performed a longer first phase than the expert, comparing each frame sequentially might lead to compare a forward displacement of the user's hand to a backward displacement of the expert which is non-sense. To deal with this time variability we propose to use Dynamic Time Warping (DTW) [Myers1981] which consists in a non-linear temporal alignment of the two signals for comparison. It has been extensively used in speech recognition and signal processing, and has also been used to compare, combine motion or extract style [Héloir2006]. Dynamic time warping (DTW) is thus a well-known technique to fiĄnd an optimal alignment between two given (time-dependent) sequences under certain restrictions. Intuitively, the sequences are warped in a nonlinear fashion to match each other. In fields such as data mining and information retrieval, DTW has been successfully applied to automatically cope with time deformations and different speeds associated with time-dependent data, as depicted in Figure 5.2.

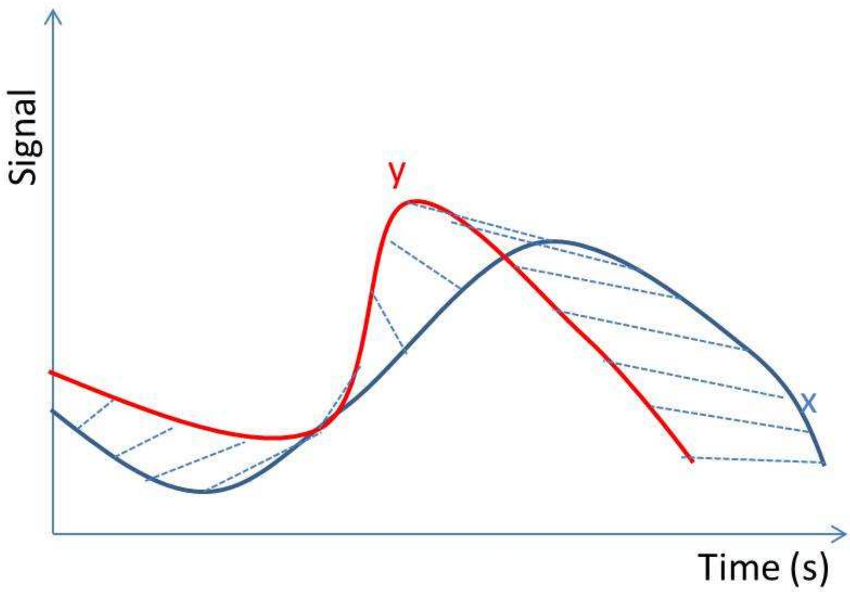


Figure 5.2 - Non-linear time alignment of two signals using Dynamic Time Warping.

The objective of DTW is to compare two (time-dependent) sequences $X := (x1, x2, ..., xN)$ of length N and Y := (y1, y2, . . . , yM) of length M . These sequences might be discrete signals (time-series), such as the morphology-independent data sampled at the motion capture frame rate. An Euclidian distance metrics is introduced to measure the similarity of each pair of $(xi, yj)\forall i, j$. However contrary to monodimensional signals, a pose is modeled as a high-dimensional vector which makes it difficult to use simple Euclidian distance. Some authors proposed to reduce the pose vector using the Principal Components Analysis method [Héloir2006]. In that thesis, each motion is strictly defined by the displacement of a specific body part, such as the hand for the tsuki or the foot for the mae geri. Timing information is therefore intrinsically contained in that specific body part which could then be used as a synchronization signal for all the body. For the tsuki, we selected the displacement of the hand in the forward/backward direction. For the mae geri we selected the forward/backward displacement of the foot. For the soto uke, we again selected the forward/backward displacement of the hand which is performing an hIkite (fast backward displacement of the hand). Finally, for each type of motion we get unique synchronization signals x and y, as in the common case.

Computing the Euclidian distance between each pair $(xi, yj)\forall i, j$ provides us with a Distance Matrix $Dist$. Low values in $Dist$ for xi and yj mean that these two values are similar and could correspond in the two sequences x and y. Then the goal is to fiĄnd an alignment between x and y having minimal overall cost in $Dist$. Intuitively, such an optimal alignment runs along a "valley"Ăİ of low cost within the cost matrix $Dist$, see Figure 5.3 for an illustration.

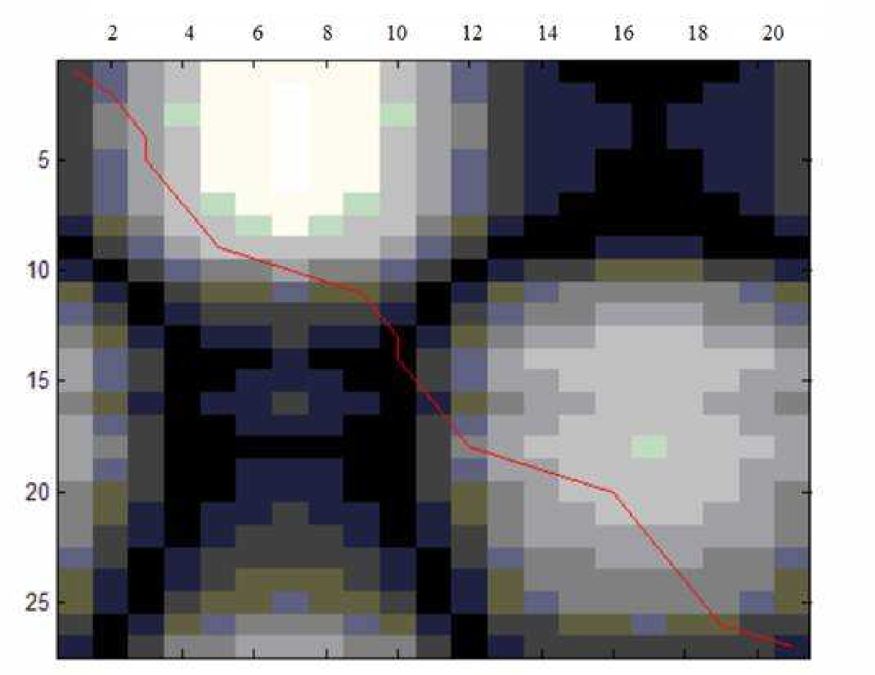


Figure 5.3 - Distance matrix $Dist$ which provides the Euclidian distance between each couple of points xi and yi $\forall i, j$.

Alignment between the two signals x and y is given by a (N,M)-wap path. An (N, M)-warp path is a sequence $p = (p_1, ..., p_L)$ couples of values $p_l = (n_l, m_l) \in [1 : N]$ÃŮ$[1 : M]$ for $l \in [1 : L]$ satisfying the following three conditions.

- Boundary condition: $p_1 = (1, 1)$ and $p_L = (N, M)$.
- Monotonicity condition: $n_1 \leq n_2 \leq \ldots \leq n_L$ and $m_1 \leq m_2 \leq \ldots \leq m_L$.
- Step size condition: p_{l+1}âĹŠ$p(l) \in (1, 0), (0, 1), (1, 1)$ for $l \in [1 : L$âĹŠ$1]$.

The total cost $c_p(x, y)$ of a warping path p between x and y with respect to the local cost measure $Dist$ is defined as:

$$c_p(x, y) = \sum_{l=1}^{L} Dist(n_l, n_l) \tag{5.1}$$

As a result, the DTW returns the list of couples (n_l, m_l) which leads to the minimal cost path between (n, m) and $(1, 1)$. This cost $c_p(x, y)$ is also provided by the method and is generally used as a distance between the two signals after being aligned. In our case, it could provide a distance between a motion performed by a subject and the corresponding reference motion performed by the expert. However, this type of distance limited to one signal is not totally adapted to compare two motions which involve several body parts and thus signals.

It is well known that DTW applied to signals of different amplitudes may fail to properly align two signals [Héloir2006]. To partially avoid this problem a classical solution consists in computing $Dist$ on the derivatives of the signals instead of the signals. Hence two extrema with different values could be aligned because their corresponding derivative is zero while a classical Euclidian distance will not be able to make them correspond. Let us consider $DDist$ the distance matrix between $\dot{x}$ and $\dot{y}$. DTW algorithm can be applied on that matrix instead of $Dist$ without changing anything in the method. However, if the two signals do not exhibit the same number of null derivative, that approach may lead to some misalignment while $Dist$ could lead to better result. A compromise between these two distances $Dist$ and $DDist$ offers a good solution. $Dist$ could thus be replaced by $0.5Dist + 0.5DDist$ to address that problem. As $Dist$ and $DDist$ may have different range of values it is necessary to normalize each distance by its maximum potential value. Finally, in the following, $Dist$ is replaced by

$$0.5\frac{Dist(xi, yj)}{max(Dist)} + 0.5\frac{DDist(xi, yj)}{max(DDist)}$$

To address that problem we used a two-steps process. First, we compute the warp path according to the signal selected for synchronization for each type of motion (such as the longitudinal translation of the hand for the Tsuki). Then, the warp path is used to compute different distances that are linked to the subject's performance such as the 3D coordinate of specific body parts or relevant rotations. With that approach it is possible to evaluate separately different performance criteria while taking timing into account. These parameters are summarized in Table 5.1.

Tsuki	Mae Geri	Soto Uke
Attacking wrist trajectory	Attacking leg ankle trajectory	Defending wrist trajectory
Attacking wrist rotation	Attacking leg ankle rotation	Defending wrist rotation
Attacking arm internal/external rotation	Kicking leg internal/external rotation	Defending arm internal/external rotation
Arming wrist trajectory		Arming wrist trajectory
Arming wrist rotation		Arming wrist rotation
Arming arm internal/external rotation		Arming arm internal/external rotation

Table 5.1 - Performance Criteria Used in the DTW to Compute Distances from the Instructor

5.2.0.9 Statistical Analysis of the Distance Matrix

The outcome of the DTW is a distance matrix. That matrix contain the distance of every trial against every other with a zero diagonal representing the distance of a trial against itself. From that matrix, it is possible to retrieve information about the distance of a participant's trials from the reference trial, the intra-subject distance that we called the variability, and the intra-subject symmetry.

5.2.0.9.1 Distance from the Instructor Reference Trials

As explained in section 5.2.0.7, the participants performance is evaluated in function of the model they learn from. Effectively, in our studies, the goal was to learn by imitation of the instructor. The instructor gestures are therefore the reference gestures of the participants. As explained in section 5.2.0.4, for each of the three gestures, sixteen trials were retain for every participant; eight left-hand side trials, and eight right-hand side trials. To establish the distance of a participant performance against the performance of the instructor, we added the average distance of the eight left-hand trials of the participant against the reference left-hand trial of the instructor, and the average distance of the eight right-hand trials of the participant against the reference right-hand trial of the instructor. That computation is done for each of the three gestures. The averages of the averages of every participant of a same group for every gesture are the measure presented in the results section. Evidently, the smaller distance means better performances.

5.2.0.9.2 Intra-subject Variability

What we called the variability is the computation of the average distance of a participant against himself. It is a measure that gives information about the consistency of the participant in is performance of the gesture. It is computed by adding the average distance of every left-hand trials against all the other left-hand trials of the same participant with the average distance of every right-hand trials against all the other right-hand trials of the same participant. As it was the case for the distance from the instructor, that measure is performed for every gesture and the averages of the averages of each group is what is presented in the results section. Normally, the participants' performances should be more consistent after training and therefore their intra-subject variability should decreased.

5.2.0.9.3 Intra-subject Symmetry

Similarly, the intra-subject symmetry is the measure of the consistency of the performance of the gesture from one laterality to the other. It is computed by adding the average distance of every left-hand trials against all the participant's right-hand trials and the average of every right-hand trials against all the participant's left-hand trials. The averages of the averages for each group and each gesture are presented in the results section. In that case also, the participants' performances should be more consistent after training and therefore the intra-subject symmetry distance value should decrease.

5.2.0.10 Testing of the Automatic Method Evaluator

In order to interpret the results of the automatic evaluator, we need a measure of its precision. In a similar way as it was done with the grading scale of the evaluation grids of the second experiment (see 4.2.2.1.2), we can have an idea of the precision of the system by observing if it can distinguished untrained novices from experts and even trained novices from experts. Furthermore, another test that could be done is to compare the difference of the performance of the expert instructor against himself in two different captures.

5.2.0.10.1 Distance From a Panel of Experts

In order to test the automatic system capacity to distinguish novices from experts, motion capture of the six experts used to evaluate the grids' scale was performed in the same way it was done for the instructor and the participants of the studies (see 2.1.3.2.2). The experts trials were prepared and tested against the instructor reference trials in the same way it was done for the participants trials (see 5.2.0.6). The distance from the instructor reference trials, the intra-subject variability and symmetry were computed in the same manner (see 5.2.0.9). The experts' group averages were then statistically compared to these of the two groups at the two evaluations in order to determine if there is a significant difference between the experts and the novices values. These results are presented in the following sections.

5.2.0.10.2 Distance Between Two Captures of the Instructor

The intra variability measure of the instructor against itself in a same capture session gives a measure of his capacity to repeat the same performance of a gesture over a series of repetitions; that is his own degree of precision. Since the instructor is an expert, we assume that : 1) from one capture to another is variability will remain in the same range 2) that the distance of his performances of the first capture against that of the second capture would be in the same range of values of that of his variability or slightly higher, but, in any way, smaller than the range of values observed for the novices where the performance from one evaluation to the other evolve due to the training. That implies that his variability over a short period of time is similar to his variability over a longer period of time since he his an expert. Assuming that, any value outside that range can be considered as noise in the measure.

Noise can occur at different steps of the complete evaluation loop. It can be due to :

- Markers placement between one capture and another;
- Reconstruction of the motion capture data;
- Retargeting of the motion capture;
- Conversion to BVH.

5.2.1 Results

The following sections summarize the results of the automatic evaluation of the performance. Three metrics were used for each gesture, namely the distance from the reference trial of the instructor, the intra-subject variability and the intra-subject symmetry. These metrics were explained in section 5.2.0.9. For the tsuki, six performance criteria were evaluated using these metrics, three for the mae geri and six for the soto uke. These performance criteria are list in table 5.1. These are trajectories and rotations of the wrists for the tsuki and the soto uke and of the ankle for the mae geri, and the arm or leg internal/external rotation that basically mean the position of the elbows or knees with respect of the other segments of the arm or leg and the body. When reading the graph, it is important to remember that a better performance means a smaller level on the scale.

5.2.1.1 Tsuki

The first set of results (figure 5.4) concerned the distance of the participants performance from the reference trial of the instructor for the tsuki. Only a very slight difference can be observed between the initial and the final evaluation. A deterioration can even be observed for the arming wrist rotation of the without mirror group. However, the only significant difference is for the attacking arm's wrist trajectory of the mirror group.

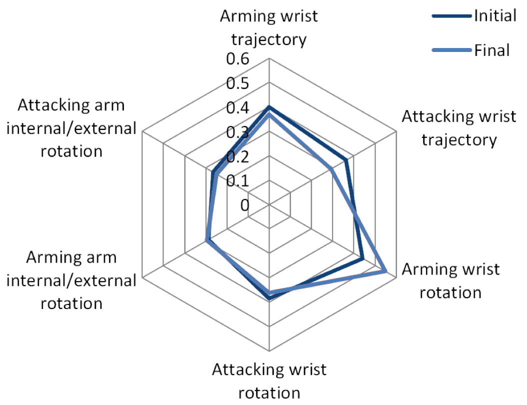
The initial level of the two groups were similar, although the mirror group level performed insignificantly better. A significant difference between the two group could be observed only for the trajectory of the arming wrist in favor of the mirror group.

Similarly, the final level of both group is equivalent with an insignificant advantage for the mirror group except on the defending arm wrist trajectory were the mirror group performance was significantly better than that of the without mirror group. However, no significant difference can be observed in the improvement of the two groups.

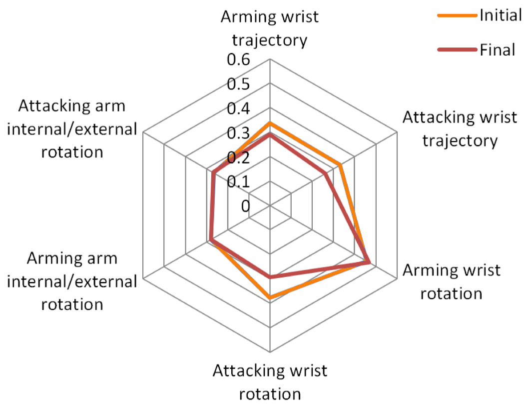
These results are in contradiction with the experts' evaluations were an improvement in the trajectories and in the wrist rotation were observed. There is no exactly corresponding performance criteria for the internal/external arm rotation, but that performance criteria can be related to starting and ending position of the elbows where the expert evaluators observed an improvement of the final position.

That second set of results (figure 5.5) concern the intra-subject variability on the same performance criteria as the first set. A clear improvement can be observed between the initial and final evaluation for both group. That improvement is statistically significative for all performance criteria except both wrist rotations and the arming wrist trajectory in the case of the without mirror group. However, there is no significant difference in the initial and final results of the two groups, neither then in their improvement. Although, the without mirror group performed slightly better at the final evaluation then the mirror group. There is no possible comparison with the experts grading were no evaluation of the variability was performed.

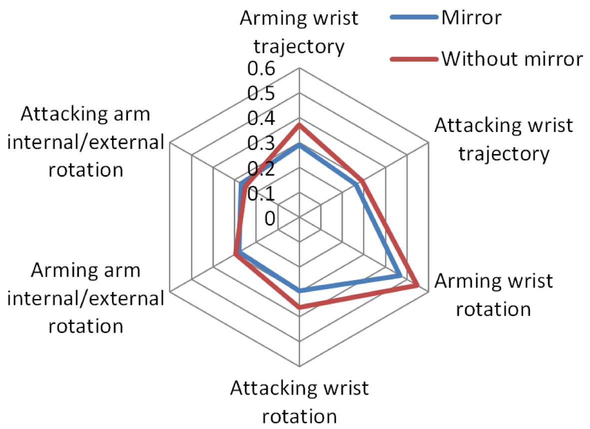
The last set of results (figure 5.6) for the tsuki concerned the intra-subject symmetry. There is no significant difference on the initial and final level of both groups. However, the mirror group significantly improved on all criteria except both wrists' rotations. On the other hand, the without mirror group only significantly improved its internal/external arming arm rotation. Nevertheless, there is no statistically significant difference in the improvement of the two groups. As it was the case for variability, symmetry is not measured by the experts grading.



(a) Progression of the Without Mirror Group

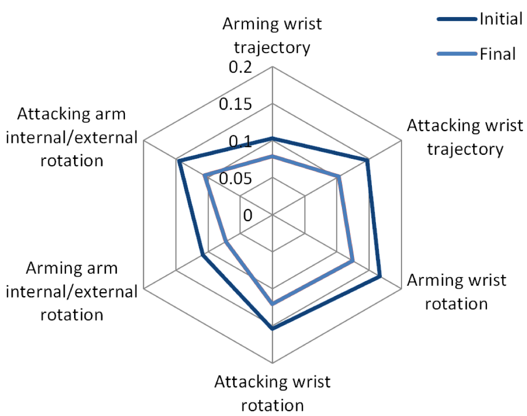


(b) Progression of the Mirror Group

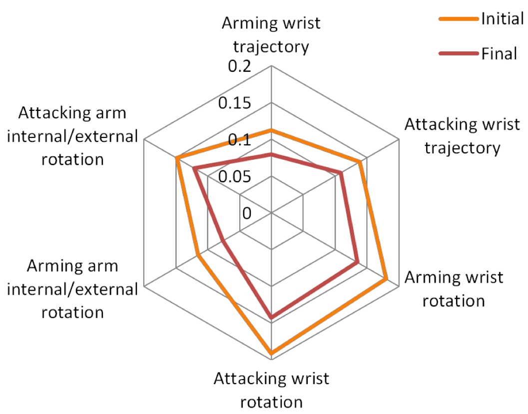


(c) Comparison of the Final Results of the 2 Groups

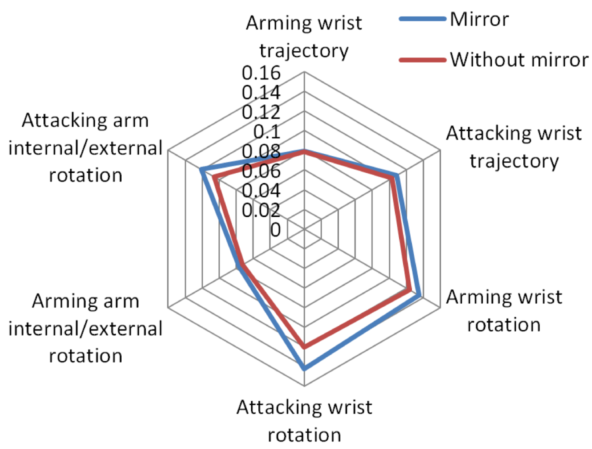
Figure 5.4 - Tsuki Distance from the Instructor



(a) Progression of the Without Mirror Group

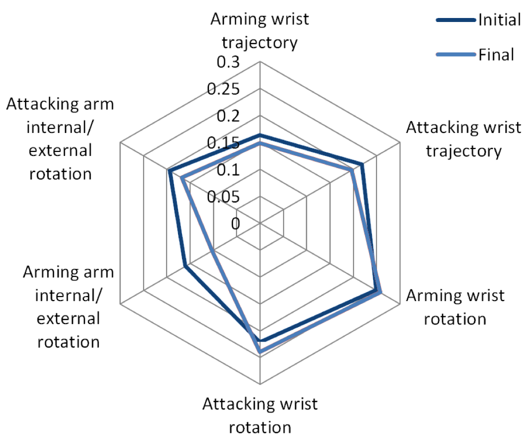


(b) Progression of the Mirror Group

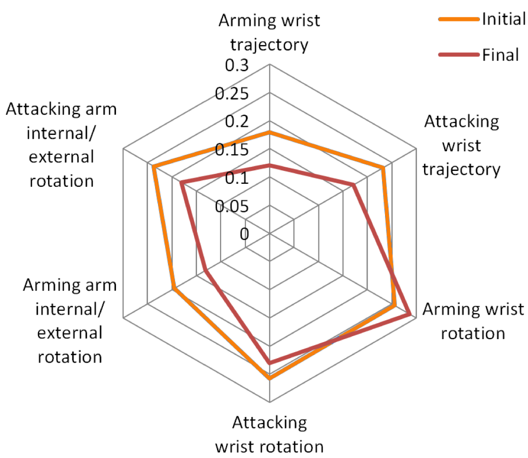


(c) Comparison of the Final Results of the 2 Groups

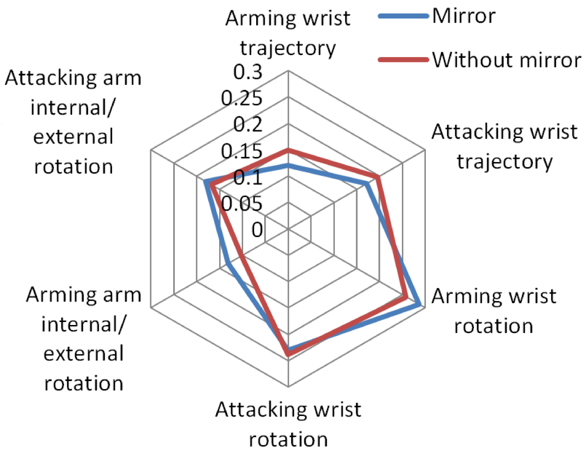
Figure 5.5 - Tsuki Intra-Subject Variability



(a) Progression of the Without Mirror Group



(b) Progression of the Mirror Group



(c) Comparison of the Final Results of the 2 Groups

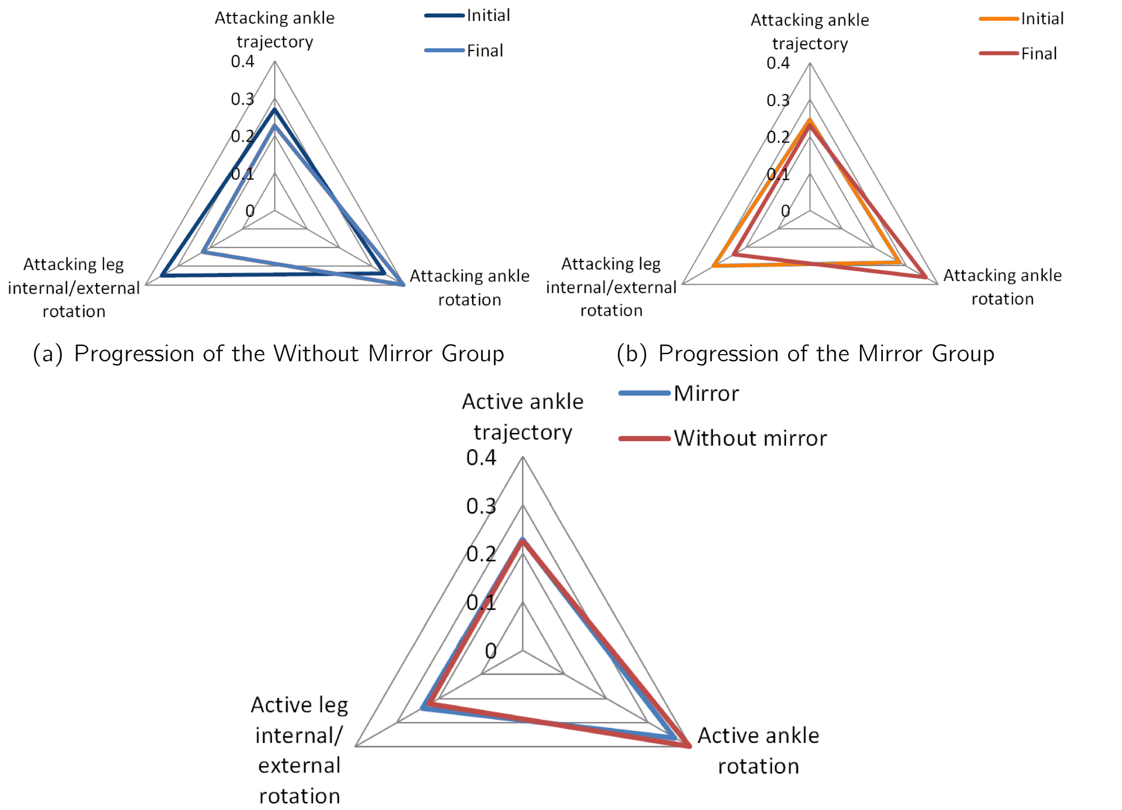
Figure 5.6 - Tsuki Intra-Subject Symmetry

5.2.1.2 Mae Geri

The results for the mae geri are also presented on three sets of figures. The first set (figure 5.7) presents the distance of the performance of the participants from that of the reference trials of the instructor for three performance criteria. As it was the case for the tsuki, the next two sets present the results of the intra-subject variability (figure 5.8) and the intra-subject symmetry (figure 5.9).

For the mae geri, the automatic evaluator did not found any significant difference in any of the initial and final levels of the two groups, neither than in the improvement. The only exception is on the final level of the symmetry of the ankle rotation, where the mirror group significantly outperformed the without mirror group. There is no significant improvement of any group on any metric and on any criteria except for the without mirror group that significantly improved its distance from the instructor in the case of its ankle trajectory and its internal/external leg rotation.

There is no exact correspondence to the trajectories and rotations criteria from the automatic evaluator to the experts grading, but we can assume that these are implied in the different positions and posture of the foot and knee at the different phases. Consequently, an improvement should have been observed.

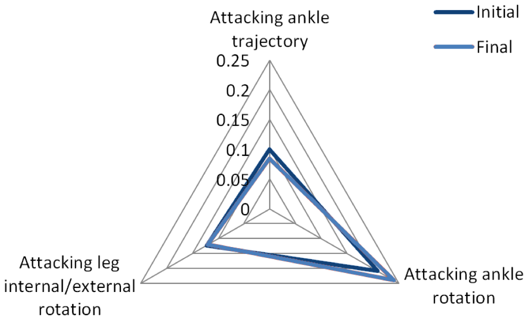


(a) Progression of the Without Mirror Group

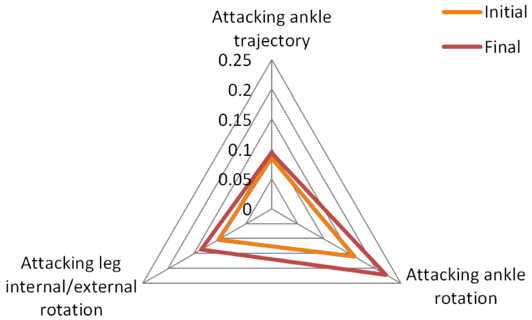
(b) Progression of the Mirror Group

(c) Comparison of the Final Results of the 2 Groups

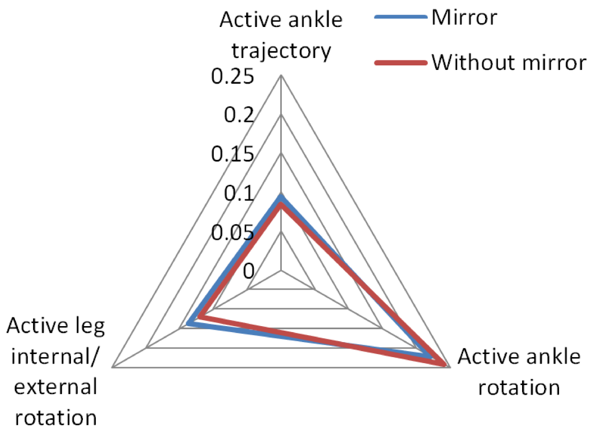
Figure 5.7 - Maegeri Distance from the Instructor



(a) Progression of the Without Mirror Group

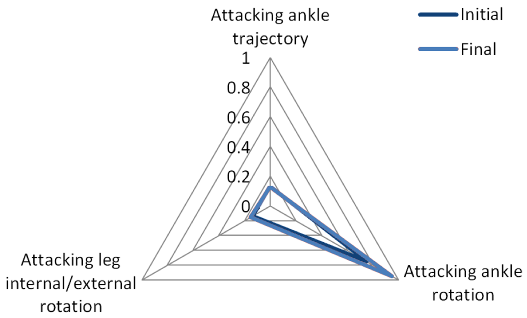


(b) Progression of the Mirror Group

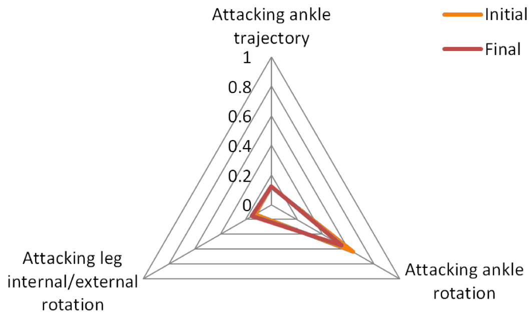


(c) Comparison of the Final Results of the 2 Groups

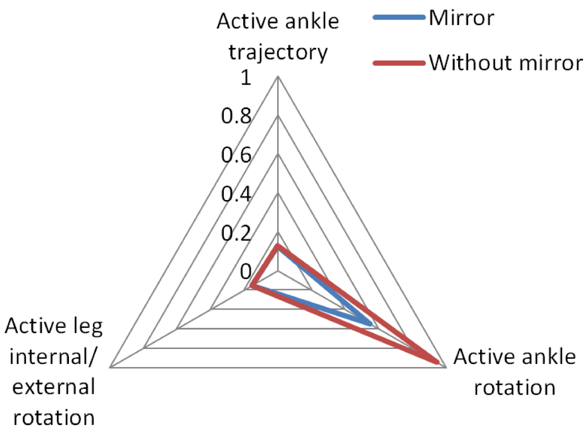
Figure 5.8 - Maegeri Intra-Subject Variability



(a) Progression of the Without Mirror Group



(b) Progression of the Mirror Group



(c) Comparison of the Final Results of the 2 Groups

Figure 5.9 - Maegeri Intra-Subject Symmetry

5.2.1.3 Soto Uke

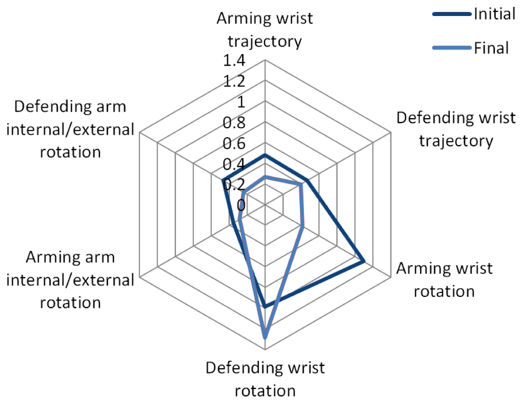
Three sets of figures are presented for the soto uke. The first set, illustrated by figure 5.10, is the distance of the participants performances against the reference trials of the instructor. The initial level of both groups is equivalent on most criteria. However, there is a significant difference between the two groups at the advantage of the mirror group in the case of the internal/external defending arm rotation and the arming wrist rotation.

Both groups improved there performance on the arming wrist trajectory. The mirror group also improved it for the defending arm trajectory. The without mirror group improved its arming wrist rotation and its defending arm internal/external rotation for which it had started at a worst level than the mirror group.

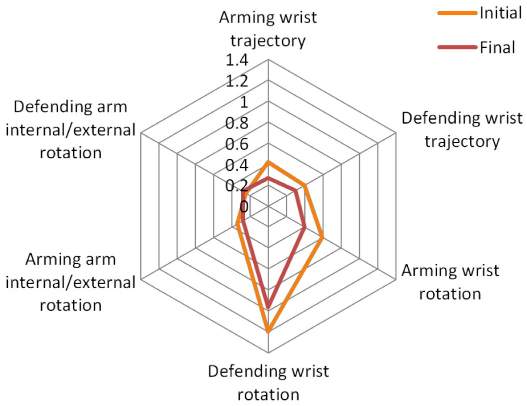
The final level of both groups is equivalent, except for the defending arm trajectory where there is a significant difference at the advantage of the mirror group. There is a significant difference in the improvement of the internal/external defending arm rotation for which the without mirror group had significantly started at with a larger distance from the instructor. The improvement on all the other criteria is equivalent between the group.

According to the expert graders both groups significantly improved their trajectories and rotation. They also improved there elbow positions and postures on the starting and ending of the gesture. Consequently, the automatic results is partially in contradiction with the graders since it has not observe all the improvements.

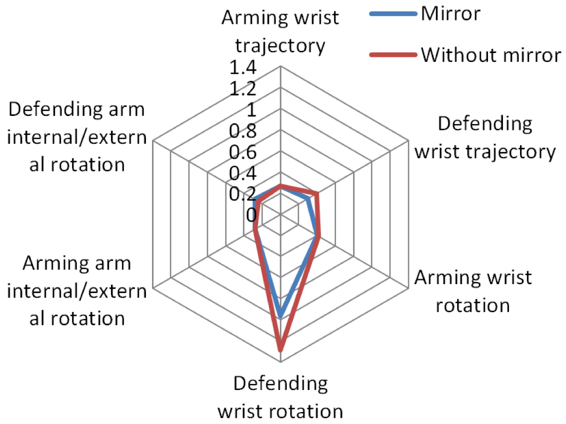
Figure 5.11 presents the results of the intra-subjects variability. As it was the case for the first



(a) Progression of the Without Mirror Group



(b) Progression of the Mirror Group

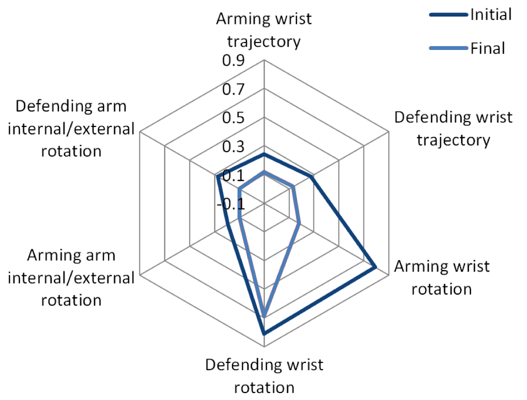


(c) Comparison of the Final Results of the 2 Groups

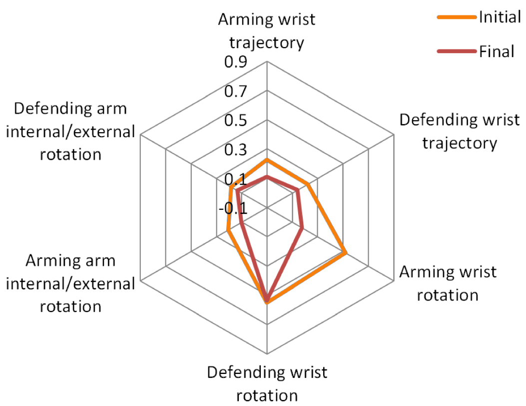
Figure 5.10 - Soto Uke Distance from the Instructor

set, the two groups started at equivalent level except for the the internal/external defending arm rotation and the arming wrist rotation where the without mirror group had a worse performance than the mirror group. Both groups improved there performance on all the criteria except the rotation of the defending wrist. The without mirror did not improved on the internal/external rotation of the defending arm neither.

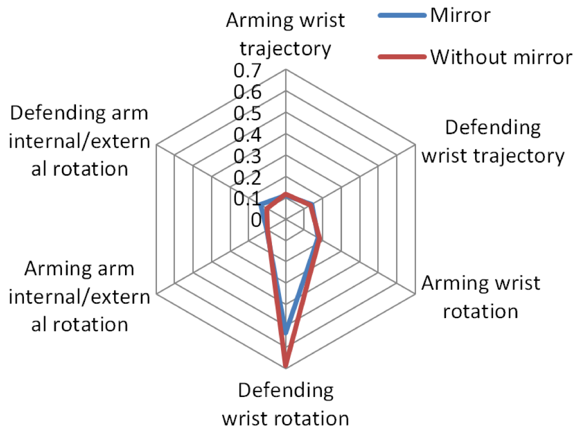
The final level of both groups is equivalent and there is no significant difference on the improvement neither except for the defending arm internal/external rotation. As it was the case for the first set, the without mirror significantly improved, but had also started at a significantly worse level than the mirror group. No comparison with the experts grading is possible, since variability is not evaluated by the experts.



(a) Progression of the Without Mirror Group



(b) Progression of the Mirror Group

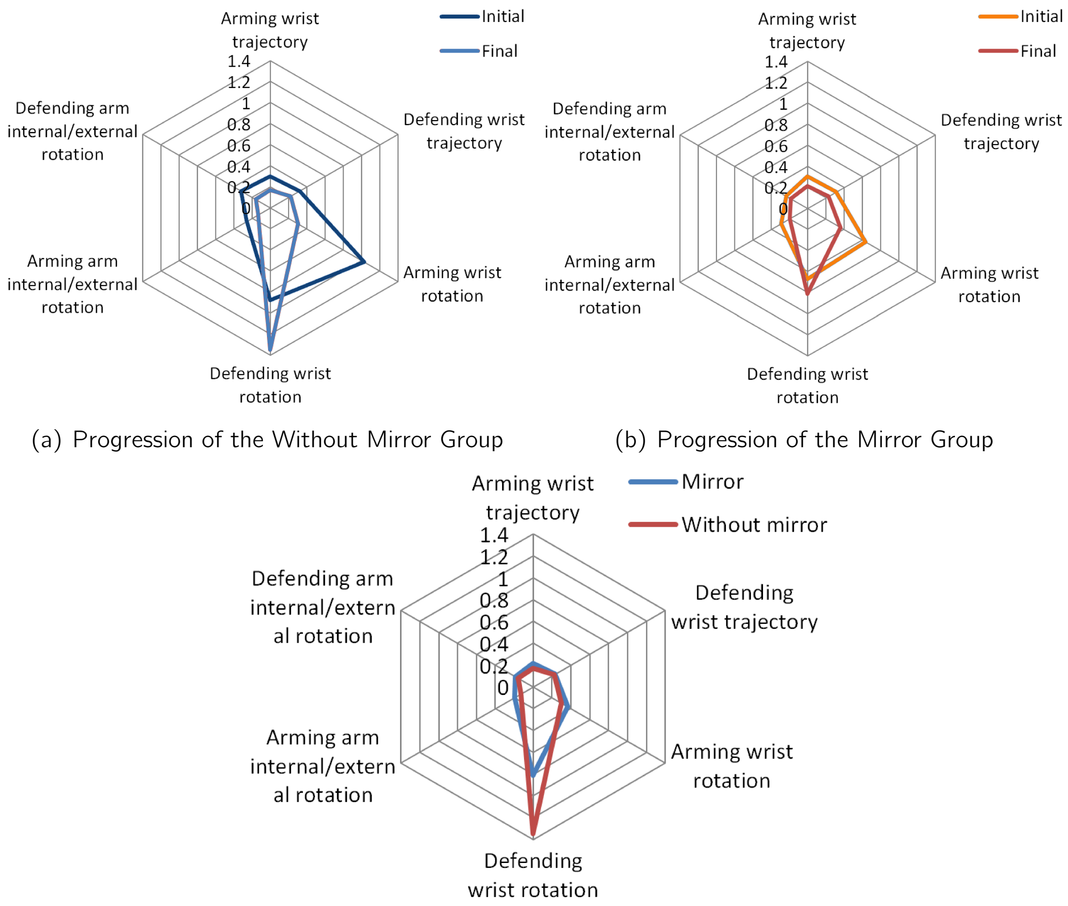


(c) Comparison of the Final Results of the 2 Groups

Figure 5.11 - Soto Uke Intra-Subject Variability

The last set illustrated in figure 5.12 presents the results for the intra-subject symmetry. The scenario is similar to that of the preceding sets of result. The initial level of both groups is equivalent with a significant difference only on the arming arm rotation where the without mirror had a worse performance than the mirror group.

The without mirror group improved its performance on all the criteria except for the rotation of the wrist of the defending arm. The mirror group significantly improved its performance on the trajectory of the defending wrist and on the internal/external rotation of the arming arm. There is not significant difference between the final level nor between the improvement of both groups. Although there is a large difference between the final level of both groups for the defending wrist rotation, the standard error mean is so large that the difference is not significant. Intra-subject symmetry is not evaluated by the expert graders, therefore no comparison can be established.



(a) Progression of the Without Mirror Group (b) Progression of the Mirror Group

(c) Comparison of the Final Results of the 2 Groups

Figure 5.12 - Soto Uke Intra-Subject Symmetry

5.2.1.4 Comparison with the Evaluation of Expert Level Subjects

We consider that the automatic evaluator is able to distinguish experts for novices when for an evaluation there is a significant difference between the expert group and both novices group. In the case of the distance from the instructor reference trials at the initial evaluation, that happens only for the case of the arming wrist trajectory for the tsuki, and for no criterium of the mae geri and the soto uke. However, it also find a significant difference with the without mirror group for two criteria of the mae geri (angle trajectory and internal/external rotation) and three criteria of the soto uke (arming wrist trajectory and rotation, and internal/external rotation of the defending arm). We have to remember that in the case of the trajectory and internal/external rotation at the soto uke, the without mirror group had started significantly worse than the mirror group. It is important to recall that the expert graders were able to distinguish experts from novices in all cases at the initial evaluation, with three exceptions linked to the a starting/ending position of the wrist and the timing of the tsuki gesture in the case of the mirror group for the first evaluator and two criteria linked to the stating position of the arming wrist in the case of the soto uke for both group but for the first instructor only.

In the case of the variability criteria at the initial evaluation, there is a significant difference between the results of the experts and the novices group for half of the criteria, namely both internal/external rotation and the attacking wrist trajectory. It is also true between the mirror group and the experts for the arming wrist trajectory. For the mae geri, the automatic evaluator is unable to distinguish experts from novices except for the case of the without mirror group on the internal/external knee rotation parameter. In the case of the soto uke, it is able to distinguish with a statistically significant difference four criteria out of six. The criteria where there is no significant difference are the arming wrist trajectory and the defending wrist rotation.

In the case of the symmetry criteria at the initial evaluation, the is no significant difference between the both novices groups and the experts group on any criteria. However, there is a significant difference in the case of the mirror group for the attacking wrist trajectory in the tsuki, and for the arming wrist trajectory and arm internal/external rotation for the mirror group at the soto uke, and for the arming wrist trajectory and the defending arm internal/external rotation for the without mirror group.

In the case of the tsuki, that significative difference between the novices and the experts groups is still present at the final evaluation in the case of the distance from the instructor for the arming wrist trajectory and for the variability of the defending wrist trajectory and attacking arm internal/external rotation. No significant difference remain for the mae geri and the soto uke with two exception, the mirror group internal/external knee rotation variability for the mea geri and the internal/external arm rotation of the mirror group for the soto uke. In the first case it is because the criterium performance worsen between the initial and final evaluation and in the second case it is because there is no improvement in its performance.

5.2.1.4.1 Distance Between Two Captures of the Instructor

When we perform the test of evaluating the instructor against itself using the data of two different capture sessions, his variability and symmetry metrics remain consistent. However, its distance with respect with his reference trials falls in the same range of distance as that of the other experts with respect to his reference trials. That is largely outside the average +/- the standard error mean of his variability. Consequently, that mean that the complete cycle from capture to the output of the evaluation results introduce a noise that is probably too large to draw any conclusions from the distance measurements. That is consistent with the difficulty of the system to distinguish experts from novices and from initial and final evaluations. Therefore, conclusions can only be drawn from variability and symmetry results.

5.3 Discussion

Evaluation by experts is time consuming and subject to inconsistencies due to the human nature. Furthermore, to attenuate the subjective character of human evaluations, many graders would be required. That is in contradiction with the fact that for very specific domains, experts are rare. Moreover, since that type of studies duration can be spread over many years, in the case of the comparison of many learning environments, the probability of being able to keep the same evaluator for all the duration of a study is low. Besides, the second study demonstrated that grading method varies largely between two graders, even if they were formed at the same school. Therefore, changing graders in the course of an experiment would bias the interpretation of the results.

Consequently, there is a need for an objective grader that would be available and consistent over time. That can be achieved throughout the creation of an automatic grader. As the grids of the second studies demonstrate (refer to appendix 7.2), the evaluation of a performance as a high number of variables. It is also difficult to relate and give a ponderation to these variables in order to obtain a global score. Furthermore, human graders probably consider elements that are not strictly related to quantifiable parameters of the kinematic of the gesture. For all these reason, the creation of an automatic grader for the evaluation of a motor skill is a complex problem that represent a research project in itself.

In the scope of that thesis, we decided to rely on an already established method for the comparison of two signals varying in duration (related to the execution speed) and timing (related to variable pause duration between different phases of a gesture). That evaluation method was developed in the context of the biofeedback project and consequently had to respect the project constrain, namely to provide the motion to analyze in the BVH format. The computational tool used to compare the participants signal to reference signal of the instructor is derivative dynamic time wrapping (DDTW) [Keogh2001]. The preceding sections explained in detail the implementation of the automatic grader and the preparation of the performance captures.

The performance criteria chose for evaluation in the automatic grader are these that we estimated that would correctly be analyzed by the DDTW method. These performance criteria are summarized in table 5.1. They correspond to trajectories and rotations of the main limbs implied in the gesture. For the punching (tsuki) and the defending (soto uke) gesture, they are both wrists trajectories and rotation, and the internal/external rotation of the arms. For the kicking gesture, they are the ankle trajectory and rotation, and the leg internal/external rotation. The internal/external rotation of the arms and legs are computed by the creation of morphologically independent knee or elbow spacial positions. That method as been developed by Kulpa et al. [Kulpa2005b].

The participants' performances are evaluated by computing their distance from the reference trials of the instructor. The instructor was chosen as the reference to be consistent with the teaching method where the instructor, teaching by demonstration, is the model the learners tried to achieve. However, results concerning the distance from the instructor are inconsistent with the experts' evaluations. Effectively, a statistically significant improvement between the initial and the final evaluations is observed only on a few criteria although it should be observed always. Moreover, the comparison with automatic evaluation of experts' performances confirmed that the system is not precise enough to observe these improvements. The evaluation of the instructor against himself in different capture moments, suggest that noise is introduced by the capture and preparation protocol.

Nevertheless, intra-subject results are accurate since the same bias is introduced in all the trials of a same participant for a same capture. In the case of the tsuki and the soto uke, the variability is precise enough to distinguish experts from novices before training in most cases and after training in some case. The precision seems to be sufficient to detect significant progression between an evaluation and the other. Variability and symmetric give no information about the correctness of the gesture, however, they provide information about the capacity of a participant to repeat a gesture consistently and for both laterality. We can hypothesis that that is an external measure of the degree of appropriation of the gesture by the learner.

As it was the case of the other external measures, it is not possible to observe a significant difference between the two groups. For example, on the symmetry criteria of the tsuki, the mirror group has a significant improvement on more criteria than the without mirror group, but that tendency is exactly the inverse for the criteria of the soto uke. The automatic evaluator would need to be refine to be more accurate and precise and to include other analysis methods and performance criteria to be useful. However, one of the conclusions of the second study saying that external measures of the performance are probably not sufficient to evaluate the relevance of a learning environment remains true.

5.4 Conclusion

The main objective of the third study was to evaluate the usage of an automatic grader based on derivative dynamic time wrapping and developed in the context of the Biofeedback project. An automatic grader is required to palliate to the inconsistent character of intra-human grading over time and of inter-human grading. Effectively, a consistent grading system would be required for the comparison of the multiple learning environments developed in the context of that thesis and for those to be developed in the future. Furthermore, an automatic system could provide information that are difficult for human to grade such as the variability and symmetry of a participant over many repetitions of the same gesture. These criteria might provide interesting information about the degree of appropriation of the gesture by the participant performing it.

Unfortunately, the automatic grader evaluated in that study proved to be insufficient in term of accuracy and precision to correctly evaluate the distance between a reference gesture and another performance. The problem appears to be due to the introduction of noise in the capture and preparation of the of the trials to be sent to the automatic grader. However, intra-subject criteria are still valid and improvement between the two evaluations were observed. However, as it was the case for the other external criteria, these are insufficient to conclude on the relevance of a learning environment.

Chapter 6

General Discussion

6.1 Summary of the Studies

The main question of that thesis is on the relevance of using virtual human to teach complex motor skills. The question was explored throughout the conception of a case study based on three karate gestures. Karate gestures were chosen because they are good representative of complex motor skills and it was possible to establish a precise performance criteria list for the evaluation of their performance. A virtual learning environment was built using the XVR virtual reality platform. That virtual environment was extremely basic in order to study the impact of the virtual human on the learning process of the participant in isolation of other factors related to the virtual reality media. Participants were immersed in the virtual environment throughout a human size tridimensional stereoscopic and egocentric projection. A karate lesson was built based on a teaching by demonstration method. Teaching by demonstration is the most common teaching method used in sports. In the learning virtual environment, the emphasis was put on motion fidelity rather than on any other factors. Motion fidelity is of first importance in the case of teaching by demonstration since the participant build its internal representation of the task to perform based on the visual and oral information he received from the instructor. Furthermore, studies have shown that even in the case of low graphical fidelity, subjects are able to correctly identify gestures [Vignais2009a, Vignais2010, Johansson1973].

A first study was performed to answer the question of the feasibility of learning complex motor skills from the imitation of a virtual human. That study compared the performance of thirty-one novices divided among three groups, namely a traditional karate class, a video instructor, and a virtual human instructor. All the participants of that study followed the same karate lesson in different learning environments. The training was at the pace of one hour per week during three weeks. The participants performance were evaluated by the instructor from video captures of their performance. The expert instructor graded in a similar manner he would used for a traditional class. Two evaluations were performed, one week prior to the training in order to assess their initial level, and one week after the last training in order to assess their final level. Results showed that every participants were novices on the three karate gestures prior to the training and that every participants improved their performance as a result of the training. No significant difference in the improvement and on the final level of the participants was found among the groups. These results permitted to conclude that learning from the imitation of a virtual human is possible. Furthermore, in the limit of the precision of the evaluation method used in that study, learning by imitation of a virtual human is equivalent to learning by imitation of a video reproduction of a human, and even to learning from imitation of a physical human.

The question pertaining to the second study was to evaluate if the presence of a virtual self representation in the learning environment has an influence on the learning task of the participants. To answer that question, the virtual environment was augmented with a mirrored projection of a cylindrical gray avatar displaying the participant motion in realtime. The participant avatar was created from cylindrical shapes in order to represent the participant morphology with high fidelity. As it was the case for the reproduction of the instructor motion, motion fidelity was prioritized. In order to evaluate the impact of the mirrored avatar on the performance improvement, eighteen participants were divided in two groups. One group trained in the basic virtual environment and the other one trained in the mirror version of the environment. The training lesson and pace was the same as that of the first study. The second study question was answered with two different and complementary approaches: 1) the evaluation of the performance 2) the point of view of the participants throughout the usage of evocation interviews.

One critic that could be formulated about the first study, is that the performance evaluation method is not precise enough. Even if the global performances of the participants are equivalent, the media use for teaching might have an influence on different performance criteria. From the evaluation method used in the first study, it is possible to know if the global performance improvement is similar but it is impossible to know if the participants improved differently on specific performance criteria. To assess that critic, grading grids and scales were developed with a precise list of performance criteria for every gesture. In that second study, every single criteria was evaluated separately on a seven degrees Likert scale. A score for the global performance was also attributed for each performance on the same scale. In order to assess the validity of the grading scale, a second evaluator was asked to grade the same performances. Both graders were also asked to grade experts' performances.

Evocation interview were performed at the end of the first and the third training session. Their aim is to let the participants talk about what they felt in the training environment. The participant is accompanied in is discourse to express the experience he lived while trying to accomplish the learning task. The verbatim of the interview is then analyzed to identify the important aspect of the discourse of the participant. Important aspects are : 1) the participants description of the learning task for the three gestures 2) the participants goals in the learning task 3) what the participants are using in the learning environment to accompanied their learning 4) what are the participants internal state, how do they feel, and how do they perceive the environment. The results of these interview was used to reinterpret and contextualize the performance evaluation results.

Results of the second study were interpreted with regards of tendencies observed by both expert evaluators. As it was the case for the first study, it was impossible to conclude on the superiority of one learning environment over another based on the external measures of the performance only. In term of the final evaluation, the mirror group seems to have performed better, but in therm of global improvement, the inverse conclusion could be drawn. The evocation interview results permitted to understand these results. We observed that the mirror was rarely used, particularly in the first training. From the participants discourse, we can hypothesis that it is too early in the learning process for the participants to regulate their action using that type of visual feedback. At the third training, we observed that the mirror was used, but not always with the goal to regulate the action. Some participants used the mirror as a motivational factor. Effectively, after the three training session, most participants were bored of all the repetitions and searched for a distraction. That observation is not only negative. It also mean that the mirror could be used to keep the participants attention.

Moreover, an unexpected result was learned from the evocation interview. Most of the participants strongly rely on auditory information to regulate their action. It can therefore be hypothesis that a learning environment using audio feedback would help the participants to improve their performances. Participants also asked for more a more plausible environment with interaction and evaluation of their performance. They asked for targets to animate the repetitions of the gesture. Additionally, they want to take full advantage of the individual and personalized aspect of the virtual lesson. They want to have full control on the pace of the lesson and on the point of view from which they observed the instructor. Evocation interview were, therefore, useful to contextualized the performance evaluations, to analyze the learning activity of the participants, and to get insight of the participants wish for a virtual learning environment.

However, one observation of both studies is that performance evaluations are time consuming and subject to human inconsistency. In order to evaluate many learning environment over a long period of time, a consistent method to evaluate the performance is required. The aim of the third study was to evaluate an automatic grader developed in the context of the Biofeedback project. That automatic evaluator is based on derivative dynamic time warping. It is consequently limited to a small amount of performance criteria. The performance criteria that were chosen concerned the wrists and ankles rotations and trajectories and the internal/external arm and leg rotations. The automatic evaluator was run on the motion captures of the performance evaluations of the participants of second study. The participants performances were evaluated with respect to reference trials of the instructor.

Unfortunately, the results for the distance to the instructor proved not to be precise enough to provide significant information about the performance. Tests of the automatic graders identify the introduction of noise in the preparation of the motion capture to BVH files as a potential source of imprecision. Nevertheless, results about the intra-subject variability and symmetry were accurate and provided information difficult to obtain from human grader. Improvement in both these performance criteria can indicate a better appropriation and construction of the internal model of the gesture since the participant is able to repeat it more consistently and using both laterality. However, no global significant difference was found between the two groups for these criteria.

In conclusion, evaluations of the performance alone are not sufficient to evaluate the relevance of a learning environment. In order to evaluate a learning environment, the learning task need to be understood and that can be done only with insight on the point of view of the learners. From the performance evaluation alone, it was only possible to conclude that all the learning environment of that thesis permit an improvement on the performance of the three karate gesture. However, the addition of the evocation interview gave us interesting insights on the development of future environments with better feedback methaphors.

6.2 Future Work: Toward a Virtual Coach

In order to have a virtual environment with a virtual coach, some improvements in our basic virtual environment are required. That section presents some of these improvements. A first category of improvement concerns an automatic evaluator able to provide feedback in differed time, and ideally in realtime. A second category concerns improvement of the plausibility and interactions of the virtual environment.

6.2.1 Toward an Automatic Evaluator

In order to develop an efficient automatic grader, the evaluation task of the human graders need to be understood. Biomechanics analysis of the kinematic of the gestures can permit to establish a list of performance criteria that could be analyzed using diverse computational methods, but the process of giving a global score is not just to add results of diverse criteria. Furthermore, there are potentially some criteria that are not based on kinematic information. The study of the evaluation task of the experts grader could be based on these two suggestions:

1) Anonymize the evaluation by experts process:
Problems:
(a) the bank of local experts is relatively small, consequently all experts know each other and therefore the evaluators could easily know who was an expert in the pool of beginners before and after training and experts. That might have influence the grade attributed to the participants of the experiment versus the grade attributed to experts.
(b) When grading beginners, it might be possible that experts evaluators were able to remember having seen another video of same the participant and therefore might have been able to determine which of the videos was before and after training and grade an improvement accordingly.
How:
All performances at both evaluations were also captured using tridimensional motion capture, we could use these captures and map these to amorphological virtual characters. The expert evaluators would then grade videos of these mapping. We could even imagine having the evaluators grade tridimensional and stereoscopic virtual characters. It could be interesting to observe if the grading would be significantly different for these two conditions with respect to the video one.

2) Use evocation interview method on the evaluators:
Problems:
(a) We observe that the performance criteria provided by the expert evaluators (and taught by the instructor) sometime differ from what the biomechanics analysis measures. We want to know if these variation result from an adaptation and an appropriation of the theoretical performance criteria from the experts or if it is an abusive language problem. In both cases, we want to know how the experts interpret these when they evaluate the participants. (b) Experts always succeed in differentiating experts from novice and even trained novice performance and almost always succeed in differentiating experts from novice even on individual performance criteria. The automatic system fails to do so except on some specific performance criteria. We want to know how the expert evaluators use their knowledge of morphologic adaptation and appropriation of a gesture by an expert in order to grade, for example, a trajectory that when considering only its kinematic might seem equivalent or even worse then a novice one.

6.2.2 Toward a more Plausible Virtual Learning Environment

We observed that after 3 weeks of training on the same lesson, the participants are extremely annoyed. That situation is probably less true in a traditional environment even if the instructor teach exactly the same lesson content. This is due to slight variations of the context that are inerrant to humans. Having the instructor looking at you, making small language or motion mistakes and correcting himself, coughing or panting creates small variations that keep the participants attention. Having a group surrounding the participants with subjects learning at various pace, is also a motivational factor. These ideas together with the suggestions of using targets, of giving control on the lesson, that combined with the discovery of the importance of audio feedback should be used to develop future version of the virtual environment.

Improvements to the virtual environment can be think in relation with the european project Traverse in the context of which it was develop during an internship at the Event Lab, university of Barcelona. That project emphasize three important aspects :

1. The illusion of body distortion: in other words, the ownership of a virtual body in the virtual environment. That virtual body can correspond exactly to the physical one or be different. For example, in our second study, the avatar was performing the same action the participant did. In another environment, the avatar could perform by exaggeration the participant mistake or on the counter side by performing better than the participant. These variation could help the participant notice his mistake or at the contrary become more confident in his capacities.

2. Making virtual reality physical: that point as not been explored in the studies presented in that thesis, but that would imply having haptic feedback. Effectively, we could imagine having vibrotactile feedback to help the participant. For example, the punching gesture should be performed in straight line. The instructor verbally ask the participant to imagine his arm is going throughout a pipe. We could imagine having a visual pipe on screen and having vibromotor vibrate if the arm hits the sides of the pipe.

3. Making virtual reality plausible: that implies all the slight variations in a human facial expression or language that make every situation unique. That also implies the possibility to have virtual participants in the classroom and make them interact with the physical participant and with the virtual instructor.

In conclusion, the protocol developed in that thesis can be used to evaluate any type of learning by demonstration environments. It should therefore be used to create further versions of the environment. These versions should be based on the knowledge gain on the learning task of the participant. These should also be based on the directions suggest by the Traverse project. An automatic evaluator is an important component both of the evaluation protocol in of future interactive version of the learning environments. In order to develop an efficient automatic evaluator, the evaluation task of the human graders need to be understood. That could be done using evocation interview in a similar way it was done to study the learning task. An automatic evaluator would need to take into account many variables and would need to rely on diverse computation tools. The problem of the noise introduce by the actual system would need to be resolved.

Conclusions and Perspectives

That thesis presented different environments for teaching by demonstration. A protocol was elaborated to study: 1) the performance of the learner in these environments 2) the point of view of the learner on the learning task presented in these environments. That protocol could be used to study any learning environment based on teaching by demonstration. The literature review showed that virtual reality can be used as a behavioral study tool. It has been used to that aim in psychotherapy and in sports sciences. Furthermore, Desmurget [Desmurget2006] mentioned that although it is the most common practice in sport teaching, teaching by demonstration has been studied rarely. The protocol we developed could be used to create standard and controlled virtual environments to study motor skills learning by imitation in a laboratory setup.

Moreover, the knowledge about the learning activity thereby obtained could be reinvested in the development of more efficient virtual learning environments. That protocol therefore permits the creation of an engineering loop were the knowledge gained at every iteration of the loop is reinvested in further versions of the environment. A typical example of that, is the knowledge that was gained from the evocation interview of the second study about the usage the learner made of all the indices pertaining rhythmic information. That knowledge could be used to create a feedback metaphor based on sound information rather than on visual one, such as the environment proposed by Takanata et Al. [Takahata2004].

An understanding of the learning task is essential in the development of training accelerators. That type of training environments investigated by the european project SKILLS supposed a complete comprehension of the learning process related to the acquisition of a specific skill since they proposed to pinpoint some components of that skill and train them using the potential of virtual reality. An example of that is a virtual juggling system were gravity is altered to ease the learning of juggling [Lagarde2011]. In that regards, the protocol we developed in that thesis could be used 1) to pinpoint the specific aspects that could be exploited by the training accelerator and 2) to evaluate the pertinence of the training accelerator and 3) to reinvest the knowledge gain at each of the two previous steps to refine the training accelerator.

The same is true of exergames. The health issues related to the obesity crisis are a danger for occidental society. Studies have shown [O'Loughlin2012] and it was also mentioned in the evocation interviews presented in the second study that among the reasons for not practicing sports, there is the social pressure of being judge negatively by peers. That is particularly true of female teenagers. These studies have also shown a displacement of the time dedicated to sports toward the practice of sedentary activities including video gaming. Therefore, there exist a real potential for individual practice of video game sports at home, but that potential need to be address by multidisciplinary studies including serious sports and physical activities sciences. Exergames could consequently largely benefit of a protocol like the one we proposed in our studies. For example, the evocation interviews permitted to outline that participants confronted with their mirrored avatar were more motivated then the one from the other group. Moreover, the participants of our studies proposed many ideas to improve the game play of our environments. These ideas could be investigated throughout the loop created with our protocol. Exergame's environments built from sports and augmented with feedback metaphors aimed at improving the game play could potentially be better responses to a safe and efficient physical activity video games than video games augmented to resemble sports. Furthermore, practicing a video sport at home, could potentially help people gain more confidence in their physical abilities, and consequently encourage their sportive practice in general. However, to correctly invest the exergames study field, it would be necessary to augment our protocol with physiological measures of, for example, energy expenses.

Finally, our studies permitted to conclude that learning motor skills from the imitation of a virtual human is possible. Consequently, virtual learning environments for motor skills teaching are relevant. Furthermore, these environments can be used in various types of applications. They can be used as a study tool for standard and controlled investigation of teaching by demonstration. They can also be used in an engineering loop for the development of further learning environments and training accelerators. They also have a potential usage in the development of exergames in response to the international obesity crisis.

Contributions

That research interested the domain of serious games, exergaming, and virtual training and teaching environments that itself interested many fields of research including branches of computer sciences, sports sciences, learning sciences, psychology and social health. Our main contribution is in the development of an innovative evaluation protocol combining external measures of the performance and an analysis of the task from the participant point of view throughout the use of evocation interviews. Other contributions are in the creation of a complete virtual environment and lesson (explanations, drills, exercises) for motor skills teaching, and in the creation of a sport virtual environment rendering in realtime and in high motion fidelity the action of the users.

To our knowledge, evocation interviews have not been used to perform that type of analysis were questionnaires are the common tools that are used. Evocation interviews presented the advantage of not being directive and letting the participants freely talk about their experience as questionnaires and even open questionnaires direct the participant to formulate an answer to a precise question. Slater et Al. have already point out the problem of relying on sole questionnaires to assess presence of the virtual experience of a participants [Slater2007] [Slater2004]. What is also new, is using evocation interview to assess motor skills learning.

In addition, as it was outlined in the "Motivations and Objectives" chapter, very few attempts were made to create and investigate virtual learning environments dedicated to motor skills teaching. That type of environments, is more frequently used to train on specific aspects of a skill, like it is the case with training accelerators, motivate users to perform a mandatory but otherwise annoying and repetitive task, like it is the case in physical rehabilitation or study an already developed behavior of the subjects, like it is the case in psychology and sports sciences. Some examples, that might come closer to what we developed are the Nitendo Wii Yoga and both of the Tai Chi applications developed and investigated by Chua et Al. in 2003 [Chua2003] and by Patel et Al. in 2006 [Patel2006]. However, what further distinguished our studies from these is the evaluation protocol comprising:

1. The pre and post evaluation of all participants outside of their respective learning environment;

2. The post evaluation after a retention period of one week and not during the learning process;
3. The comparative usage of two evaluation measures of the performance (evaluation by experts, biomechanical analysis);
4. The study of the participants internal states using the evocation interview technique;
5. The comparative study of internal and external measures of learning;
6. The comparative study of three learning environments (traditional class, video, virtual);
7. The study of the impact of the virtual human, in isolation, on the learning process.

The precedent studies found in the literature either do not investigate these points because the question of the relevance of virtual reality do not pose in the context where these environments are used or only partially investigated the question.

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Chapter 7

Appendix

7.1 First Study Evaluation Grids

7.1.1 Tsuki Evaluation Grid in French

Évaluateur :	**Date :**
Étudiant :	**Évaluation :**
Synchronisation des bras et mouvement de rotation Hikite Tsuki	
Respect de l'alignement (bras, poignets, coudes) Coudes collés (ne pas sortir les coudes) Poing dans l'axe	
Relâchement global Contraction au bon moment	
Position des épaules Relâché Au même niveau	
Vitesse de réalisation Énergie conservée	
Respiration Synchronisée avec les mouvements	
Résultat :	/10

Table 7.1 - Study 1 Tsuki Evaluation Grid French Version

7.1.2 Tsuki Evaluation Grid in English

7.1.3 Mae Geri Evaluation Grid in French

Évaluateur :	**Date :**
Étudiant :	**Évaluation :**
Respect des 3 phrases Arme	

Table 7.2 - Study 1 Mae Geri Evaluation Grid (continued on next page. . .)

Tend Ramène et pose	
Posture (buste droit, talon au sol) Appui plié Bassin rétro	
Positionnement du pied lors de la frappe Koshi relevé Cheville tendue	
Équilibre	
Respiration Expiration lors du mouvement	
Résultat :	/10

Table 7.2 - Study 1 Mae Geri Evaluation Grid French Version

7.1.4 Mae Geri Evaluation Grid in English

7.1.5 Soto Uke Evaluation Grid in French

Évaluateur :	**Date :**
Étudiant :	**Évaluation :**
Synchronisation des bras (rotation des poignets, respect du temps) Hikite Uke	
Respect des 2 phases Arme Bloque	
Attracteur du bras qui bloque Position coude-poing	
Position des épaules	
Mouvement des hanches	
Respiration	

Table 7.3 - Study 1 Soto Uke Evaluation Grid (continued on next page. . .)

Expiration lors du mouvement Fin de l'expiration au moment de l'impact	
Résultat :	/10

Table 7.3 - Study 1 Soto Uke Evaluation Grid French Version

7.1.6 Soto Uke Evaluation Grid in English

7.2 Second Study Expert's Evaluation Grids

7.2.1 Tsuki Evaluation Grid in French

Fiche d'évaluation - Tsuki

Évaluateur :	**Date :**
Étudiant :	**Évaluation :**
Critères de performance	**Échelle d'évaluation**
Sur toute la durée du geste	
(a) poing effecteur dans l'alignement de l'avant-bras	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) poing antagoniste dans l'alignement de l'avant-bras	pas du tout 1 2 3 4 5 6 7 parfaitement
(c) dos droit	pas du tout 1 2 3 4 5 6 7 parfaitement
(d) pieds parallèles largeur des épaules	pas du tout 1 2 3 4 5 6 7 parfaitement
(e) relâchement des épaules	pas du tout 1 2 3 4 5 6 7 parfaitement
Début et fin du geste	
(a) bras antagoniste tendu, coude non verrouillé	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) poing antagoniste centré sur le sternum niveau chudan	pas du tout 1 2 3 4 5 6 7 parfaitement
(c) poignet antagoniste tourné vers le bas	pas du tout 1 2 3 4 5 6 7 parfaitement
(d) bras effecteur en hikite (coude serré, poing niveau crête iliaque)	pas du tout 1 2 3 4 5 6 7 parfaitement
(e) poignet effecteur tourné vers le haut	pas du tout 1 2 3 4 5 6 7 parfaitement
(f) épaule de face	pas du tout 1 2 3 4 5 6 7 parfaitement

Table 7.4 - Study 2 Tsuki Evaluation Grid (continued on next page. . .)

Critères de performance	Échelle d'évaluation
(g) hanche de face	pas du tout 1 2 3 4 5 6 7 parfaitement
Temporalité du geste	
(a) trajectoire du poing effecteur en ligne droite	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) trajectoire du poing antagoniste en ligne droite (ramener hikite)	pas du tout 1 2 3 4 5 6 7 parfaitement
(c) synchronisation début translation poings effecteur / antagoniste	pas du tout 1 2 3 4 5 6 7 parfaitement
(d) synchronisation fin translation poings effecteur / antagoniste	pas du tout 1 2 3 4 5 6 7 parfaitement
(e) synchronisation début rotation poings effecteur / antagoniste	pas du tout 1 2 3 4 5 6 7 parfaitement
(f) début rotation des poignets au bon moment (à la fin du geste)	pas du tout 1 2 3 4 5 6 7 parfaitement
(g) vitesse constante translation / rotation	pas du tout 1 2 3 4 5 6 7 parfaitement
(h) mouvement des hanches	pas du tout 1 2 3 4 5 6 7 parfaitement
(i) synchronisation de la respiration	pas du tout 1 2 3 4 5 6 7 parfaitement
Note globale :	pas du tout 1 2 3 4 5 6 7 parfaitement

Table 7.4 - Study 2 Tsuki Evaluation Grid French Version

7.2.2 Tsuki Evaluation Grid in English

Evaluation Grid - Tsuki

Évaluator :	**Date :**
Subject Name :	**Evaluation :**
Performance Criteria	**Evaluation Scale**
Gesture While Postural Performance Criteria	
(a) Attacking fist alignment in the forearm axis	not at all 1 2 3 4 5 6 7 perfectly
(b) Arming fist alignment in the forearm axis	not at all 1 2 3 4 5 6 7 perfectly
(c) Trunk posture (straight)	not at all 1 2 3 4 5 6 7 perfectly
(d) Feet position (parallel, shoulder wide)	not at all 1 2 3 4 5 6 7 perfectly
(e) Shoulders posture (relax)	not at all 1 2 3 4 5 6 7 perfectly
Gesture Starting and Ending Postural Performance Criteria	
(a) Arming arm posture (straight, not overstreched)	not at all 1 2 3 4 5 6 7 perfectly
(b) Arming Arm Position (fist centered on the sternum at chudan level)	not at all 1 2 3 4 5 6 7 perfectly
(c) Arming fist orientation (palm looking down)	not at all 1 2 3 4 5 6 7 perfectly
(d) Attacking arm posture (retracted in hikite, elbow close to the body, fist just over the hip)	not at all 1 2 3 4 5 6 7 perfectly
(e) Attacking fist orientation (palm looking up)	not at all 1 2 3 4 5 6 7 perfectly
(f) Shoulders orientation (frontal)	not at all 1 2 3 4 5 6 7 perfectly
(g) Hips orientation (frontal)	not at all 1 2 3 4 5 6 7 perfectly
Gesture Execution Performance Criteria	
(a) Attacking fist trajectory in straight line	not at all 1 2 3 4 5 6 7 perfectly

Table 7.5 - Study 2 Tsuki Evaluation Grid (continued on next page. . .)

Performance Criteria	Evaluation Scale
(b) Arming fist trajectory in straight line (ramener hikite)	not at all 1 2 3 4 5 6 7 perfectly
(c) Gesture start synchronization	not at all 1 2 3 4 5 6 7 perfectly
(d) Gesture stop synchronization	not at all 1 2 3 4 5 6 7 perfectly
(e) Wrist rotation synchronization	not at all 1 2 3 4 5 6 7 perfectly
(f) Wrist rotation timing (at the end of the gesture)	not at all 1 2 3 4 5 6 7 perfectly
(g) Gesture speed uniformity	not at all 1 2 3 4 5 6 7 perfectly
(h) Hips motion	not at all 1 2 3 4 5 6 7 perfectly
(i) Breathing synchronization	not at all 1 2 3 4 5 6 7 perfectly
Global Score :	not at all 1 2 3 4 5 6 7 perfectly

Table 7.5 - Study 2 Tsuki Evaluation Grid English Version

7.2.3 Mae Geri Evaluation Grid in French

Fiche d'évaluation - Tsuki

Évaluateur :	**Date :**
Étudiant :	**Évaluation :**
Critères de performance	**Échelle d'évaluation**
Sur toute la durée du geste	
(a) dos droit	pas du tout 1 2 3 4 5 6 7 parfaitement

Table 7.6 - Study 2 Mae Geri Evaluation Grid (continued on next page. . .)

Critères de performance	Échelle d'évaluation
(b) centre de gravité abaissé (genoux fléchis)	pas du tout 1 2 3 4 5 6 7 parfaitement
(c) relâchement des épaules (bras détendus)	pas du tout 1 2 3 4 5 6 7 parfaitement
(d) pieds parallèles largeur des épaules	pas du tout 1 2 3 4 5 6 7 parfaitement
(e) talons au sol	pas du tout 1 2 3 4 5 6 7 parfaitement
(f) rétroversion du bassin	pas du tout 1 2 3 4 5 6 7 parfaitement
Phase armé	
(a) genou au-dessus de la ceinture	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) orteils relevés, pieds parallèles au sol	pas du tout 1 2 3 4 5 6 7 parfaitement
Phase tendue	
(a) jambe tendue, genou non verrouillé	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) pied pointé	pas du tout 1 2 3 4 5 6 7 parfaitement
(c) orteils relevés	pas du tout 1 2 3 4 5 6 7 parfaitement
(d) pied centré par rapport au corps	pas du tout 1 2 3 4 5 6 7 parfaitement
Phase ramenée	
(a) genou au-dessus de la ceinture	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) orteils relevés, pieds parallèles au sol	pas du tout 1 2 3 4 5 6 7 parfaitement
Temporalité du geste	
(a) vitesse du fouetté	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) équilibre	pas du tout 1 2 3 4 5 6 7 parfaitement

Table 7.6 - Study 2 Mae Geri Evaluation Grid (continued on next page. . .)

Critères de performance	Échelle d'évaluation
(c) synchronisation de la respiration	pas du tout 1 2 3 4 5 6 7 parfaitement
Note globale :	pas du tout 1 2 3 4 5 6 7 parfaitement

Table 7.6 - Study 2 Mae Geri Evaluation Grid French Version

7.2.4 Mae Geri Evaluation Grid in English

Evaluation Grid - Mae Geri

Évaluator :	**Date :**
Subject Name :	**Evaluation :**
Performance Criteria	**Evaluation Scale**
Gesture While Postural Performance Criteria	
(a) Trunk Posture (straigth)	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) Standing Posture (lower the barycenter by slightly bending the knees)	pas du tout 1 2 3 4 5 6 7 parfaitement
(c) Shoulders posture (relax)	pas du tout 1 2 3 4 5 6 7 parfaitement
(d) Feet position (parallel, shoulder wide)	pas du tout 1 2 3 4 5 6 7 parfaitement
(e) Heels position (on the ground)	pas du tout 1 2 3 4 5 6 7 parfaitement
(f) Hips posture (retroverted)	pas du tout 1 2 3 4 5 6 7 parfaitement
Arming Phase Performance Criteria	

Table 7.7 - Study 2 Mae Geri Evaluation Grid (continued on next page. . .)

Performance Criteria	Evaluation Scale
(a) Attacking leg knee position (knee over the belt)	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) Attacking foot and toes posture (foot parallel to the ground, toes pointing up)	pas du tout 1 2 3 4 5 6 7 parfaitement
Kicking Phase Performance Criteria	
(a) Attacking leg posture (straight but not overstretch)	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) Attacking foot posture (pointing)	pas du tout 1 2 3 4 5 6 7 parfaitement
(c) Attacking toes posture (pointing up)	pas du tout 1 2 3 4 5 6 7 parfaitement
(d) Attacking foot position (centered with respect to the body)	pas du tout 1 2 3 4 5 6 7 parfaitement
Retiring Phase Performance Criteria	
(a) Attacking leg knee position (knees over the belt)	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) Attacking foot and toes posture (foot parallel to the ground, toes pointing up)	pas du tout 1 2 3 4 5 6 7 parfaitement
Gesture Execution Performance Criteria	
(a) Kicking speed	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) Equilibrium	pas du tout 1 2 3 4 5 6 7 parfaitement
(c) Breathing synchronization	pas du tout 1 2 3 4 5 6 7 parfaitement
Global Score :	pas du tout 1 2 3 4 5 6 7 parfaitement

Table 7.7 - Study 2 Mae Geri Evaluation Grid English Version

7.2.5 Soto Uke Evaluation Grid in French

Fiche d'évaluation - Soto Uke

Évaluateur :	**Date :**
Étudiant :	**Évaluation :**
Critères de performance	**Échelle d'évaluation**
Sur toute la durée du geste	
(a) poing effecteur dans l'alignement de l'avant-bras	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) poing antagoniste dans l'alignement de l'avant-bras	pas du tout 1 2 3 4 5 6 7 parfaitement
(c) dos droit	pas du tout 1 2 3 4 5 6 7 parfaitement
(d) pieds parallèles largeur des épaules	pas du tout 1 2 3 4 5 6 7 parfaitement
(e) relâchement des épaules	pas du tout 1 2 3 4 5 6 7 parfaitement
Au départ du geste	
(a) bras antagoniste tendu, coude non verrouillé	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) poing antagoniste centré sur le sternum niveau chudan	pas du tout 1 2 3 4 5 6 7 parfaitement
(c) poignet antagoniste tourné vers le bas	pas du tout 1 2 3 4 5 6 7 parfaitement
(d) poing effecteur à l'oreille	pas du tout 1 2 3 4 5 6 7 parfaitement
(e) poignet effecteur tourné vers le haut	pas du tout 1 2 3 4 5 6 7 parfaitement
(f) épaule de profil	pas du tout 1 2 3 4 5 6 7 parfaitement
(g) hanche de profil	pas du tout 1 2 3 4 5 6 7 parfaitement
À la fin du geste	
(a) bras effecteur 90°	pas du tout 1 2 3 4 5 6 7 parfaitement

Table 7.8 - Study 2 Soto Uke Evaluation Grid (continued on next page...)

Critères de performance	Échelle d'évaluation
(b) poing effecteur centré sur le sternum niveau chudan	pas du tout 1 2 3 4 5 6 7 parfaitement
(c) poignet effecteur tourné vers le corps	pas du tout 1 2 3 4 5 6 7 parfaitement
(d) bras antagoniste en hikite	pas du tout 1 2 3 4 5 6 7 parfaitement
(e) poignet antagoniste tourné vers le haut	pas du tout 1 2 3 4 5 6 7 parfaitement
(f) épaule 3/4	pas du tout 1 2 3 4 5 6 7 parfaitement
(g) hanche 3/4	pas du tout 1 2 3 4 5 6 7 parfaitement
Repositionnement	
(a) monter poing antagoniste position de départ effecteur	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) tendre effecteur position de départ antagoniste	pas du tout 1 2 3 4 5 6 7 parfaitement
Temporalité du geste	
(a) trajectoire circulaire du poing effecteur	pas du tout 1 2 3 4 5 6 7 parfaitement
(b) trajectoire du poing antagoniste en ligne droite (ramener hikite)	pas du tout 1 2 3 4 5 6 7 parfaitement
(c) synchronisation début translation poings effecteur / antagoniste	pas du tout 1 2 3 4 5 6 7 parfaitement
(d) synchronisation fin translation poings effecteur / antagoniste	pas du tout 1 2 3 4 5 6 7 parfaitement
(e) synchronisation début rotation poings effecteur / antagoniste	pas du tout 1 2 3 4 5 6 7 parfaitement
(f) début rotation des poignets au bon moment (à la fin du geste)	pas du tout 1 2 3 4 5 6 7 parfaitement
(g) vitesse constante translation / rotation	pas du tout 1 2 3 4 5 6 7 parfaitement
(h) mouvement des hanches	pas du tout 1 2 3 4 5 6 7 parfaitement
(i) synchronisation de la respiration	pas du tout 1 2 3 4 5 6 7 parfaitement

Table 7.8 - Study 2 Soto Uke Evaluation Grid (continued on next page. . .)

Critères de performance	Échelle d'évaluation
Note globale :	pas du tout 1 2 3 4 5 6 7 parfaitement

Table 7.8 - Study 2 Soto Uke Evaluation Grid French Version

7.2.6 Soto Uke Evaluation Grid in English

Evaluation Grid - Soto Uke

Évaluator :	**Date :**
Subject Name :	**Evaluation :**
Performance Criteria	**Evaluation Scale**
Gesture While Postural Performance Criteria	
(a) Attacking fist alignment in the forearm axis	not at all 1 2 3 4 5 6 7 perfectly
(b) Arming fist alignment in the forearm axis	not at all 1 2 3 4 5 6 7 perfectly
(c) Trunk posture (straight)	not at all 1 2 3 4 5 6 7 perfectly
(d) Feet position (parallel, shoulder wide)	not at all 1 2 3 4 5 6 7 perfectly
(e) Shoulders posture (relax)	not at all 1 2 3 4 5 6 7 perfectly
Gesture Starting Postural Performance Criteria	
(a) Arming arm posture (straight, not overstreched)	not at all 1 2 3 4 5 6 7 perfectly
(b) Arming arm position (fist centered on the sternum at chudan level)	not at all 1 2 3 4 5 6 7 perfectly

Table 7.9 - Study 2 Soto Uke Evaluation Grid (continued on next page...)

Performance Criteria	Evaluation Scale
(c) Arming fist orientation (palm looking down)	not at all 1 2 3 4 5 6 7 perfectly
(d) Defending arm posture (fist near the ear, elbow pointing back)	not at all 1 2 3 4 5 6 7 perfectly
(e) Defending fist orientation (palm looking up)	not at all 1 2 3 4 5 6 7 perfectly
(f) Shoulders orientation (3/4 profile)	not at all 1 2 3 4 5 6 7 perfectly
(g) Hips orientation (3/4 profile)	not at all 1 2 3 4 5 6 7 perfectly
Gesture Ending Postural Performance Criteria	
(a) Defending arm posture (arm/forearm at 90° angle)	not at all 1 2 3 4 5 6 7 perfectly
(b) Defending arm position (fist centered on the sternum at chudan level)	not at all 1 2 3 4 5 6 7 perfectly
(c) Defending fist orientation (palm looking to the body)	not at all 1 2 3 4 5 6 7 perfectly
(d) Arming arm posture (retracted in hikite, elbow close to the body, fist just over the hip)	not at all 1 2 3 4 5 6 7 perfectly
(e) Arming fist orientation (palm looking up)	not at all 1 2 3 4 5 6 7 perfectly
(f) Shoulders orientation (3/4 profile)	not at all 1 2 3 4 5 6 7 perfectly
(g) Hips orientation (3/4 profile)	not at all 1 2 3 4 5 6 7 perfectly
Repositioning Performance Criteria	
(a) Arming to defending switch (circular motion of the fist going from hikite to the ear)	not at all 1 2 3 4 5 6 7 perfectly
(b) Defending to arming switch (going from 90° angle to stretch arm)	not at all 1 2 3 4 5 6 7 perfectly
Gesture Execution Performance Criteria	
(a) Defending fist trajectory (circular swiping)	not at all 1 2 3 4 5 6 7 perfectly
(b) Arming fist trajectory in straight line	not at all 1 2 3 4 5 6 7 perfectly

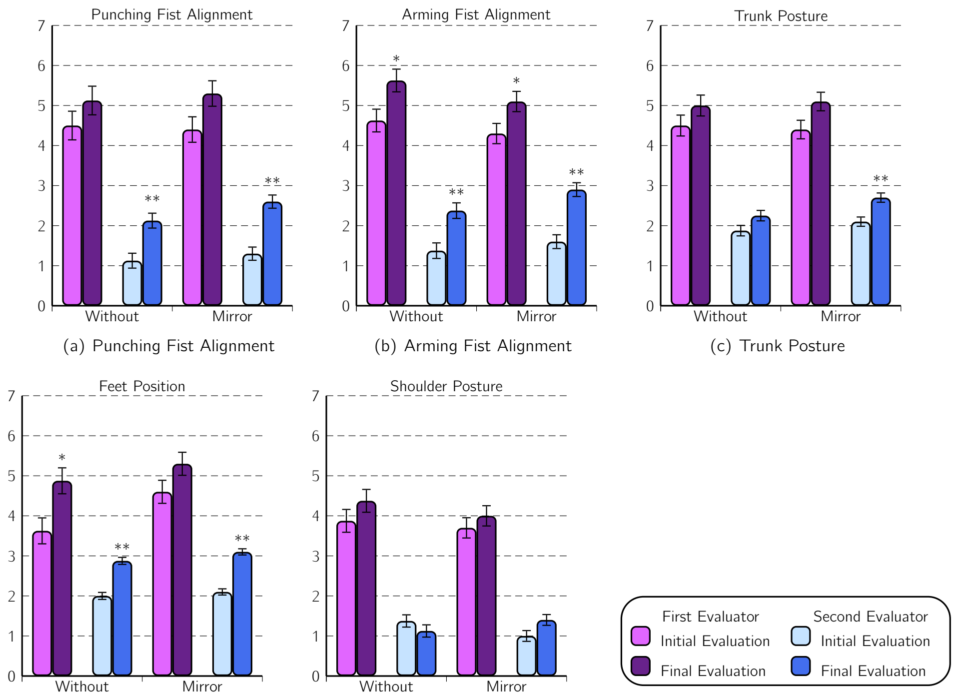
Table 7.9 - Study 2 Soto Uke Evaluation Grid (continued on next page. . .)

Performance Criteria	Evaluation Scale
(c) Gesture start synchronization	not at all 1 2 3 4 5 6 7 perfectly
(d) Gesture stop synchronization	not at all 1 2 3 4 5 6 7 perfectly
(e) Wrist rotation synchronization	not at all 1 2 3 4 5 6 7 perfectly
(f) Wrist rotation timing (at the end of the gesture)	not at all 1 2 3 4 5 6 7 perfectly
(g) Gesture speed uniformity	not at all 1 2 3 4 5 6 7 perfectly
(h) Hips motion	not at all 1 2 3 4 5 6 7 perfectly
(i) Breathing synchronization	not at all 1 2 3 4 5 6 7 perfectly
Global Score :	not at all 1 2 3 4 5 6 7 perfectly

Table 7.9 - Study 2 Soto Uke Evaluation Grid English Version

7.3 Second Study Evaluation by Experts Results

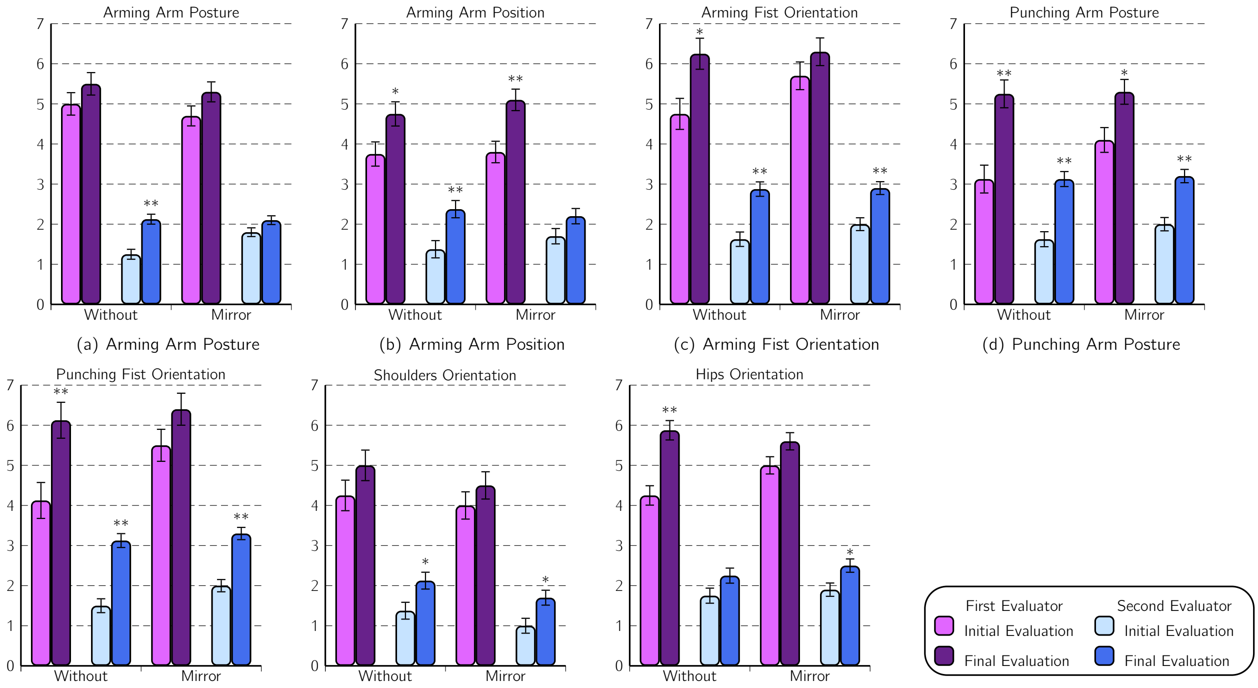
7.3.1 Tsuki Evaluation by Experts Results



(a) Punching Fist Alignment (b) Arming Fist Alignment (c) Trunk Posture

(d) Feet Position (e) Shoulders Posture

Figure 7.1 - Tsuki Gesture While Postural Performance Criteria Evaluated by Experts



(a) Arming Arm Posture (b) Arming Arm Position (c) Arming Fist Orientation (d) Punching Arm Posture

(e) Punching Fist Orientation (f) Shoulders Orientation (g) Hips Orientation

Figure 7.2 - Tsuki Starting and Ending Postural Performance Criteria Evaluated by Experts

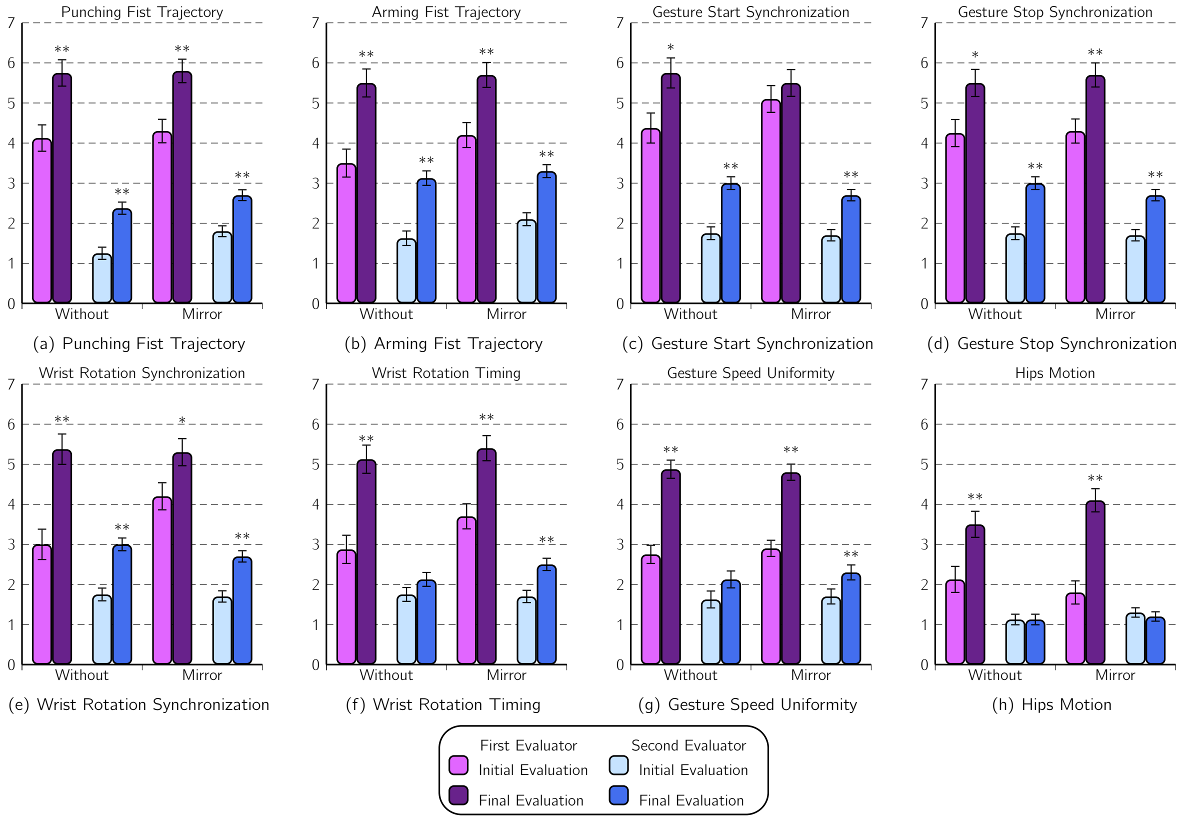


Figure 7.3 - Tsuki Execution Performance Criteria Evaluated by Experts

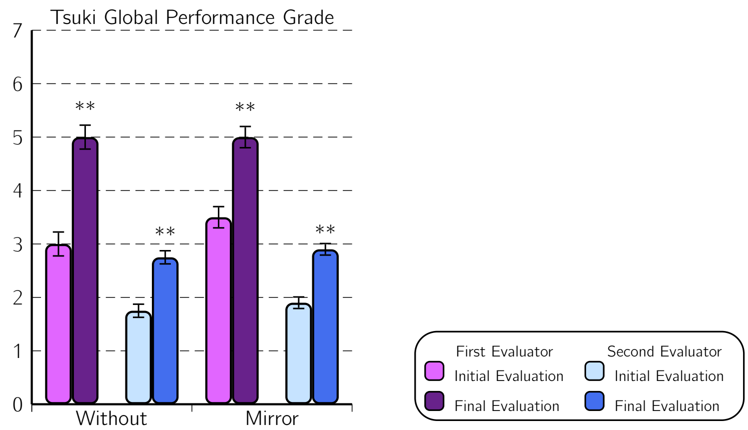
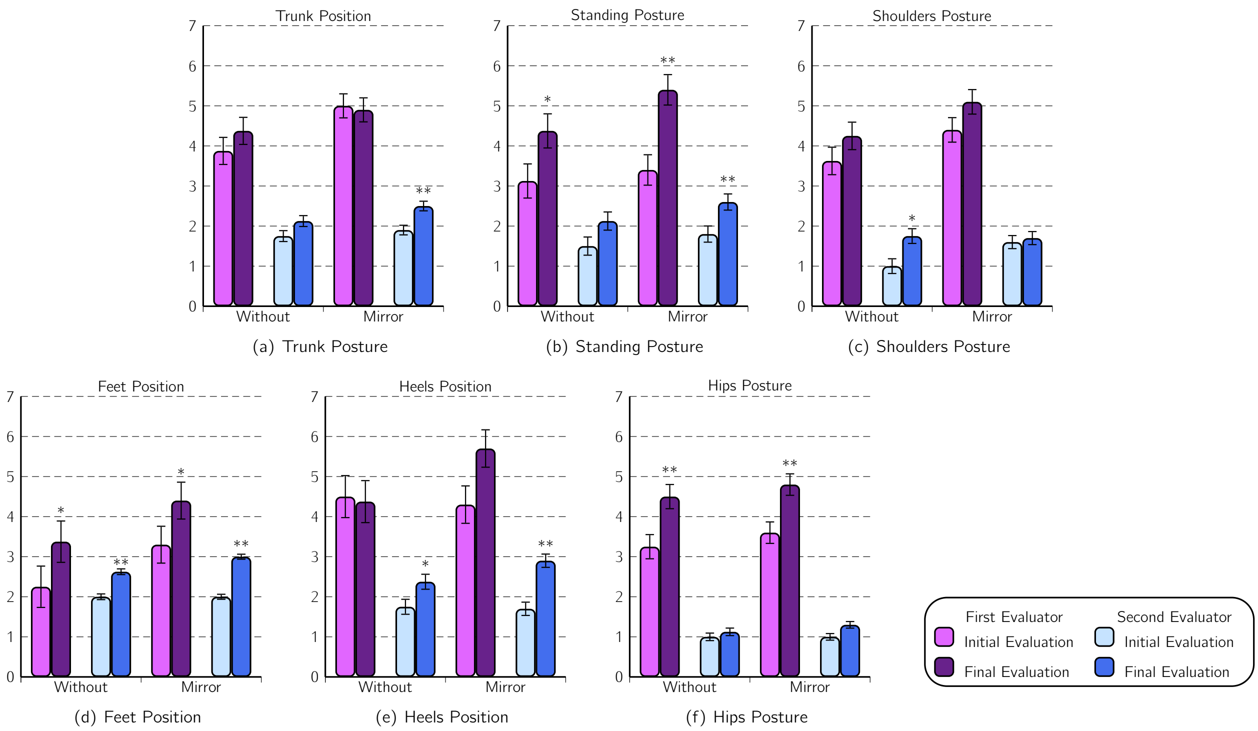


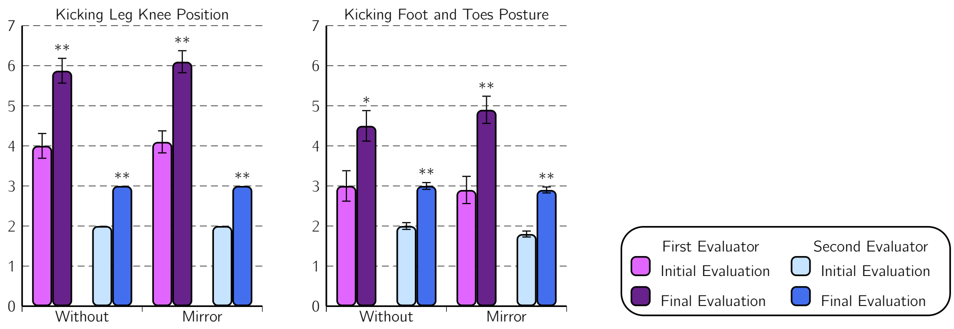
Figure 7.4 - Tsuki Global Performance Grade

7.3.2 Mae Geri Evaluations by Experts Results



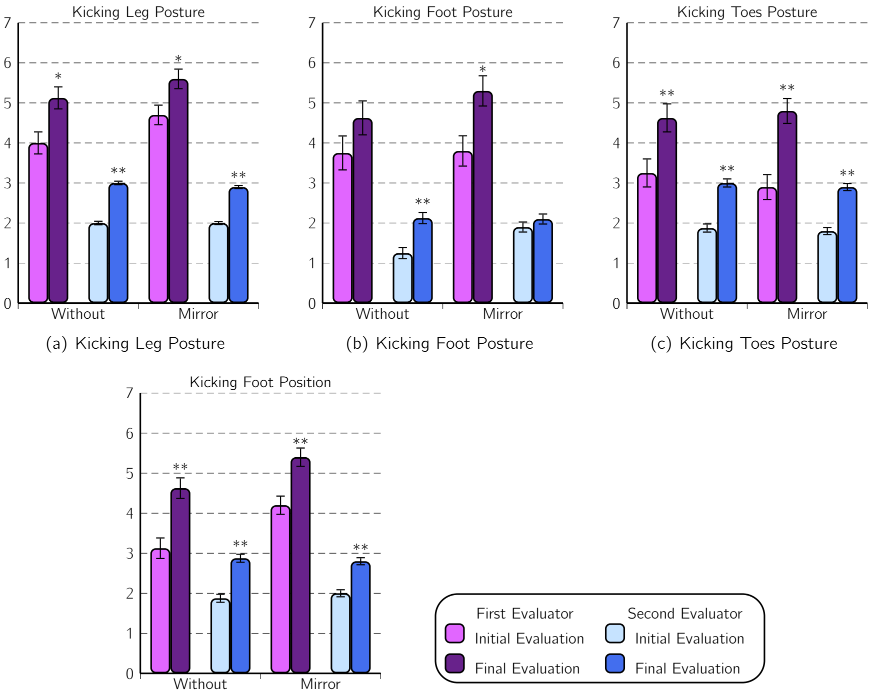
(a) Trunk Posture
(b) Standing Posture
(c) Shoulders Posture
(d) Feet Position
(e) Heels Position
(f) Hips Posture

Figure 7.5 - Mae Geri Gesture While Postural Performance Criteria Evaluated by Experts



(a) Kicking Leg Knee Position (b) Kicking Foot and Toes Posture

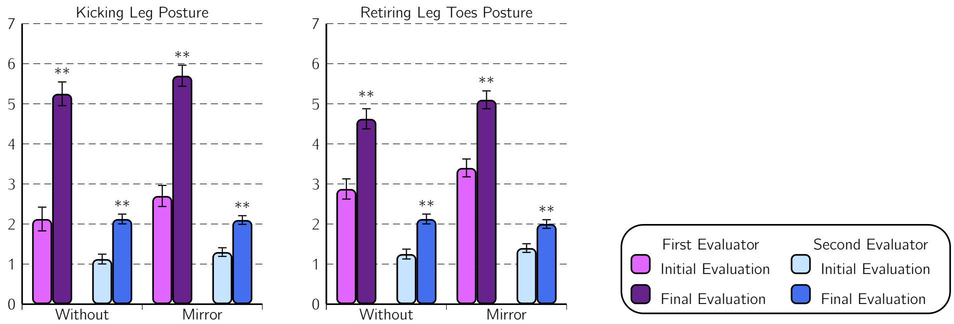
Figure 7.6 - Mae Geri Arming Phase Performance Criteria Evaluated by Experts



(a) Kicking Leg Posture (b) Kicking Foot Posture (c) Kicking Toes Posture

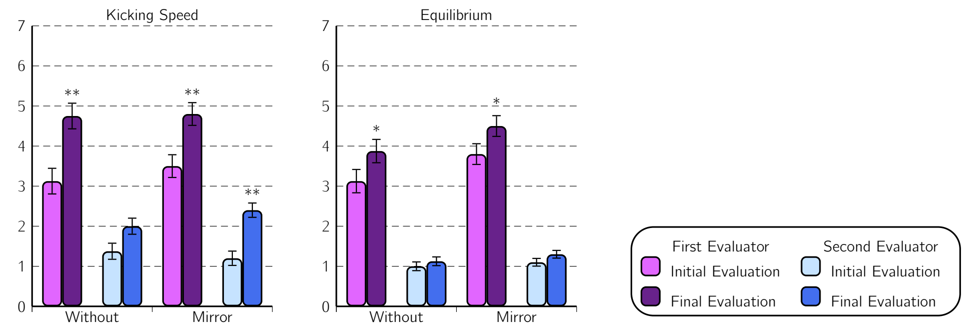
(d) Kicking Foot Position

Figure 7.7 - Mae Geri Kicking Phase Performance Criteria Evaluated by Experts



(a) Retiring Leg Knee Position (b) Retiring Leg Toes Posture

Figure 7.8 - Mae Geri Retiring Phase Performance Criteria Evaluated by Experts



(a) Kicking Speed (b) Equilibrium

Figure 7.9 - Mae Geri Gesture Execution Performance Criteria Evaluated by Experts

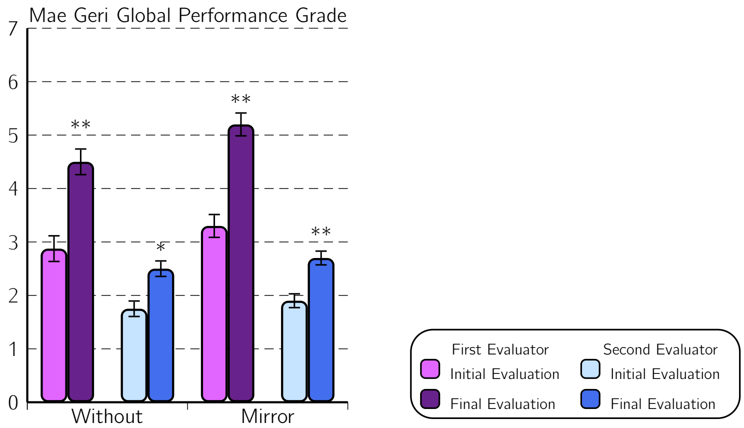
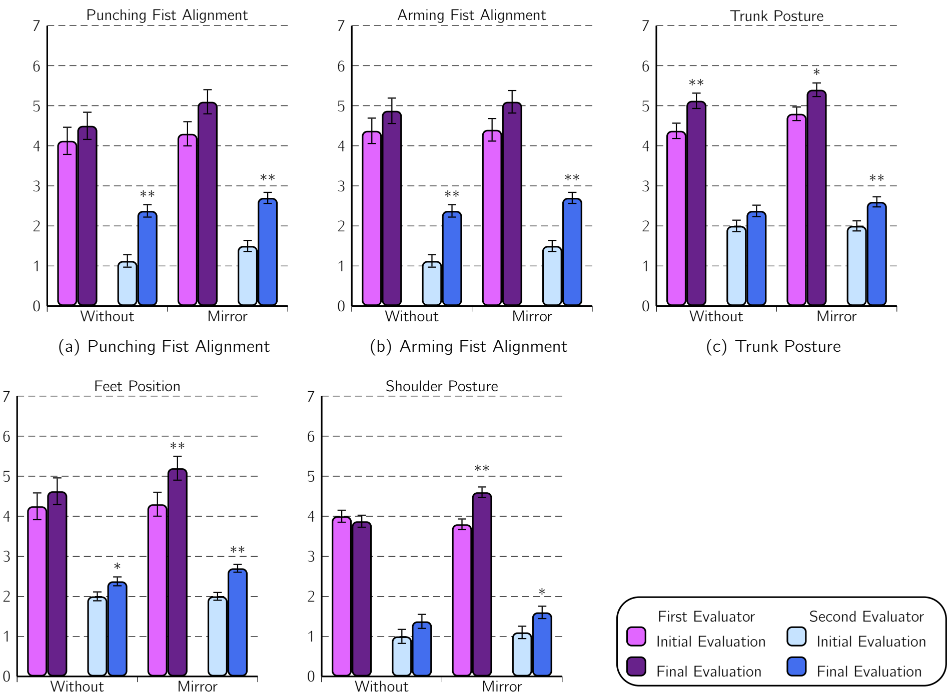


Figure 7.10 - Mae Geri Global Performance Grade

7.3.3 Soto Uke Evaluations by Experts Results



(a) Punching Fist Alignment

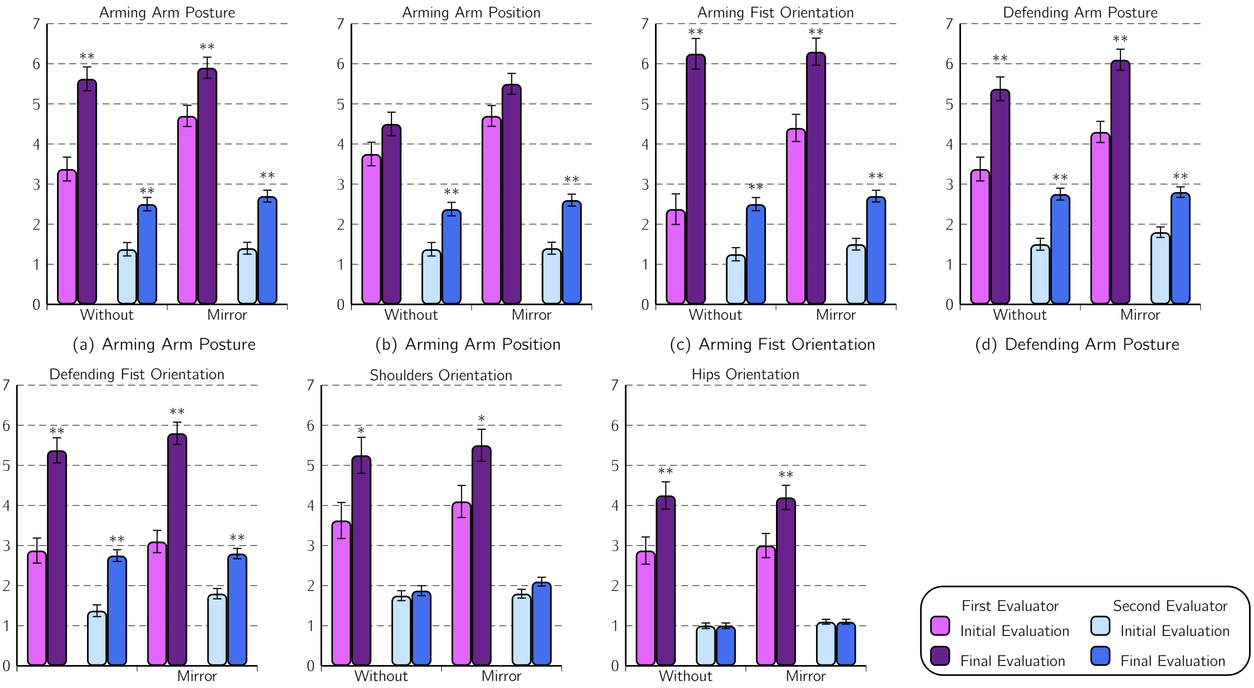
(b) Arming Fist Alignment

(c) Trunk Posture

(d) Feet Position

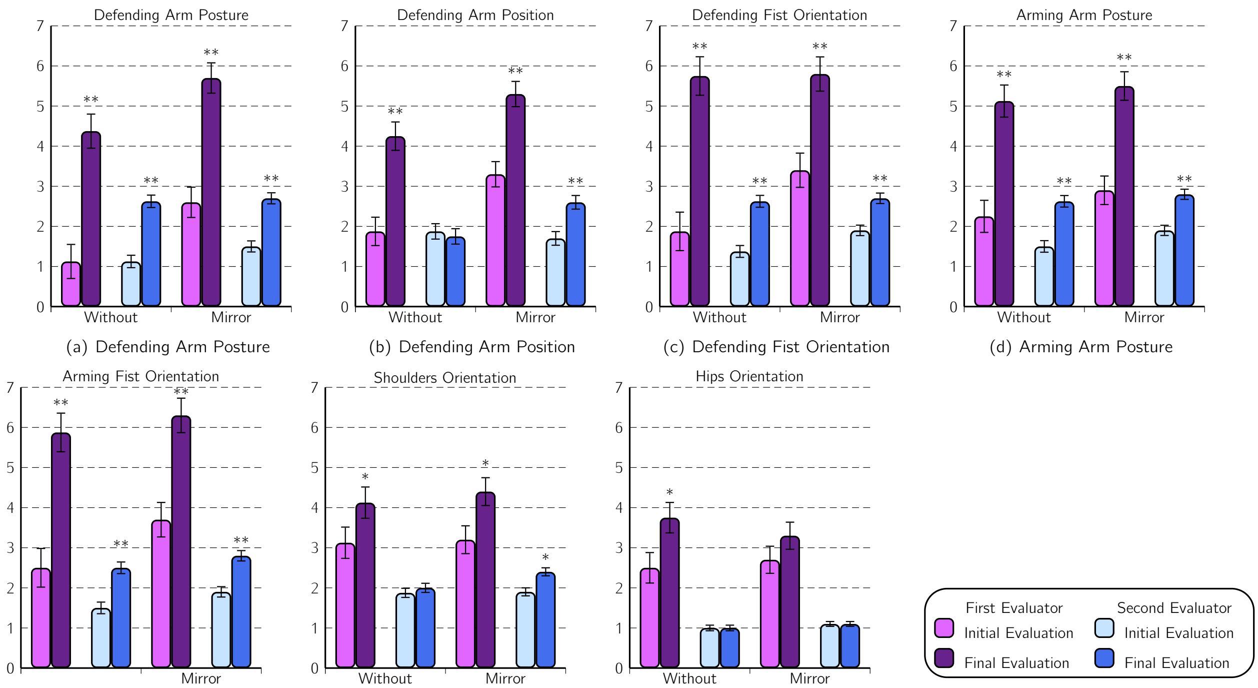
(e) Shoulders Posture

Figure 7.11 - Soto uke Gesture While Postural Performance Criteria Evaluated by Experts



(a) Arming Arm Posture
(b) Arming Arm Position
(c) Arming Fist Orientation
(d) Defending Arm Posture
(e) Defending Fist Orientation
(f) Shoulders Orientation
(g) Hips Orientation

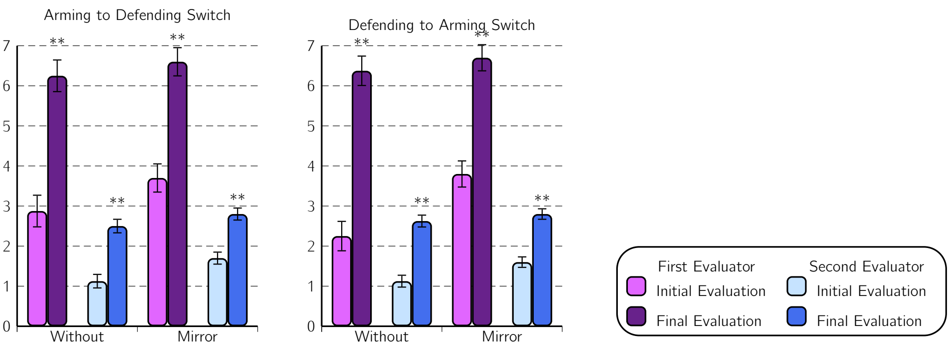
Figure 7.12 - Soto uke Starting Postural Performance Criteria Evaluated by Experts



(a) Defending Arm Posture (b) Defending Arm Position (c) Defending Fist Orientation (d) Arming Arm Posture

(e) Arming Fist Orientation (f) Shoulders Orientation (g) Hips Orientation

Figure 7.13 - Soto uke Ending Postural Performance Criteria Evaluated by Experts



(a) Arming to Defending Switch (b) Defending to Arming Switch

Figure 7.14 - Soto uke Repositioning Performance Criteria Evaluated by Experts

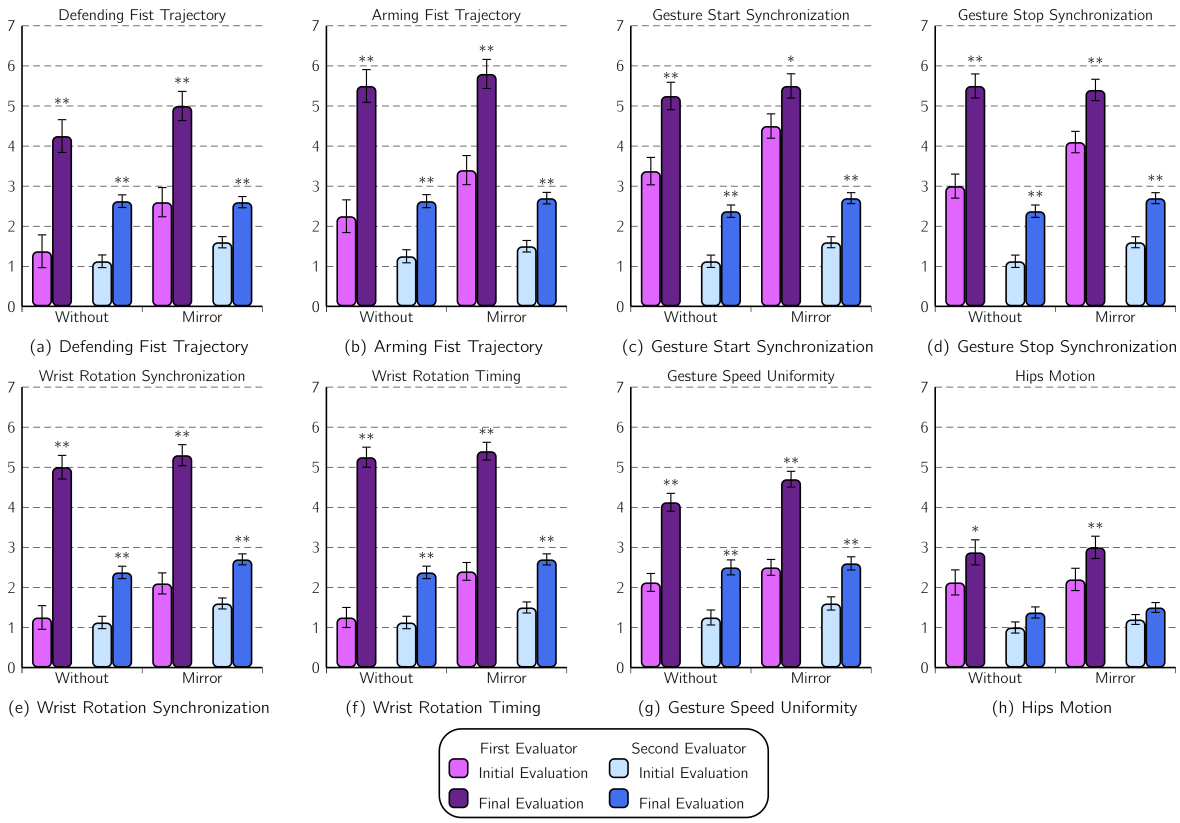


Figure 7.15 - Soto Uke Execution Performance Criteria Evaluated by Experts

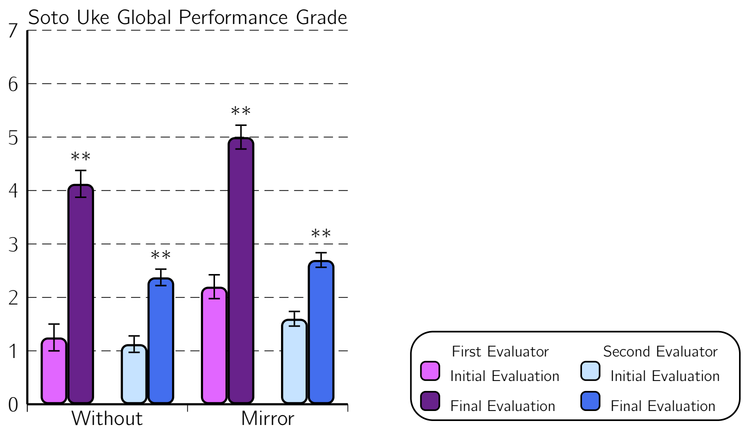


Figure 7.16 - Soto uke Global Performance Grade

7.4 Second Study Evocation Interview Results

7.4.1 Without Mirror Group

7.4.1.1 First Training Session

Sujet 1, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description globale et générale des différentes phases du geste	Description globale et générale des différentes phases du geste	Description confuse
But	Faire la rotation des poignées en même temps en relâchant les épaules	Contrôler l'équilibre	Faire mouvement fluide
Indices perçus	Regarde ses propres mains à partir consigne auditive	Cherche à sentir l'équilibre	Comparaison entre ses bras et la position des bras du prof
Etats internes	Fait pour faire	Gêné par les lunettes	Énervé car il ne comprend pas

Table 7.10 - Study 2 Evocation Interview, Without Mirror Group, First Training Session, Subject 1

Sujet 2, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description à partir des prescriptions de la tâche	Description à partir des prescriptions de la tâche	Description confuse
But	Construire une image du geste à réaliser	Réaliser le geste de manière globale	Construire une image du geste à réaliser
Indices perçus	Regarde ses propres mains à partir consigne auditive	Cherche à sentir l'équilibre	Observer le prof. . . pas le temps de faire
Etats internes	Ne veut pas répéter (car sait faire)	S'amuse	Énervé car il ne comprend pas

Table 7.11 - Study 2 Evocation Interview, Without Mirror Group, First Training Session, Subject 2

Sujet 3, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description globale et générale des différentes phases du geste	Description confuse	Description confuse
But	Rester relâché	Contrôler l'équilibre	Ne sait pas quoi faire. . . cherche à imiter
Indices perçus	Regarde ses propres mains et cherche à construire des repères. N'écoute pas et ne regarde pas	Cherche à sentir l'équilibre. Écoute les consignes	Regarde le prof

Table 7.12 - Study 2 Evocation Interview, Without Mirror Group, First Training Session, Subject 3 (continued on next page. . .)

Sujet 3, Séance 1	Tsuki	Mae Geri	Soto Uke
Etats internes	Essaye de construire une image du geste	Essaye de construire une image du geste	Trouve le geste trop compliqué pour lui

Table 7.12 - Study 2 Evocation Interview, Without Mirror Group, First Training Session, Subject 3

Sujet 4, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description globale et générale des différentes phases du geste	Compare ce qu'il faut faire avec un percuté en boxe française	Description confuse
But	Faire sans réfléchir (sinon, trop compliqué)	Transformer le percuté de boxe française	Protéger la cage thoracique
Indices perçus	Regarde ses propres mains. Ressent le relâchement suit le rythme donné par le prof.	Cherche à sentir l'équilibre. Écoute les consignes.	Comparaison entre ses bras et la position des bras du prof.
Etats internes	Fait pour faire mais se lasse vite des répétitions	Enervé car trop geste BF	Enervé car ne comprend pas

Table 7.13 - Study 2 Evocation Interview, Without Mirror Group, First Training Session, Subject 4

Sujet 5, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description globale et générale des différentes phases du geste	Description globale et générale des différentes phases du geste	Description confuse
But	Serrer les omoplates	Contrôler l'équilibre	Imaginer le mouvement différent des bras
Indices perçus	Observer le prof	Observer le prof	Observer et écouter le prof
Etats internes	Fait pour faire mais a du mal	Trouve le geste facile	Fait pour faire mais a du mal

Table 7.14 - Study 2 Evocation Interview, Without Mirror Group, First Training Session, Subject 5

Sujet 6, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description globale et générale des différentes phases du geste	Description globale et générale des différentes phases du geste	Description confuse
But	Relâcher les épaules et souffler à l'impact	Frapper pied face à l'adversaire	Faire comme le prof
Indices perçus	Écouter la respiration du prof et la suivre	Écouter la respiration du prof et la suivre	Écouter la respiration du prof et la suivre
Etats internes	S'ennuie et abandonne	S'ennuie et abandonne	Ne comprend pas et abandonne

Table 7.15 - Study 2 Evocation Interview, Without Mirror Group, First Training Session, Subject 6

Sujet 7, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description précise des différentes phases du geste	Description globale et générale des différentes phases du geste	Description confuse
But	Coller les omoplates et serrer les poings	Monter genou au niveau nombril et montrer le dessous du pied à l'adversaire	Contracter à la fin du geste
Indices perçus	Écouter les consignes. Sentir les omoplates se coller. Regarder hauteur du poing au sternum	Cherche à sentir l'équilibre	Ressentir la position de départ et regarder la synchronisation des mains
Etats internes	Veut comprendre	Veut comprendre	Veut comprendre

Table 7.16 - Study 2 Evocation Interview, Without Mirror Group, First Training Session, Subject 7

Sujet 8, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description précise des différentes phases du geste	Description précise des différentes phases du geste	Description confuse
But	Visualiser le mouvement	Contrôler l'équilibre	Visualiser le mouvement
Indices perçus	Regarde ses bras	Ressentir l'étirement des ischios	Regarde ses bras

Table 7.17 - Study 2 Evocation Interview, Without Mirror Group, First Training Session, Subject 8 (continued on next page...)

Sujet 8, Séance 1	Tsuki	Mae Geri	Soto Uke
Etats internes	Fait pour faire mais s'ennuie	Trouve difficile cause manque de souplesse	Enervé car n'y arrive pas

Table 7.17 - Study 2 Evocation Interview, Without Mirror Group, First Training Session, Subject 8

7.4.1.2 Second Training Session

Sujet 1, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description précise en insistant sur les positions de départ et d'arrivée	Description précise en insistant sur les différentes phases	Description globale et générale du mouvement
But	Coordonner l'action des 2 bras	Rendre le mouvement fluide (pas hacher)	Avoir la bonne position de départ et d'arrivée
Indices perçus	Ressentir l'épaule qui tire. Écouter le rythme imposé par le prof.	Ressentir l'appui au sol. Regarder loin devant soi.	Regarder le déplacement des bras
Etats internes	Satisfait - pense avoir gagné en puissance	Concentré pour mieux faire	Concentré pour mieux faire

Table 7.18 - Study 2 Evocation Interview, Without Mirror Group, Third Training Session, Subject 1

Sujet 2, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description avec les expressions du prof. Parle d'un coup avec un bras.	Description avec les expressions du prof. Coup de pied en 3 temps.	Description globale et générale du mouvement. À compris la notion de blocage.
But	Suivre ce que fait le prof.	Percer une cible imaginaire devant soi.	Se protéger d'une attaque. Visualiser une cible pour le blocage.
Indices perçus	Chercher des repères kinesthésiques	Ressentir l'appui au sol. Fixer un point devant soi. Chercher le relâchement	Ressentir le déplacement du coude
Etats internes	Satisfait car trouve le mouvement très facile	Satisfait car arrive à garder l'équilibre sur un pied	Satisfait car commence à ressentir ce que dit le prof

Table 7.19 - Study 2 Evocation Interview, Without Mirror Group, Third Training Session, Subject 2

Sujet 3, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description du geste à partir des postures de départ et d'arrivée.	Description avec les expressions du prof. Percer une cible.	Description avec les expressions du prof.
But	Cherche à réaliser le coup de poing.	Trouver l'équilibre sur 1 jambe.	Utiliser chaque bras pour guider l'action

Table 7.20 - Study 2 Evocation Interview, Without Mirror Group, Third Training Session, Subject 3 (continued on next page. . .)

Sujet 3, Séance 3	Tsuki	Mae Geri	Soto Uke
Indices perçus	Sensation des doigts serrés	Sentir contraction des cuisses et regarder position du genou	Cherche à ressentir les sensations décrites par le prof
Etats internes	Satisfait de ce qu'il fait	Insatisfait par sa réalisation	Insatisfait car ne comprend pas

Table 7.20 - Study 2 Evocation Interview, Without Mirror Group, Third Training Session, Subject 3

Sujet 4, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Réalise le mouvement pendant la description et utilise ses sensations	Description en 4 phases bien identifiées (2 phases pour déplier et ramener)	Décrit un mouvement en marteau avec le coude pour frapper et une baramine en protection devant
But	Réussir la coordination entre les 2 bras avec des postures précises	Visualiser un point d'impact pour la frappe	Imaginer ses propres gestes en écoutant ce que dit le prof
Indices perçus	Compare positions du prof et positions de son propre corps	Écoute le bruit du frottement de son pantalon pour vérifier le ramené.	Cherche sensations propres pour réaliser.
Etats internes	Satisfait de ce qu'il réalise	Satisfait de ce qu'il réalise	Insatisfait car ne pense pas avoir encore compris.

Table 7.21 - Study 2 Evocation Interview, Without Mirror Group, Third Training Session, Subject 4

Sujet 5, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description du geste avec expressions du prof	Description du geste avec expressions du prof	Description du geste avec expressions du prof
But	Chercher la fluidité	Garder l'équilibre pour frapper	Mémoriser ce qu'il y a à faire
Indices perçus	Observation du prof puis comparaison sur soi	Écouter les consignes et regarder la position de son corps	Écouter les consignes et regarder la position de son corps
Etats internes	Satisfait - trouve le mouvement facile	Satisfait quand le rythme est lent - insatisfait quand ça accélère	Joue en imaginant un adversaire face à lui

Table 7.22 - Study 2 Evocation Interview, Without Mirror Group, Third Training Session, Subject 5

Sujet 6, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description précise du geste à partir l'attaque / défense	Description précise en 3 phases en parlant d'attaque aussi	Description plus confuse mais qui repose sur l'idée de protection, de défense
But	Serrer les omoplates pour attaquer efficacement	Garder le centre de gravité bas pour l'équilibre	Réaliser le geste sans regarder le prof
Indices perçus	Chercher sensations. Utiliser le souffle	Focalisation sur l'équilibre sur 1 jambe	Attentif à la position du membre qui défend

Table 7.23 - Study 2 Evocation Interview, Without Mirror Group, Third Training Session, Subject 6 (continued on next page. . .)

Sujet 6, Séance 3	Tsuki	Mae Geri	Soto Uke
Etats internes	Jouer avec une cible imaginaire	Jouer avec une cible imaginaire	Se trouve ridicule

Table 7.23 - Study 2 Evocation Interview, Without Mirror Group, Third Training Session, Subject 6

Sujet 7, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description précise du geste insiste sur le segment qui ne bouge pas	Description du geste insiste la jambe au sol qui permet l?équilibre	Description à partir des positions de départ et d'arrivée
But	Regarder devant soi et penser aux positions de départ et d'arrivée	Percer l'adversaire et ramener vite la jambe	Suivre ce que fait le prof
Indices perçus	Sentir les omoplates se serrer	Sentir la stabilité de l'équilibre	Écouter le rythme imposé par le prof
Etats internes	S'ennui	Joue à imaginer une cible	Cherche à ressentir sa force à la fin du mouvement

Table 7.24 - Study 2 Evocation Interview, Without Mirror Group, Third Training Session, Subject 7

Sujet 8, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Pas de description - coup avant frontal	Pas de description - Coup avant du pied	Description très rapide du mouvement
But	Donner un coup dans l'écran	Fixer un point et taper. Faire aussi vite que le prof	Faire ce que le prof dit
Indices perçus	Écouter les consignes du prof. Étirement des épaules	Garder l'équilibre sur 1 jambe	Comparer observation du prof et position de son corps
Etats internes	Joue à frapper une cible	Joue à frapper une cible	Cherche à se concentrer

Table 7.25 - Study 2 Evocation Interview, Without Mirror Group, Third Training Session, Subject 8

7.4.2 Mirror Group

7.4.2.1 First Training Session

Sujet 1, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description globale et générale avec expressions du prof	Description globale du mouvement de jambe	Description confuse
But	Comprendre ce qu'il faut faire	Comprendre ce qu'il faut faire	Imiter le prof

Table 7.26 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 1 (continued on next page...)

Sujet 1, Séance 1	Tsuki	Mae Geri	Soto Uke
Indices perçus	Ce que dit et ce que fait le prof	Ce que dit et ce que fait le prof	Ce que dit et ce que fait le prof
Etats internes	Gêné par les lunettes	Cherche des indices pour comprendre	Cherche des indices pour comprendre
Perception de l'avatar	Un avatar ? . . . où ça ? il ne sert à rien		

Table 7.26 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 1

Sujet 2, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description globale et générale	Description confuse	Description confuse
But	Suivre les consignes du prof	Comprendre ce qu'il faut faire	Comprendre ce qu'il faut faire
Indices perçus	Ce que dit et ce que fait le prof	Ce que dit et ce que fait le prof	Ce que dit et ce que fait le prof
Etats internes	Gêné / sensations désagréables	Énervé parce qu'il n'y arrive pas	S'amuse mais c'est difficile
Perception de l'avatar	Avatar est un moyen de contrôle et permet de se rendre compte des difficultés.		

Table 7.27 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 2

Sujet 3, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description globale et générale avec les expressions du prof	Description globale des mouvements de la jambe libre	Description globale et générale
But	Suivre les consignes et comparer avec ses sensations	Faire l'exercice vite pour garder l'équilibre	Comprendre ce qu'il faut faire
Indices perçus	Sensations au niveau des omoplates et rotations des poignets	Chercher abaissement du Centre de gravité et étirement des cuisses	Comparaison prof / individu
Etats internes	Gêné, pas à l'aise	Insatisfait car manque d'informations	Insatisfait car ne comprend pas
Perception de l'avatar	Avatar est inutile		

Table 7.28 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 3

Sujet 4, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description anatomique du mouvement avec expressions du prof	Description générale et globale	Description confuse
But	Coordonner les rotations des poignets au même moment	Comprendre ce qu'il faut faire	Comprendre ce qu'il faut faire

Table 7.29 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 4 (continued on next page. . .)

Sujet 4, Séance 1	Tsuki	Mae Geri	Soto Uke
Indices perçus	Regarder en même temps prof et avatar pour voir les différences	Regarder en même temps prof et avatar pour voir les différences	Regarder en même temps prof et avatar pour voir les différences
Etats internes	Curieux	Énervé car ne comprend pas	Énervé car ne comprend pas
Perception de l'avatar	L'avatar c'est bien mais on n'a pas assez d'infos pour l'utiliser vraiment dans la correction du geste		

Table 7.29 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 4

Sujet 5, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description globale avec les expressions du prof	Description globale avec les expressions du prof	Description confuse - cherche à retrouver les expressions du prof
But	Imiter le prof	Imiter le prof	Imiter le prof
Indices perçus	Les postures du prof	Les postures du prof	Les postures du prof
Etats internes	Motivé - cherche à comprendre	Motivé - cherche à comprendre	Motivé - cherche à comprendre
Perception de l'avatar	Avatar ... Ok mais c'est pas moi ... et ça sert à rien		

Table 7.30 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 5

Sujet 6, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description globale. Utilise les expressions du prof.	Description globale. Utilise les expressions du prof.	Description globale. Utilise les expressions du prof.
But	Suivre les consignes	Suivre les consignes. Chercher à rester en équilibre.	Suivre les consignes. Coordonner les deux bras.
Indices perçus	Ce que dit et ce que fait le prof	Comparaison entre postures prof et ses propres postures	Comparaison entre postures prof et ses propres postures
Etats internes	Curieux et amusé	Amusé trouve l'exercice facile	Trouve que ça devient plus compliqué
Perception de l'avatar	Utilise l'avatar dans le cas du mae geri uniquement. Pas besoin pour le tsuki car geste facile et vidéo suffit / pas besoin pour le soto uke car pas assez d'infos.		

Table 7.31 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 6

Sujet 7, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description globale avec les expressions du prof	Description anatomique et analytique	Description confuse
But	Comprendre la position de départ et rechercher la synchronisation des poignets	Corriger la position du pied pour frapper	Comprendre la position de départ et rechercher la synchronisation des poignets
Indices perçus	Regard passe des mains du prof à ses propres mains	Regarde pied du prof puis ses propres pieds	Regard passe des mains du prof à ses propres mains
Etats internes	Concentré	Concentré	Concentré
Perception de l'avatar	Recherche des informations sur le prof mais pas sur l'avatar qui ne sert à rien		

Table 7.32 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 7

Sujet 8, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description confuse	Description confuse	Description confuse
But	Imiter le prof avec l'avatar	Comprendre ce qu'il faut faire	Comprendre ce qu'il faut faire

Table 7.33 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 8 (continued on next page...)

Sujet 8, Séance 1	Tsuki	Mae Geri	Soto Uke
Indices perçus	Observation prof et avatar	Sensation d'équilibre	Observation prof et avatar
Etats internes	Curieux	Veut comprendre ce qu'il faut faire	Veut comprendre ce qu'il faut faire
Perception de l'avatar	Se sert de l'avatar dans le tsuki et le soto uke pour comparer avec les postures du prof . Ne s'en sert pas du tout pour le mae geri (reste sur ses propres sensations)		

Table 7.33 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 8

Sujet 9, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description confuse	Description confuse	Description confuse
But	Comprendre ce qu'il faut faire	Comprendre ce qu'il faut faire	Comprendre ce qu'il faut faire
Indices perçus	Regarde et écoute le prof	Regarde et écoute le prof	Regarde et écoute le prof
Etats internes	Concentré	Concentré	Concentré

Table 7.34 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 9 (continued on next page. . .)

Sujet 9, Séance 1	Tsuki	Mae Geri	Soto Uke
Perception de l'avatar	Se sent bizarre dans l'EV ne commence à regarder l'avatar que pour le soto uke		

Table 7.34 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 9

Sujet 10, Séance 1	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description confuse	Description confuse	Description confuse
But	Vérifier ce que dit le prof sur l'avatar	Vérifier ce que dit le prof sur l'avatar	Cherche à comprendre
Indices perçus	Regarde et écoute le prof. Regarde l'avatar.	Regarde et écoute le prof. Regarde l'avatar.	Regarde et écoute le prof. Regarde l'avatar.
Etats internes	Joue avec son avatar	Joue avec son avatar	Joue avec son avatar
Perception de l'avatar	Se dit immergé dans un autre monde ... s'amuse avec les personnages sur l'écran.		

Table 7.35 - Study 2 Evocation Interview, Mirror Group, First Training Session, Subject 10

7.4.2.2 Second Training Session

Sujet 1, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description très précise du geste en donnant du sens	Description très précise du geste en donnant du sens	Description précises des positions de départ et de fin. Parle de blocage.
But	Vérifier sur soi les consignes du prof	Chercher à imiter ce que fait le prof	Écouter et comprendre les consignes du prof
Indices perçus	Comparaison rotation des poignets à la fin du geste sur soi et sur avatar	Comparaison hauteur du genou (soi et avatar)	Chercher des différences entre soi et avatar
Etats internes	S'ennuie - sait qu'il sait	Content - ça ressemble à ce que fait le prof	Content - ça ressemble à ce que fait le prof
Perception de l'avatar	Ne regarde que l'avatar (un peu le prof sur les positions de fin) et écoute les consignes. Son objectifă: faire que l'avatar fasse comme le prof mais parle de l'avatar à la 3ème personne.		

Table 7.36 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 1

Sujet 2, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description complète et précise avec ses propres mots.	Description complète et précise avec ses propres mots.	Description générale. Parle de parade.
But	Ressentir le geste à partir des consignes.	Comparaison prof / soi sur son corps.	Réaliser le geste sans trop chercher à réfléchir.
Indices perçus	Le marqueur sur sa main à l'armé sur les côtés.	Contrôler vitesse du coup de pied sur l'avatar.	Regarder l'avatar pour vérifier si le geste ressemble à celui du prof.
Etats internes	Préoccupé par le marqueur qui risque de tomber.	Se sent dans un autre monde.	Se sent dans un autre monde pas réel
Perception de l'avatar	L'avatar, c?est pas moi mais il reproduit mes gestes.		

Table 7.37 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 2

Sujet 3, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description précise de chaque position clé pour frapper une cible.	Description précise de chaque position clé pour taper une cible.	Description confuse. Parle de coup de blocage.

Table 7.38 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 3 (continued on next page. . .)

Sujet 3, Séance 3	Tsuki	Mae Geri	Soto Uke
But	Suivre le rythme du prof.	Respecter les consignes du prof.	Respecter les consignes du prof.
Indices perçus	Les consignes. Ressentir le geste.	Les consignes. Ressentir le geste.	Les consignes. Ressentir le geste.
Etats internes	Content - ressent bien le geste à faire	Content car commence à bien construire la coordination.	Content car n?a plus besoin de réfléchir
Perception de l'avatar	Avatar . . . il sert à rien (d'ailleurs l'a-t-il vuă?) C'est comme une vidéo.		

Table 7.38 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 3

Sujet 4, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description personnalisée à partir des sensations des contractions et du relâchement.	Description personnalisée à partir des sensations des contractions et du relâchement.	Description personnalisée à partir des sensations.
But	Rechercher les sensations justes.	Être attentif aux angles articulaires pour sentir l'efficacité du coup.	Visualise le geste pour le réaliser.

Table 7.39 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 4 (continued on next page. . .)

Sujet 4, Séance 3	Tsuki	Mae Geri	Soto Uke
Indices perçus	Se focalise sur le rythme de son geste et contrôle les positions sur l'avatar.	Visualise le geste et se parle pendant l'action. Contrôle par sensations.	Visualise le geste et imagine un adversaire. Contrôle par sensations.
Etats internes	Concentré pour bien faire.	Concentré pour bien faire.	Concentré et fatigué.
Perception de l'avatar	Jouer avec l'avatar en tsuki mais pas pour les autres gestes . . . il ne sert à rien . . .		

Table 7.39 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 4

Sujet 5, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description générale avec les expressions du prof	Description générale avec les expressions du prof	Description confuse avec quelques expressions du prof
But	Se remémorer les consignes et les appliquer.	Se remémorer les consignes et les appliquer.	Se remémorer les consignes et les appliquer.
Indices perçus	Regarder le prof et contrôler les positions de départ et de fin sur l'avatar.	Regarder le prof et contrôler les positions de départ et de fin sur l'avatar.	Regarder le prof et contrôler les positions de départ et de fin sur l'avatar.

Table 7.40 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 5 (continued on next page. . .)

Sujet 5, Séance 3	Tsuki	Mae Geri	Soto Uke
Etats internes	S'ennuie, c'est toujours la même chose	S'ennuie, c'est toujours la même chose	S'ennuie, c'est toujours la même chose
Perception de l'avatar	Avatar sert à vérifier les positions de départ et d?arrivée ... mais pas à corriger pendant l'action.		

Table 7.40 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 5

Sujet 6, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description personnalisée à partir de sa représentation et de ses sensations.	Description personnalisée à partir de sa représentation et de ses sensations.	Description personnalisée à partir de sa représentation et de ses sensations.
But	Chercher rapidité et rythme	Taper dans une cible avec rapidité	Réussir le geste comme le prof
Indices perçus	Les sensations lors de la réalisation	Les sensations lors de la réalisation	Les sensations lors de la réalisation
Etats internes	Content, pense avoir appris	Satisfait de ce qu'il a réussi à faire	Insatisfait - trop de répétitions

Table 7.41 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 6 (continued on next page...)

Sujet 6, Séance 3	Tsuki	Mae Geri	Soto Uke
Perception de l'avatar	Avatar ne sert à rien pour les gestes comme le tsuki et le Mae geri. Il devient utile pour le soto uke car ce geste est plus compliqué à comprendre.		

Table 7.41 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 6

Sujet 7, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description personnalisée accompagnée du geste	Description avec les expressions du prof	Description personnalisée accompagnée du geste
But	Ressentir la trajectoire des poings	Corriger la trajectoire du coup de pied	Respecter les consignes du prof
Indices perçus	Compare prof et son propre bras	Contrôle avec avatar. Sentir contraction cuisse	Contrôle avec avatar
Etats internes	Concentré sur ses sensations	Se considère en échec	Se considère en échec
Perception de l'avatar	Utilise l?avatar comme moyen de contrôle pour mae geri et soto uke.		

Table 7.42 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 7

Sujet 8, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Part de ce qu'il fait en boxe pour décrire le geste et expliquer les différences.	Part de ce qu'il fait en boxe pour décrire le geste et expliquer les différences.	Part de ce qu'il fait en boxe pour décrire le geste mais a des difficultés pour expliquer les bras
But	Respecter les consignes du prof	Garder l'équilibre	Comprendre la coordination avec les bras
Indices perçus	Sensations de relâchement / contraction. Contrôle avec avatar des positions	Sensations de dynamique de la frappe	Ressentir le geste
Etats internes	Insiste pour améliorer ce qu'il fait	Insiste pour améliorer ce qu'il fait	Essaye de visualiser le geste à réaliser
Perception de l'avatar	Se sert de l'avatar en tsuki (pour faire avec le prof) et en mae geri (pour vérifier les positions de départ et d?arrivée).		

Table 7.43 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 8

Sujet 9, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description précise avec les expressions du prof	Description précise avec les expressions du prof	Description précise avec les expressions du prof
But	Appliquer les consignes	Appliquer les consignes	Appliquer les consignes
Indices perçus	Corrige à partir de son avatar et s'amuse	Corrige à partir de son avatar	Compare l'avatar et le prof
Etats internes	S'ennuie - trop de répétitions	Essaye de bien faire	S'énerve car n'y arrive pas
Perception de l'avatar	Utilise l'avatar dans les 3 gestes mais de manière différente. Pour tsuki et mae geri (ne regarde que l'avatar pour se corriger - il semble penser que l'avatar c'est bien lui) pour le soto uke, compare le prof et l'avatar (mais là parle de l'avatar à la 3ème personne)		

Table 7.44 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 9

Sujet 10, Séance 3	Tsuki	Mae Geri	Soto Uke
Description de ce qu'il y a à apprendre	Description globale avec les expressions du prof	Description globale avec les expressions du prof	Description globale avec les expressions du prof
But	Vérifier sur l'avatar si geste est bon	Vérifier sur l'avatar si geste est bon	Vérifier sur l'avatar si geste est bon
Indices perçus	Avatar uniquement	Avatar uniquement	Avatar uniquement
Etats internes	S'ennuie	S'ennuie	S'ennuie
Perception de l'avatar	Se sent complètement immergé dans le dojo.		

Table 7.45 - Study 2 Evocation Interview, Mirror Group, Third Training Session, Subject 10

Publications

7.5 Thesis Related Publications

International Conferences

- Burns, A.-M., Kulpa, R., Durny, A., Spanlang, B., Slater, M., and Multon, F. Using Virtual Humans and Computer Animations to Learn Complex Motor Skills : A Case Study in Karate. In Proceedings of the International Conference SKILLS 2011, 4 pages, December, 15-16 2011, Montpellier, France

7.6 Other Publications

Summer School Workshops

- Giakoumis, D., Vogiannou, A., Kosunen, I., Devlaminck, D., Ahn, M., Burns, A.-M., Khademi, F., Moustakas, K., and Tzovaras, D. Multimodal Monitoring of the Behavioral and Physiological State of the User in Interactive VR Games. In Camurri, A., Mancini, M. et Volpe, G. (Eds.), In Proceedings of the 5th International Summer Workshop on Multimodal Interfaces (eNTERFACE'09), 17 pages, July 13th - August 7th 2009, Genova, Italy

Pertinence de l'utilisation d'humains virtuels pour l'enseignement de gestes moteurs : études de cas avec des gestes de karaté

La question principale de cette thèse est la pertinence de l'utilisation d'humains virtuel pour l'enseignement de geste moteur. Une première étude explore la question de la faisabilité d'un apprentissage par l'imitation d'un humain virtuel. Pour ce faire, l'amélioration de performance de trois gestes de karaté par trois groupes s'entraînant dans différents environnements est évaluée. Une classe traditionnel de karaté, un enseignement par vidéo et un enseignement en réalité virtuel sont comparé.

Une seconde étude évalue l'influence d'une représentation de soi dans l'environnement virtuel sur la réalisation de la tâche d'apprentissage. Les participants à cette étude ont un retour visuel de leur action sous la forme d'un avatar cylindrique représenté dans un miroir de l'environnement virtuel. L'influence de cet avatar sur la tâche d'apprentissage est évalué de deux façon : 1) par l'évaluation externe de la performance 2) par le biais d'entretiens d'explicitation qui permettent d'obtenir le point de vue du participant.

Ces deux études sont complétées par une troisième étude qui évalue un outil d'évaluation automatique de la performance. Cet outil est conçue dans le but d'éliminer les biais créés par un évaluateur humain. Un tel outil est nécessaire afin de pouvoir comparer les quatre environnements d'apprentissage présentés dans cette thèse ainsi que ceux qui seront créé dans le futur. En effet, seul un évaluateur automatique peut être parfaitement consistent sur toute la durée des études.

En conclusion, ces études ont permit d'établir que l'apprentissage par l'imitation d'un humain virtuel est possible. En conséquence, l'utilisation d'humains virtuels pour l'enseignement de gestes moteurs est pertinente. Ces environnements peuvent être utiles à plusieurs fins. Ils peuvent servir d'environnements contrôles pour l'étude de l'apprentissage par imitation. Le protocole développé dans cette étude peut être utilisé dans une boucle itérative pour le développement de version subséquentes d'environnements virtuel ou d'accélérateurs d'entraînement virtuel. Ce protocole peut également être utilisé pour le développement de jeux vidéos actifs plus efficaces pour combattre la sédentarité et la crise mondial d'obésité qui y est rattachée.

Mots clés : humain virtuel, réalité virtuelle, environnement d'apprentissage, apprentissage moteur, enseignement par la démonstration, évaluation de la performance, entretien d'explicitation.

On the Relevance of Using Virtual Humans for Motor Skills Teaching: A Case Study on Karate Gestures

The main question of that thesis is on the relevance of using virtual humans to teach complex motor skills. The first study explores the question of the feasibility of learning by imitation of a virtual human by comparing the improvement of the performance on three karate gestures for three groups, namely a traditional class, a video-based group and a virtual reality group.

The second study investigates the influence on the learning task of having a self representation in the virtual environment. The participants have a feedback of their movements represented on a mirrored cylindrical gray avatar. The impact of that avatar on the learning task of the participants is assessed by two means. Performance evaluations are performed and give an external perspective on the learning. Evocation interview are also performed to get an insight of the learning task from the participants point of view.

Finally, these two studies are completed by a third one investigating the possibility to have an automatic performance evaluator in order to reduce grading discrepancies generated by humans graders. Such a tool would be required to have an objective performance evaluation of all the participants in order to compare the four learning environments presented in that thesis and eventual further iteration of these environments.

The conclusion our the studies presented in that thesis are that learning motor skills from the imitation of a virtual human is possible. Consequently, virtual learning environments for motor skills teaching are relevant. Furthermore, these environments can be used in various types of applications. They can be used as a study tool for standard and controlled investigation of teaching by demonstration. They can also be used in an engineering loop for the development of further learning environments and training accelerators. They also have a potential usage in the development of exergames in response to the international obesity crisis.

Keywords: virtual human, virtual reality, learning environment, motor skill, teaching by demonstration, performance evaluation, evocation interview.