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Magic Mirror for Neurorehabilitation of People with Upper Limb Dysfunction Using Kinect

Orlando Erazo
University of Chile
Department of
Computer Science
oerazo@dcc.uchile.cl

José A. Pino
University of Chile
Department of
Computer Science
jpino@dcc.uchile.cl

Rosario Pino
Dr. Alfonso Asenjo
Institute of
Neurosurgery
tallopink@yahoo.com

Carmen Fernández
Dr. Alfonso Asenjo
Institute of
Neurosurgery
carmenferl@gmail.com

Abstract

Most patients requiring neurorehabilitation continue training at home without supervision of their therapists. They have troubles such as loss of motivation, routine difficulty, and lack of a guide to execute a task. We propose to support these patients with an application that follows the Magic Mirror paradigm, using a Natural User Interface and Microsoft Kinect. The software is aimed at patients suffering from various types of upper limb dysfunction. It is composed of three routines that allow patients to train their injured upper limbs to reach and grasp objects. The performed tests show the proposed application suitability. Therapists as well as adults with upper limb dysfunction participated in the study. These patients undergo rehabilitation at the Institute of Neurosurgery in Santiago, Chile. The application includes nine functions that received positive evaluations.

1. Introduction

The central nervous system (brain and spinal cord) of humans is affected by certain diseases. A consequence of these diseases is the decrease of one or more extremity functions which is called dysfunction. Such dysfunction may occur in the aftermath of a stroke, removal of a brain tumor, or due to other causes. People who suffer from such dysfunction require neurorehabilitation, which in turn requires substantial time, money, effort, and perseverance for their recovery.

The neurorehabilitation conducted by the therapist contributes significantly, but it is essential that patients continue their training at home where there are factors that might adversely affect them [1] [2] [3]. Some of these troubles are: Patients do not know whether they are doing the training routine well or not; they lack motivation, or their motivation decreases during the rehabilitation process; the task may be too complicated or too simple for them (level of difficulty).

In order to support patient rehabilitation, several applications have been developed. These applications may or may not require additional elements. Some examples are: the use of Nintendo Wii Remote for the rehabilitation of people with hemiparesis [4]; Kinect-based game for rehabilitation of neurological damage and adult balance training [5]; a combination of an Android based mobile phone with eGlove for upper limb recovery in stroke patients [6]; neurorehabilitation using virtual reality [7] [8]; the use of programs to assist in cognitive impairment due to stroke, without additional sensors or devices [9].

Existing applications have made significant contributions, but they can be improved further. Various applications do not include some important aspects, or they do it in a limited manner. Some of these aspects are: 1) Patients differ with regard to limitations, thus we must take into account their progress, interactivity, and motivation [1] [3]; 2) visual feedback is normally used, but we would obtain more benefits if combined with other types of feedback [10]; 3) we should emphasize understanding and results rather than entertainment [2].

The focus of this paper is on supporting the neurorehabilitation process that patients with upper limb dysfunction must carry out at home. For this goal, we developed and evaluated a computer application based on Magic Mirror [11] and Natural User Interfaces (NUI) [12]. The patients are adults who attend rehabilitation in the areas of Kinesiology and Occupational Therapy at the Dr. Alfonso Asenjo Institute of Neurosurgery, in Santiago, Chile.

2. Theoretical background

One way to support software development is to use modeling techniques in HCI. In order to optimize

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performance, models enable predicting user interaction with the system. "A model is useful only if it helps in designing, evaluating, or otherwise providing a basis for understanding the behavior of a complex artifact such as a computer system" [13]. Models can vary in detail and complexity, from engineering models, which use mathematical expressions to predict performance, to descriptive models, which provide a framework for designers to describe and reflect on problems [13]. Although models are useful in evaluating interfaces, there is no way of knowing whether predictions are accurate unless tested with users [14].

2.1. MHP (Model Human Processor)

Model Human Processor (MHP) is one of the most widely recognized human information processing models [15]. It was developed by Card, Moran and Newell [16]. It is an engineering model which supports predicting processing sequences and durations. This model is based on the idea that the human mind is an information processing system.

In some studies, researchers used MHP models to predict the behavior of disabled people and found that it took more time for disabled individuals to do perceptual, cognitive, and motor processing [17] [18]. According to Keates et al. [17], the motor performance varies significantly depending on the deterioration degree of experienced movement by the participant. They conclude the participants' additional workload is caused by the effort required to control the physical movement.

2.2. GOMS (Goals, Operators, Methods, and Selection rules)

GOMS (Goals, Operators, Methods, and Selection rules) is a well-known predictive modeling technique in HCI [14], developed by Card, Moran and Newell in the 1980s [16]. This technique may be useful in determining whether a proposal interface is optimal. GOMS is a rather generic term used to refer to a family of specific models [19]. These variations of GOMS are: Keystroke-Level Model (KLM), CMN-GOMS, Natural GOMS Language (NGOMSL), and Cognitive-Perceptual-Motor GOMS (CPM-GOMS).

KLM [20] is the simplest variant of GOMS. KLM predicts how long it takes to execute a task. Basically, it lists a sequence of actions using keystrokes (such as pressing keys, moving the mouse, pressing a button, etc.) that a user follows to carry out a task.

GOMS has been used in research that involves the participation of people with physical disabilities or used for clinical purposes. Koester and Levine [21] have conducted an extensive study creating and validating KLM GOMS models for word prediction systems. In order to show clinical applications of the model simulations, they examined the effect of different system configurations and user strategies. In general, their work is an excellent example of the benefits that can be obtained in the design and clinical evaluation through modeling and simulation. In another study, Tonn-Eichstädt performed a GOMS model extension generating "an interaction model of blind users' interaction strategies" [22]. The model allows calculating the time required to execute a task on a web page. It was developed from the results of field studies and watching users. This study also required to extend the classic GOMS notation adding new structures. These studies demonstrate the utility of GOMS and its applicability in evaluation of interfaces for users with certain limitations.

2.3. Fitts' Law

Fitts' law is another well researched, useful, and successful model [23]. It was developed in the 1950s and is related to human movement.

Fitts' law can be applied to both non-disabled users and users with disabilities, although the latters may present different interaction patterns than their healthy counterparts. Wobbrock and Gajos [24] demonstrated the usefulness of Fitts' law, applying it to people with and without motor disabilities. Furthermore, Smits-Engelsman et al. [25] found it is applicable to children with congenital spastic hemiplegia. Despite obvious limitations in fine control, the study shows this law is solid and even children with damage to their central nervous system may adhere to it.

3. Requirements

Prior to the deployment, and in order to obtain the requirements for the application, we conducted observation sessions. In these sessions, we observed patients performing their therapy led by the therapist. At the same time, the therapist was providing necessary explanations. We performed an open observation—the observer did not interact—; and we took notes about the observations and comments from therapists. Specifically, we registered the patients' pathology, the tasks performed, the procedure, and the therapists' comments. The observations were performed in the therapy center at the Dr. Alfonso Asenjo Institute of Neurosurgery. We did two sessions of three hours each. From the observations and using our intuition, we made a list with candidate functionalities. Then, these ideas were discussed and validated together with an Occupational Therapist and a Physical Therapist. Thus, we obtained the functionalities to implement.

The software should be interesting and comfortable for patients and designing it like a game may help encourage users. Use of background music (calming music, such as classical) is part of the setting. We follow the Magic Mirror paradigm [11] so that the user observes his/her own performed movements on the screen and tries to improve them. The system should provide visual (e.g. text, images) and hearing instructions (e.g. speech synthesis) that lead the user to a successful training routine. It also must generate motivational phrases to encourage the patient to continue with his/her task. Therapists should be able to adjust the configuration of the application (e.g. level of difficulty, affected limb, background music, routine to execute) according to the patient's conditions. Virtual objects must represent equivalent real objects. The application must use NUIs, so patients may control the application with their healthy upper-limb, with only minimal assistance or without the help of another person. For the implementation of NUI and Magic Mirror, we used Microsoft Kinect (c.f. Appendix 1). With these functionalities, we expect patients to continue their rehabilitation at home using the software, and preventing them from discontinuing its use because it is too difficult, or from them losing motivation or getting bored.

With this neurorehabilitation tool, patients should be able to perform their therapies in an independent, simple, and interesting way. That is, patients may have a Magic Mirror at home, or medical centers may incorporate it in their rehabilitation units. Furthermore, patients may continue their rehabilitation without constant supervision of their work and progress by therapists.

4. The system

The developed system is a serious game application that follows the Magic Mirror paradigm and uses NUIs. According to Zyda, a serious game is "a mental contest, played with a computer in accordance with specific rules, that uses entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives" [26]. Serious games may help in cases where a user must achieve a specific goal that is more than simply entertainment (e.g. rehabilitation [27]).

Magic Mirror is an application of interactive multimedia mirror. Its hardware consists of: a microphone and speakers for voice and audio interactions, a camera, and a screen or LCD TV covered by a reflective glass [11] [28] [29]. The software may include: video detection, speech recognition, speech synthesis, 3D graphics, multimedia, etc. [11] [28] [29]. These allow human interaction with the video. There are also other similar implementations, such as AwareMirror [28].

Magic Mirror is easily deployed using a computer with existing devices and corresponding software [28]. It may even be useful for neurorehabilitation because it allows the user to watch his/her movements and perform the routines in a fun and interactive manner.

A new alternative to implement Magic Mirror is to use the Microsoft Kinect sensor. Mirracle is an example of this [29]. In that study, the authors use a Kinect and a screen to implement a learning anatomy system, showing several virtual organs intuitively.

Kinect is used to implement NUIs too. A NUI is "a user interface designed to reuse existing skills for interacting appropriately with content" [12]. A NUI allows for the interaction with an application without using input devices on graphical user interfaces, such as a mouse (e.g. [30], [31]). Interfaces of this type have been developed to help improve user experience when using software.

The application was developed using two Microsoft's SDKs. The Kinect for Windows SDK v1.5 was used to manage Kinect (i.e. manage the RGB video and track human body motions.) The second—the Speech Platform SDK 11.0—was employed to convert text to speech (Speech Synthesis). The selected programming language was C#. Both the application development and the user testing were carried out with a laptop computer Intel Core i7 processor, 8 GB of RAM; however, the application can run on some lesser systems (c.f. Appendix 1).

The application development has involved the construction of three prototypes. The first included one training routine, tested by two therapists (an Occupational Therapist and a Physical Therapist). The second included two more routines. This prototype was tested by both the same therapists and two patients: women with right hemiparesis. The third prototype was considered definitive and it was used in the final tests.

The application consists of three routines. These allow patients to train in reaching and grasping of objects with their injured upper limbs. The first is to simulate the action of drinking a liquid from a glass or bottle (Fig. 1), and if a user employs the corresponding real objects, he/she can train on grasping as well. The tic-tac-toe (Fig. 2) was considered as the second routine to simulate object reach. The user plays against the computer in tic-tac-toe. Thirdly, we consider a game to catch virtual water drops with a glass (Fig. 3). The drops fall from one level to another, at random time intervals. The latter allows a patient to train both the reaching and grasping of objects (when the user uses the corresponding real object). Both the first and third routines display the users' progress (or score). At the end of each task, the software reports results to the patient, telling whether or not he/she has achieved the goal. The three routines are configurable (Fig. 4) according to patient limitations (five levels of difficulty, and upper extremity to train).

5. Data

Data was obtained from test patients at the aforementioned Institute of Neurosurgery, where they carried out their rehabilitation in the Kinesiology or Occupational Therapy areas. Ten adults of both genders participated (three men and seven women). Three participants had some experience with video games. All participants had some dysfunction of their upper limbs (e.g. hemiparesis).

The experiment consisted of each participant using the software and completing a questionnaire (shown on Appendix 2). Each patient used the program for about twenty minutes. Two of the three implemented routines (except tic-tac-toe) were tested, both with and without a corresponding real object (glass or bottle). The patients then answered the twenty items of a questionnaire divided into two parts and using the Likert scale with three values (1 = disagree, 2 = indifferent, 3 = agree). The first part was used to evaluate the functionalities and describe the application. With the second part we evaluated the application's usability. This part was designed based on Nielsen's Ten Usability Heuristics [32].

Each test was supervised by the patient's therapist, while the patient performed the routine. The therapist explained to each patient how they would be trained in the session. The patient then used the program. When the patient finished, the therapist filled out a questionnaire about his/her appreciation of user interaction with the system. Again, we used a Likert scale similar to the patients' questionnaire. This helped the patients feel safer when they were performing the therapy and it also gave us a double control mechanism.

Moreover, we carried out another assessment of healthy people. In this evaluation six Physical Therapy students (four men and two women) participated who were doing their internship at the Institute of Neurosurgery. They executed the test in the same way as the patient and completed the same questionnaire. All of the above is called "Experiment 1" below.

Figure 1. Routine 1: simulating drinking (with both virtual and real objects). Translation of original instructions: (top): Drink as much as you can; (cloud): Raise.

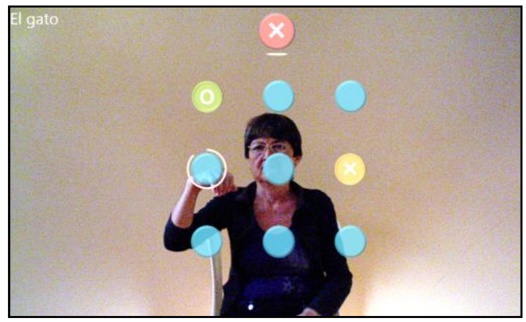

Figure 2. Routine 2: The tic-tac-toe.

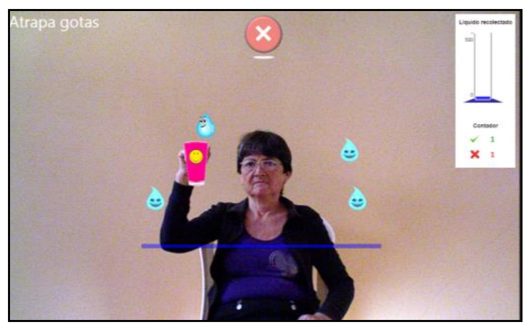

Figure 3. Routine 3: Catch virtual water drops (without real object).

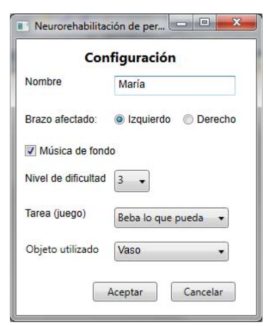

Figure 4. Configuration of the application. Translation of the form (top-down): Name; affected limb (left, right); background music; difficulty level (1-5); task (routines); object (glass, bottle).

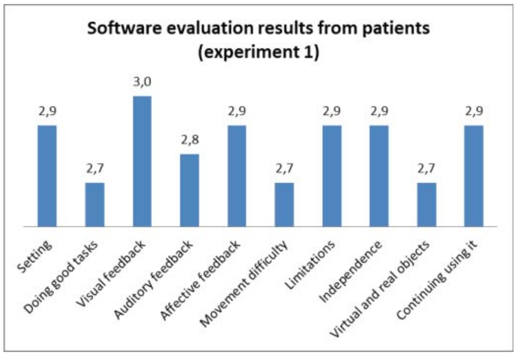

Figure 5. Software evaluation results from patients (experiment 1).

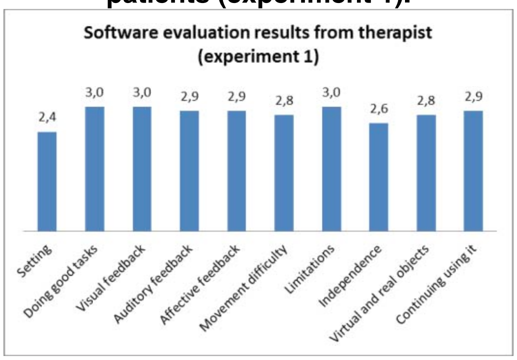

Figure 6. Software evaluation results from therapist (experiment 1).

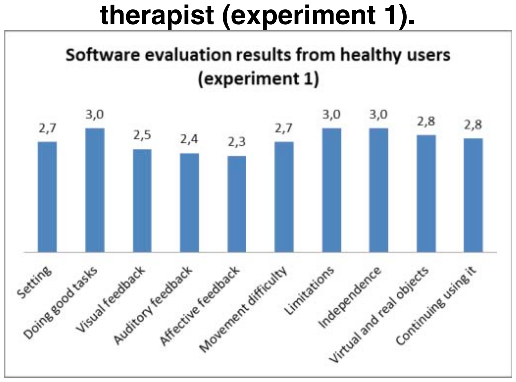

Figure 7. Software evaluation results from healthy users (experiment 1).

Later, we carried out the experiment again for expanding the sample size and gaining more insight about the patients' perception of the application. We performed this experiment in a similar way to the first one, but with different patients. Eleven subjects participated in this experiment (four men and seven women, age range 29-73 years). These subjects had some dysfunction of their upper limbs and carried out their rehabilitation at the same Institute of Neurosurgery. The patients answered the same questions but using a five-points Likert scale (1 = strongly disagree, 2 = disagree, 3 = indifferent, 4 = agree, 5 = strongly agree). This experiment is called "Experiment 2" below.

6. Results

Following the procedure explained above, we calculated the average of each question (the max. value is 3 in the first experiment and 5 in the second one). Figures 5 and 8 show the software evaluation results by patients in each experiment. The assessment results obtained from the therapists when patients use the application are shown in Fig. 6 (experiment 1) and 9 (experiment 2). Finally, Fig. 7 shows the results of the software evaluation by healthy users (Physical Therapy students).

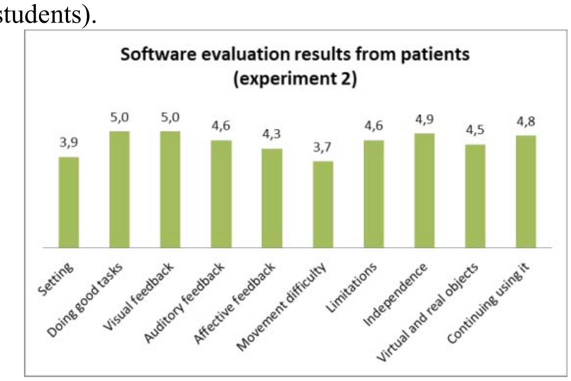

Figure 8. Software evaluation results from patients (experiment 2).

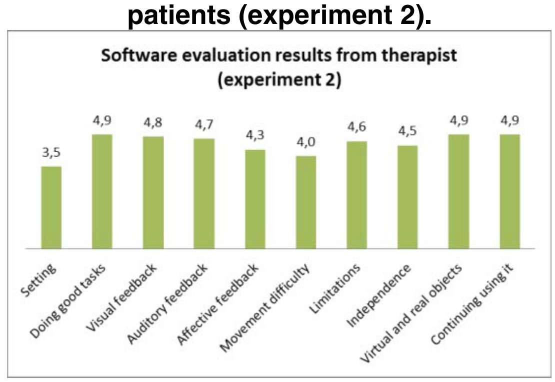

Figure 9. Software evaluation results from therapist (experiment 2).

Data was homogenized to simplify the analysis and presentation of results. Specifically, we changed negative questions (c.f. Appendix 2, questions number 1, 6, 8, 12, 15 and 16) to positive questions and inverted the answers. For example, if a user answered that he agreed with the first question, we registered a value of 2, but we used a 4 for the computations and analysis.

Furthermore, the questions intended to measure usability show promising results. The lowest score—as indicated by patients in the first experiment—is 2.8 for the question "When I used the application I knew what was going on and what I had to do". The lowest score expressed by healthy people is 2.5 for the question "If I selected a wrong option, I can return to previous location". In the second experiment, the lowest score was 4.5 for questions number 13 and 14 (c.f. Appendix 2).

In general, the results obtained from the two experiments are coherent. The major differences are in the *Setting* and the *Movement difficulty*. This is discussed in the next section.

7. Discussion

The results presented in the previous section show that users accepted the developed application. The reason for this is the implemented functionalities.

The background music (c.f. the bar labeled as *Setting*) included as part of the application setting is considered beneficial by users [3]. However, according to the observations of the therapists during the test sessions (in both experiments) and the patients' opinion (in the second experiment), the background music could be indifferent. Thus, we conclude the background music must be optional.

We posed that a user will see himself/herself reflected on a screen, which helps when he/she is performing a routine (*Doing good tasks*). We have confirmed it with the experiments and think this will help to decrease patient distraction, because we have placed more emphasis on providing understanding of the task rather than in the patient's entertainment value [2]. This does not mean that the application does not encourage patients.

The combination of visual feedback with other types of feedback [10] has also been taken into account (the third, fourth and fifth bars). According to the patients' criterion, the three types of feedback included are suitable. However, the affective feedback (included as motivational phrases) may be indifferent for some patients. The therapists are in agreement. Additionally, considering the opinion of the healthy evaluators, feedback needs to be improved.

Other positively evaluated aspects are *movement difficulty* and *user limitations*. In general, these are in accordance with patients, thus contributing to better progress, interactivity, and motivation [3]. The implemented difficulty levels contribute positively too. However, we observed that the use of several levels of difficulty was insufficient (for this reason, some patients answered that the level of difficulty was not in accordance to their mobility). We then believe that it is necessary for a neurorehabilitation application to analyze patient movement and suggest a level of difficulty, or adapt to him/her (therapists must verify that difficulty level is suitable).

Another significant factor in obtaining positive results is when we use Natural User Interfaces. We used NUIs to minimize the intervention of other people helping the patient (*independence*). The implemented NUI uses innate and everyday user life skills (e.g. reaching for an object with a hand), which reduces the need to acquire new abilities and the cognitive load [12]. We did not use a Graphical User Interface (GUI) because it introduces problems: the user needs to use a mouse (or another device) to control the application with his/her dominant hand. NUI also seems to be more suitable for people with little or no experience using computers. We observed this in our experiments: three participants had never used a computer and they used our application without any problems. We expect more benefits using NUIs for neurorehabilitation, but more tests are necessary.

We used Kinect to implement the NUI, although there are alternatives. Nintendo Wii Remote is an inexpensive and easy to use option, but it detects hand movements only. Despite it being small and light, a patient must use it with his/her hand and may trigger discomfort or difficulty on upper limb movement. Wearable motion sensors are another option that can be quite accurate once calibrated. However, it can be tedious, uncomfortable, or difficult to place for patients. Human body detection based on video is an interesting suitable option. In this case, Kinect provides depth data too. Thus, by using Kinect we can create solutions that keep or increase patient interest, and target a larger group of people.

The last functionality tested was the combination of *virtual and real objects*. The patients said this combination was useful. Therapist and healthy people are in agreement.

All this leads to people declaring their interest in *continuing using* the software (c.f. the last bar). For instance, when we were performing the tests, a patient told us that after using our application, she bought an Xbox with Kinect.

The described application is an experimental work, but we think it can evolve to become a product. One of the possible evolutions is to become a telerehabilitation system. This system allows therapists to configure the necessary routines for each patient. The data from patients and their routines are stored in a database and analyzed afterwards. The analysis results can then be used by therapists to supervise and adjust patient training. In addition, the system could allow communication between patients and therapists (e.g. video calls). Thus, patients could train at home and undergo better neurorehabilitation.

8. Conclusions and future work

Through the testing, we have verified that the developed application is suitable to support the neurorehabilitation process of people with upper extremity dysfunction. This application follows the

Magic Mirror paradigm and uses Kinect. The application has a relatively low cost (e.g. one must only own a computer and buy a Kinect sensor). Thus, the tool can help patients to continue their rehabilitation at home.

We determined several functionalities to develop the application. These functionalities were obtained from the observation of patients undergoing their therapies. We asked patients about the following: the setting, doing good tasks, visual feedback, auditory feedback, affective feedback, movement difficulty, patient limitations, patient independence and a combination of virtual and real objects.

With the execution of the usability test, we verified that the application had user acceptance and that they were interested in continue using it.

In this paper we described some theoretical models used in HCI, but we did not apply them (for predictions, e.g. time). We have emphasized the benefit that patients and therapists may obtain from the application, however, we are thinking of using them in future work. For example, KLM can be adapted to estimate time that patients require in executing a routine and defining new operators, according to patients limitations. Subsequently, these values may be used to encourage patients to continue training (e.g. achieve the value established as a goal).

Despite having tested the application with real patients, we expect to carry out further tests. This also will include developing new routines for more types of patients (e.g. different conditions or limitations). We will expect to develop these routines using a Kinect for Windows sensor of the new generation. The new Kinect should facilitate to design 3D models of real objects, recognize the opening and closing of the hand, improve the setting, etc.

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Appendix 1: Kinect

Kinect is a motion sensing input device developed by Microsoft for the Xbox 360 video game console. Kinect has the capability to capture human body movement to use it as a control. It allows the controlling of applications using Natural User Interfaces without physical contact. Originally, it was named “Project Natal”. Nowadays, Kinect competes with Nintendo Wii Remote and Sony PlayStation Move systems.

Fig. 10 shows the main components of Kinect. The 3D depth sensors allow tracking human body motion on game area. The RGB camera allows video and photos to be obtained. At the lower front, the sensor includes an array of four microphones that can be used for voice recognition commands. Kinect has a mechanical unit at its base to tilt the sensor down or up which is handled by software, not manually.

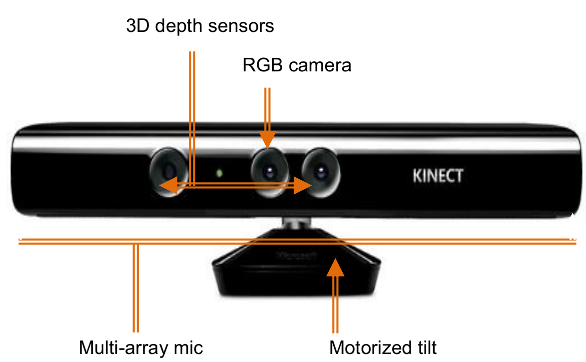

Figure 10. Main components of Kinect.

Developers can create their own applications using Kinect on Microsoft Windows, Linux or Mac OS. For Windows 7 or higher, Microsoft provides the Kinect for Windows SDK that contains necessary tools and APIs. The SDK includes support for color images, depth images, audio input and data from user skeleton representation. Applications may be built using C++, C# or Visual Basic, on Microsoft Visual Studio 2010 or later with .NET Framework 4.0. The hardware requirements are 32 bit (x86) or 64 bit (x64) processor, dual-core 2.66-GHz or faster processor, dedicated USB 2.0 bus, 2 GB RAM.

Overall, Kinect works with different lighting conditions (light or dark), except outdoor environments, where sunlight interferes with the proper functioning due to infrared tracking. This aspect is irrelevant in close quarters.

Appendix 2: Questionnaire answered by patients

Part 1

1. *Trabajar con música de fondo fue incómodo*. (Working with background music was uncomfortable.)
2. *Mirarme a mí mismo reflejado fue de utilidad para hacer bien la tarea*. (Look at myself reflected was useful for doing the task well.)
3. *Las imágenes ayudaron a entender mejor lo que hacía*. (The images helped better understand what I was doing.)
4. *Los sonidos sirvieron para guiarme al realizar la tarea*. (The sounds served to guide me to accomplish the task).
5. *Las frases de motivación me ayudaron a no desanimarme*. (The motivational phrases helped me not to be discouraged.)
6. *La dificultad no estuvo acorde a mis limitaciones de movimiento*. (The difficulty was not according to my limited mobility.)
7. *Controlé el programa mediante el movimiento de mi brazo sano*. (I controlled the program by moving my healthy arm.)
8. *Trabajé la mayor parte del tiempo con ayuda de otra persona*. (I worked most of the time with the help of another person.)
9. *Emplear objetos reales, junto a los virtuales (vaso y botella del programa), fue de mayor provecho*. (Using real and virtual objects together—glass and bottle of the program—was more benefit.)
10. *Deseo continuar entrenando de esta forma en mi casa*. (I want to continue training in this way at my home.)

Part 2

11. *Al utilizar la aplicación sabía lo que estaba pasando y lo que tenía que hacer*. (When I used the application I knew what was going on and what I had to do.)
12. *El lenguaje (términos) empleado no está acorde a mi comprensión*. (The language—used terms—used is not according to my understanding.)
13. *Al seleccionar una opción incorrecta, se puede volver al lugar anterior*. (If I selected a wrong option, I can return to previous location.)
14. *Todas las opciones e imágenes iguales tienen significados equivalentes*. (All equal options and images have equivalent meanings.)
15. *Se produjeron errores graves y éstos no han sido prevenidos*. (There were serious errors and they have not been prevented.)
16. *Su forma de uso es difícil de recordar*. (The application usage is difficult to remember.)
17. *Puede ser utilizado de forma eficiente*. (The application can be used efficiently.)
18. *Las pantallas contienen sólo la información necesaria*. (The screens contain only the necessary information.)
19. *Los mensajes de información y error son claros y adecuados*. (The information and error messages are clear and appropriate.)
20. *Incluye la ayuda necesaria*. (The application includes the necessary help.)