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Virtual haptic perception as an educational assistive technology: a case study in inclusive education

Raquel Espinosa-Castañeda, Hugo I. Medellín-Castillo

***Abstract*—The traditional educational process of blind people is a complex practice that relies on the haptic perception (tactile perception) of physical models. However, physical models may be costly, inaccessible or may require a large storage space. To overcome these difficulties, in this paper a virtual haptic perception approach to support the teaching and learning process of blind people is proposed. The proposed approach combines the use of virtual reality and haptic technologies. The research aim is to objectively evaluate the feasibility and effectiveness of using virtual haptic perception in the education of blind children. For this purpose, an experimental methodology was defined and used to teach maths, in particular fundamental 3D shapes, to blind children. The results are analysed in terms of the participants' ability to explore and recognize virtual objects, and the knowledge gain after the virtual perception learning period. From this analysis it is concluded that haptic virtual perception is a valid and effective assistive technology for the education of blind children.**

***Index Terms*—blind children; haptic perception; learning performance; task completion time (TCT); virtual haptic.**

I. Introduction

IN the teaching and learning process it is important to communicate meanings, concepts, ideas, and to generate the appropriate educational situations that lead to an appropriate learning environment. Many of these situations and educational environments are based on visual representations. However, the teaching and learning process of blind people is a challenging practice because conventional Information and Communication Technologies (ICT) and visual materials may be ineffective. Educational subjects comprising shape, size, and volumetric concepts, such as 3D geometry, biology and architecture, may seem easy to teach to students with no visual disabilities; but when dealing with blind students this process becomes a challenge. Traditional educational tools for blind people includes the haptic perception (tactile perception) of physical models. The main disadvantage of this approach is the need of a large variety of models, which may be costly and require large storage spaces. Moreover, some models may be inaccessible because of their complexity or size (too small or too large), for example when teaching cellular biology or ancient architecture.

Modern computer technologies comprises virtual reality and computer haptic systems, which add the sense of touch to the human-computer interaction and provide information about the dimensional and physical properties of virtual objects. Consequently, computer haptics can be used to generate mental representations of virtual objects [1], [2]. However, although virtual reality and haptic systems have been widely used in science and engineering, little research work has been done in education. Indeed, there are still some perceptual, technological and methodological impediments that limit the use of computer haptics in education [3]. These impediments are greater in the teaching and learning process of blind or visually impaired people.

A haptic virtual reality tool to train visually impaired people was proposed and evaluated in [4]. A Cyber-Grasp haptic device was used and several applications were developed. It was concluded that the proposed system can be used for educational purposes, mobility and orientation training, and exploration/navigation in 3D spaces. The use of virtual reality to assist blind people in their anticipatory exploration and cognitive mapping of an unknown space was presented [5]. It was observed that virtual reality is effective in the construction of cognitive maps for the exploration of virtual environments, which can then be used to navigate in the real environment. Auditory and haptic feedback were provided at different levels (e.g. the name of an object, indication of end points, indication of turning points), in order to assist the participants in the mapping of the virtual objects [6]. Similarly, a haptic-interface videogame to improve the orientation and mobility skills of blind people was presented in [7]. The user interface comprised a standard computer keyboard, a Novint Falcon haptic device and earphones. On the other hand, the spatial knowledge that blind people gain by studying an audio-haptic map of a multisensory application, which included a Novint Falcon haptic device, was investigated in [8]. They concluded that

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Raquel Espinosa-Castañeda is with the Communication Sciences Faculty, Universidad Autónoma de San Luis Potosí, San Luis Potosí, México (e-mail: raquel.espinosa@uaslp.mx).

Hugo I. Medellín-Castillo is with the Mechanical and Electrical Engineering Department, Engineering Faculty, Universidad Autónoma de San Luis Potosí, San Luis Potosí, México (e-mail: hugoivanmc@uaslp.mx).

blind people were able to build significant spatial knowledge after using the proposed multisensory application. More recently, a haptic cane controller to allow visually impaired people navigate in virtual environments was presented in [9]. Physical resistance, vibrotactile and spatial 3D auditory feedbacks were provided to the user. Indoor and outdoor VR scenes were evaluated and the results demonstrated that the proposed controller allows visually impaired users to navigate virtual environments.

Although a clear consensus about the capability of computer haptic technologies to induce mental representations in blind people is observed in the literature, most of the existing research works have focused on enhancing the orientation and mobility skills on blind people. Moreover, very few works have formally addressed the use of virtual haptic perception as an educational approach for blind people.

In this paper the use of virtual haptic perception is proposed as an educational approach to overcome some of the current limitations and difficulties in blind people education. The research aim is to objectively evaluate the feasibility and effectiveness of the proposed haptic learning approach. For this purpose, an experimental study is conducted and comprises three stages: a) application of a pre-test to measure the behaviour level of learning prior to the intervention; b) teaching of blind students using the proposed haptic-virtual approach, and c) application of a post-test to measure the level of learning after the intervention.

II. Background and Related Works

After the discovery of the human capacities to perceive both tactile and kinesthetic sensations, the haptic perception concept was introduced and described as "our experience of the world based on a combination of tactile and kinesthetic sensation" [10]. This concept was derived from Gibson´s experiments, which consisted in the tactile recognition of 10 moulds with different shapes and sizes. Sighted and blind participants had to manually recognize each mould. From the results, it was observed the existence of a partial equivalence between the visual aspects and the haptic representation of objects, suggesting that objects can be recognized by touching them before seeing them or vice versa. The influence of visual experience on material representations, and the relationship between visual and haptic perception, was investigated in [11]. After carrying out an experiment with 5 blind and 12 fully sighted blindfolded participants, it was concluded that haptic material representations can emerge independently of visual experience, and that there are no advantages for either group of observers (blind and sighted) in haptic categorization.

In the last years, several studies have been conducted to investigate the haptic perception in blind people. These studies have considered the scene perception [12]; the sensory substitution [13]-[15]; the scene recognition [16]; the artistic abilities through tactile perception [17]; the raised line drawings and mental imagery [18]; the object identification [19]; the shape information [20]; the material perception and texture discrimination [21], [22]; the Bouba/Kiki effect as a cross modal correspondence between senses [23], [24]; and the active touch [25]. The results have revealed that the haptic perception is an alternative to sight perception to recognize the size, shape, surface structure and properties of physical objects. It can also be used to acquire spatial knowledge and generate mental representations of the surrounding environment. Moreover, by means of haptic perception, humans are able to accurately recognize physical objects in just one or two seconds [26]. This recognition ability has been considered in the development of assistive technologies, such as the long cane aid proposed in [27].

According to The United Nations Educational, Scientific and Cultural Organisation (UNESCO), ICT can contribute to universal access to education, equity in education, and delivery of quality learning and teaching [28]. However, although the use of ICT in education has increased exponentially in the last two decades, relatively little research has been made to develop assistive technologies for the education of people with disabilities, in particular blind people. Thus, one of the main challenges of education is to generate inclusive and assistive educational technologies for people with visual disabilities.

Since many years ago, the use of computer haptic technologies to assist blind people has been proposed [27]. The first recommendations to incorporate haptics into computer interfaces for blind and visually impaired people were presented in [29]. Similarly, some suggestions to improve the accessibility of blind and visually impaired people in 3D virtual environments were also presented in [30].

An auditory game platform for blind and visually impaired people was proposed in [31]. The proposed tool is based on sonic and haptic interaction by means of a sound screen and a graphic tablet, respectively. The results suggested the use of the proposed platform as a help for teaching basic planar geometry. On the other hand, a system for the manual exploration of virtual 3D copies of art works via a haptic display was presented in [32]. The system aimed to assist blind visitors to museums, improving their experience and perception of art. The haptic interface consisted of a fixed arm exoskeleton that provided force feedback to the upper limb. However, it was observed that the virtual interaction with 3D objects was different than when interacting with real objects, and that more user-friendly haptic displays needed to be developed.

The training of visually impaired people using haptic virtual environments was addressed in [4]. The training scenarios included object recognition and manipulation, and cane simulation by means of a CyberGrasp haptic device. The results suggested its use in other applications such as education, mobility and orientation training, and exploration/navigation of 3D spaces. Later, the use of virtual reality with auditory and haptic feedback to help blind people in exploring and mapping unknown spaces, was proposed in [5],[6]. A design of an

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educational haptic game for blind and visually impaired students was presented in [33],[34]. The aim was to allow the students to practice and learn about 3D objects using a single contact point haptic device. Experimental tests on the manipulation and recognition of primitive 3D objects by blind users were conducted, including interviews with their parents and teachers. The results were analysed in terms of the user experiences and the improvements needed in the system. In addition, it was mentioned that the exploration time was not important but the involvement of blind students in the evaluation of the haptic technology.

A preliminary research to evaluate the use of multi-sensory learning materials that incorporate computer haptics, audio cues and high-contrast images, was presented in [35]. Several applications covering topics in maths and science were developed and tested using a Novint Falcon haptic device. A group of four visually impaired students tested each app and were interviewed about their experiences. The results showed that computer haptics could be a useful tool for teaching blind and visually impaired middle school students. Similarly, the use of vibratory touchscreens and audible sounds to transfer mathematical graphical concepts to students with visual impairments was reported in [36]. The results also suggested that vibratory touchscreens are useful for communicating graphical math concepts to visually impaired people.

From the previous literature review, it is observed that although computer haptics is a vast research area, little research work has been done on the use of computer haptics for the education of blind and visually impaired people. In addition, most of the research works in this area have only focused on testing the feasibility of using computer haptics for blind people education, but without conducting a proper objective evaluation of the learning process efficacy. Therefore, more research work to understand and evaluate the learning process of blind people when using computer haptics is still needed.

III. Materials and Methods

A. System description

In order to investigate the use of virtual reality and haptics as learning approach for blind children, the ClayTools software together with a Phantom Omni haptic device from Geomagic® (formerly Sensable®) were used as shown in Fig. 1. The ClayTools software is a virtual clay modeler that allows users to feel and touch 3D models by means of a haptic device, enabling the virtual haptic perception. On the other hand, the Phantom Omni device has a moulded-rubber stylus that the user must grasp and move during the virtual interaction in order to explore, touch or manipulate the virtual objects. The haptic device works as a 3D dimensional pointer with six degrees of freedom (6 DOF) for the user to move freely in the virtual environment. Force feedback is provided to the user at a frequency of 1 kHz, which is in the range of the natural human touch perception. Notice that although there are commercially available haptic devices that can provide multipoint contact feedback, such devices are very costly and complex; consequently, they may not be accessible for public education institutions, particularly in low-income countries.

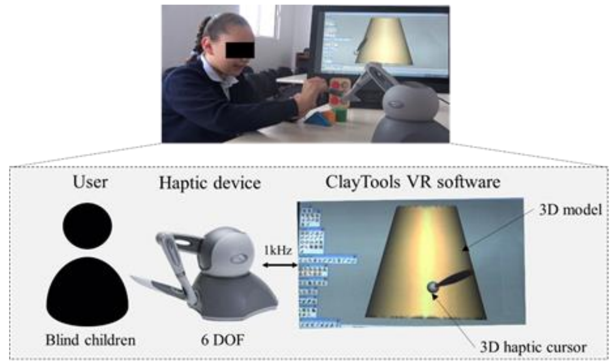

Fig. 1. Architecture of the system.

B. Experimental methodology

An experimental procedure was designed and implemented to teach 3D basic shapes using the virtual haptic system described before. The dependent variable (effect-consequent) was defined as the level of learning and understanding of basic 3D shapes, whereas the haptic-enabled virtual reality tool was defined as the independent variable (cause-antecedent). The overall experimental methodology is illustrated in Fig. 2 and comprises the following three main stages:

(1) Application of a pretest to measure the behaviour of the dependent variable prior to the haptic-virtual learning;
(2) Execution of the haptic-virtual learning; and
(3) Application of a posttest to measure the behaviour of the dependent variable after the haptic-virtual learning.

The complete experimental procedure was explained to the participants and approved by the blind educational institution. Two trained researchers acted as teachers and classroom assistants during the study, conducting the interviews and controlling the assessments of the children. Three data collection instruments were developed to gather the quantitative and qualitative information: 1) video recording of all tests and interviews, 2) pretest and posttest to evaluate the effectiveness and efficiency of the haptic-virtual learning, and 3) open interviews after the exploration task for the participants to verbally describe their experience.

C. Participants

Six participants were selected based on five criteria: total blindness (without any visual ability), ranged in age from 10 to 11 years old, not multi-handicapped, no previous experience with virtual reality and haptic systems, and comfortable with the use of computers. The information of each participant is shown in Table 1. Four participants are part of the boarding school, and the other two participants live with their parents but attend the blind school. All participants performed all tasks and gave informed consent prior to data collection. It must be mentioned that because of the nature of the experiment and

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participants, it was not possible to work with a larger number of participants; however, in such especial cases the requirement of having a minimum number of subjects can be omitted, [35],[37].

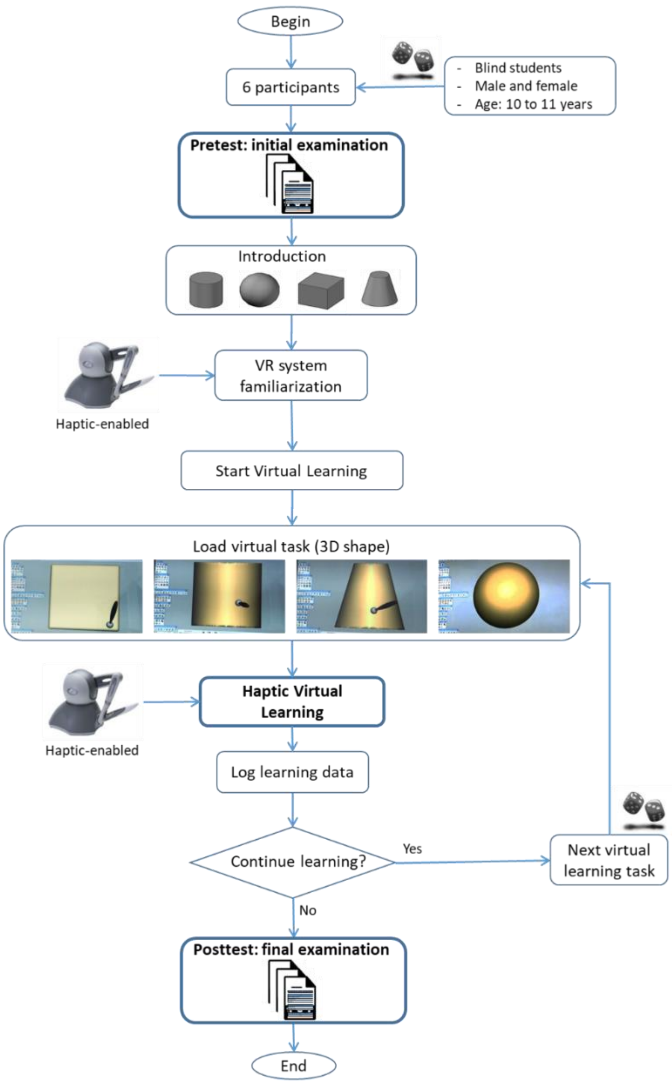

Fig. 2. Experimental methodology.

TABLE 1
INFORMATION OF THE PARTICIPANTS

Participant	Sex	Age	Cause of blindness	Age of onset	Handedness
1	M	10	no clinical record	0	R
2	M	11	retinal detachment	5	R
3	M	10	no clinical record	no record	R
4	F	11	congenital glaucoma	0	R
5	F	11	bilateral microphthalmia	0	R
6	M	11	bilateral retinoblastoma	4	R

D. *Learning material*

In order to teach fundamental 3D geometry, four 3D shapes were selected for the experimental study: 1) cube, 2) sphere, 3) cylinder, and 4) cone, as shown in Fig. 3. These virtual 3D shapes were used during the virtual learning task, whereas physical 3D objects were used during the real recognition evaluation process.

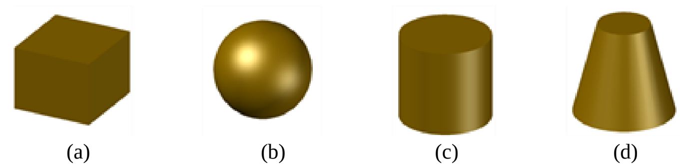

Fig. 3. 3D shapes for haptic virtual learning: a) cube, b) sphere, c) cylinder, d) cone.

E. *Pretest*

Participants were asked to complete a one-on-one interview in a quiet space. The interview was video recorded and included questions about children's familiarity with various electronic devices (i.e., computers, mobiles, tablets, videogames, etc.), their skills and frequency of using these devices. Next, to get a sense of the children's 3D geometry knowledge and experience, participants were shown four physical objects (sphere, cylinder, cone and cube) and asked to recognize them in a maximum period of 2-min per shape to avoid guessing and fatigue of the students. Participants received one point for each solid correctly appointed, and points were summed to create a score ranging from 0 to 4 points.

F. *System introduction and familiarization*

Initially, the researcher explained in detail the procedure to be followed; all participants were informed about the general background relating to the experiment, the conditions in which they would be working, and the relevant experimental procedure. It was explained to the participants that by means of the haptic device, they would be able to touch 3D objects and shapes in the computer. At this point, a short introduction to 3D shapes was given to the participants. Each participant was then given a compulsory period of familiarization and training on how to operate the system, explore the virtual environment, touch virtual objects, and feel the force feedback effect. Participants could ask questions and receive further explanations during this period.

G. *Virtual learning*

After undergoing the familiarization and training period, each participant was asked to freely explore and recognize each of the four virtual 3D shapes (cube, sphere, cylinder and cone) by means of the haptic device. The 3D shapes were randomly presented, one by one, to each participant, allowing him/her a maximum exploring period of 5-min per shape (task) and quit beforehand. Each virtual exploration task was repeated three times with a 1-min short break in-between. The time to complete the task (TCT), i.e. the time to recognize the virtual

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shape, was measured for each trial and participant.

H. Posttest

After the virtual learning period, and in order to evaluate the effectiveness of the haptic virtual learning approach, the 3D shapes were presented one by one to each participant in order to be recognized by means of the haptic device. A maximum period of 2-min per shape was given to each participant. To quantify the learning through the virtual haptic tool, the recognition was scored as incorrect (0) or correct (1), resulting in a score ranging from 0 to 4 points. The TCT values for each participant, shape and iteration were also measured.

I. Users' feedback

At the end of the study, each participant was interviewed in order to provide feedback and evaluate the proposed virtual learning approach using a 7-point Likert scale. The evaluation was carried out based on the perceptions and questions shown in Table 2, which were verbally explained and illustrated to each participant.

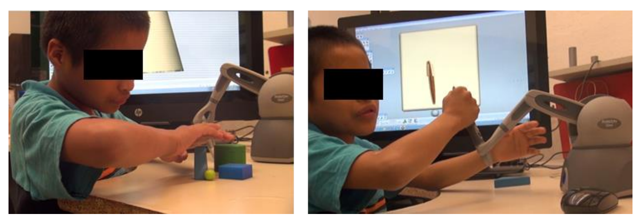
TABLE 2
USER EVALUATION OF THE HAPTIC VIRTUAL LEARNING APPROACH

Perception	Question	Description
Joy	How fun was the haptic virtual learning system?	Low values indicate that the system was boring and high values indicate that the system was great fun.
Weariness	How tired did you feel when using the system?	Low values indicate that participant felt tired and high values indicate that the participant was comfortable.
Usefulness	How useful did you find the system?	Low values indicate that the system is useless and high values indicate that the system is very useful.
Accessibility	How accessible did you find the system?	Low values indicate that the system is inaccessible and high values indicate that the system is accessible.
Learning	Is the system a good learning tool?	Low values indicate that the system is considered a bad learning tool and high values indicate that the system is a good learning tool.
Potential use	Would you like to use the system to touch and learn about objects that you are not able to touch in reality?	Low values indicate that they would not use the virtual touch and high values indicate that they are willing to use the virtual touch.
Didactic	How didactic (learning with pleasure and entertainment) did you find the system?	Low values indicate that the system was stultifying, and high values indicate that the system conveyed instructions and information as well as pleasure and entertainment.
Easiness	Did you find easy to use the system?	Low values indicate that it was difficult to use the system and high values indicate that the system was easy to use.

IV. Results and Discussion

At the beginning of the training period most of the participants needed assistance to hold and operate the haptic device. In addition, multi-sensory feedback about the shape, location, and position of each virtual object, was continuously provided to the participants during the exploration and interaction training period. The virtual haptic perception helped them to identify the shape, whereas the voice of the instructor helped them to identify its location and position. Participants were also assisted with the hand movement in order to become familiar with the smoothness and force feedback of the system, and ovoid abrupt movements during the virtual learning task. In some cases, the participants required help to move back to the virtual object and continue with the virtual haptic exploration. Fig. 4 shows the participants during the virtual haptic learning sessions, and Fig. 5 shows one of the participants during the pretest and posttest.

Fig. 4. Participants during the virtual haptic learning sessions.



(a) (b)

Fig. 5. Participant during the: a) pretest and b) posttest.

A. Virtual learning effectiveness

The knowledge results of the participants at the pretest and the posttest are summarized in Table 3. From these results it is observed that the blind children were able to recognize, on average, 0.8 shapes at the pretest. On the other hand, after the virtual learning period most of the children were able to recognize the four 3D shapes correctly. Participants' initial knowledge of 3D shapes was 0.8/4, and after the virtual haptic learning period, their knowledge increased substantially to 3.8/4. These results evidence that the participants were able to virtually perceive 3D shapes and increase their knowledge. Therefore, it can be said that the proposed virtual haptic perception approach is feasible and effective since blind children were able to haptically explore, learn and recognize virtual 3D shapes by means of the haptic device. Moreover, all participants were skilled to complete the virtual learning tasks and to recognize the characteristics of virtual objects such as edges, vertices, surfaces and shape.

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TABLE 3
PRETEST AND POSTTEST KNOWLEDGE RESULTS

Test	Participant 1	2	3	4	5	6	Average score
Pretest score	0	1	0	0	1	3	0.8
Posttest score	4	4	4	3	4	4	3.8

B. *Virtual learning performance*

Table 4 presents the TCT values corresponding to each virtual learning task of the participants, including the posttest. These values correspond to the time that each participant took to recognize each shape correctly.

The TCT values reported in Table 4 evidence that the time to recognize virtual objects decreased from the first iteration to the final iteration and posttest. In other words, the performance of recognising virtual objects increased with the practice. Table 5 presents the TCT average and standard deviation (SD) values of all the participants for each iteration and 3D shape. From this table it is observed that the maximum values correspond to the first iteration and the minimum values correspond to the posttest. These results reveal the typical learning phenomenon; the more blind children practice in the virtual system, the faster they explore and recognise the virtual objects. Fig. 6 shows the learning curves obtained from the virtual learning TCT results, which indicate that the students gradually improved their skills, achieving their best performance in the third iteration. This gradual performance improvement is due to the natural learning phenomenon that takes place during the successive virtual learning trials. Thus, it can be said that the proposed virtual haptic learning tool allowed the student to improve their recognition abilities and gain geometrical knowledge.

TABLE 4
TCT RESULTS OF THE VIRTUAL HAPTIC LEARNING STUDY

Participant	3D shape	Task completion times (TCTs) (seconds) Iteration 1	2	3	Posttest
1	cube	14	13	6	26
	cone	118	83	20	66
	cylinder	245	107	5	43
	sphere	140	17	10	28
2	cube	30	12	7	11
	cone	148	48	47	7
	cylinder	131	116	37	13
	sphere	123	69	65	26
3	cube	28	25	15	27
	cone	113	49	32	5
	cylinder	221	87	37	32
	sphere	150	31	15	12
4	cube	155	136	50	79
	cone	95	83	60	34
	cylinder	293	148	133	125
	sphere	149	35	28	83
5	cube	29	17	15	41
	cone	36	9	7	14
	cylinder	18	12	11	12
	sphere	33	15	10	14
6	cube	37	29	21	23
	cone	58	38	9	23
	cylinder	30	25	20	21
	sphere	32	23	6	4

TABLE 5
HAPTIC VIRTUAL LEARNING AVERAGE TCT

3D shapes	Average TCT (SD) (in seconds): Haptic virtual recognition Iteration 1	2	3	Posttest	Real object recognition
Cube	48.83 (47.97)	38.67 (43.96)	19.00 (14.78)	34.50 (21.74)	3.83 (2.11)
Cone	94.67 (37.66)	51.67 (25.79)	29.17 (19.40)	24.83 (20.86)	4.17 (1.67)
Cylinder	156.33 (105.25)	82.50 (48.84)	40.50 (43.07)	41.00 (39.09)	6.17 (1.95)
Sphere	104.50 (51.67)	31.67 (18.14)	22.33 (20.32)	27.83 (26.00)	4.67 (1.89)

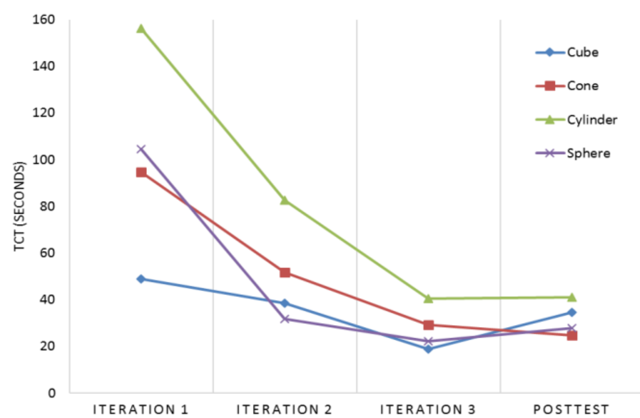

Fig. 6. Learning curves.

Table 5 also shows that the time performance of the participants also depended on the geometrical complexity of the 3D shape. It is well known that the geometrical complexity of a 3D object depends on the type of surfaces and the number of edges comprising it. High-complex shapes contains several types of surfaces and large number of edges, whereas low-complex shapes comprise few types of surfaces and small number of edges. According to this concept, the four 3D shapes used in the experimental study were classified into low, medium and high complex shapes, as shown in Table 6. The cylinder and cone are considered the most complex shapes because they comprise flat and round surfaces, whilst the sphere

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is considered the less complex shape since it only comprises a round surface with no edges. The average TCT values for each level of complexity and iteration are also presented in Table 6. These values are plotted in Fig. 7, where it is observed that, in general, as the level of complexity increases, the time to complete the task (i.e. the time to recognize the virtual shape) increases; complex shapes require more time to be recognized than simple shapes. It is also observed that as the learning process progressed from iteration 1 to iteration 3, the TCT values and the time differences among the different shapes decreased.

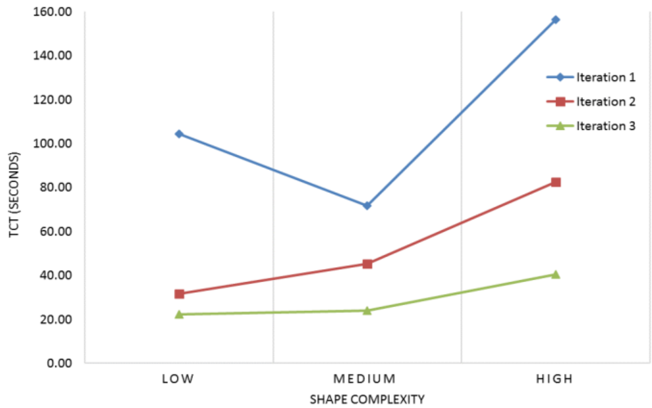

Fig. 7. Time performance (TCT values) vs shape complexity.

TABLE 6
HAPTIC VIRTUAL LEARNING TASK COMPLEXITY

3D shape	Geometrical characteristics	Complexity level	TCT (seconds) Iteration		
			1	2	3
Sphere	Round surface, 0 edges	Low	104.50	31.67	22.33
Cube	Flat surfaces, 12 edges	Medium	48.83	38.67	19.00
Cylinder & cone	Round and flat surfaces, 2 edges	High	125.50	67.08	34.83

The TCT values for the participants to recognize the real objects using their hands are also presented in Table 5. It can be observed that these values are much lower than the corresponding TCT values required in the virtual environment. This behaviour is because in real life the object recognition process using human hands is based on a multi-contact touch, whilst in the virtual haptic system the objects are touch only in one single point (haptic cursor), and therefore the user must move around the shape in order to identify it. However, this difference in the TCT values between real and virtual touch is common in computer haptics [33],[34], and does not represent a disadvantage of the proposed virtual haptic perception approach because blind students can touch and feel virtual models that may not be accessible in real life.

C. *Virtual learning perception*

The results of the users' perception and evaluation of the haptic virtual learning approach are shown in Table 7. The overall score of the system was 6.6/7, which indicates a great acceptability. The participants were very positive and enthusiastic about the proposed approach, specifically because they were able to touch and feel virtual objects. Indeed, most of them were impressed and could not believe that they were touching and feeling virtual objects, and in some occasions, they tried to touch below the haptic stylus looking for the physical objects.

TABLE 7
USERS' PERCEPTION AND EVALUATION RESULTS

Perception	Participant						Average score
	1	2	3	4	5	6	
Joy	7	7	7	7	7	7	7
Weariness	7	4	7	5	7	7	6.1
Usefulness	7	7	4	6	7	7	6.3
Accessibility	7	5	5	7	7	7	6.3
Learning	7	6	7	6	7	7	6.6
Potential use	6	6	7	6	7	7	6.5
Didactic	7	7	7	7	7	7	7
Easiness	7	7	7	7	7	7	7
Average score	6.9	6.1	6.4	6.4	7	7	**6.6**

To evaluate the feasibility of the proposed approach in teaching more complex shapes to blind children, an additional experimental test was conducted. In this test a model of the Chichen Itza pyramid, Fig. 8, was used and corresponds to a history and architecture subject. The participants were asked to explore haptically the model and describe it. Additionally, there was not any time measurement and constraint in order to let the students explore and described completely the model. All blind children managed to identify the overall geometry and features of the pyramid. By making zooms in and out, and rotating the model, some children managed to identify small features like stairs, doors and edges located at the top of the pyramid. With this case study children were even more enthusiastic about using the system as a learning tool.

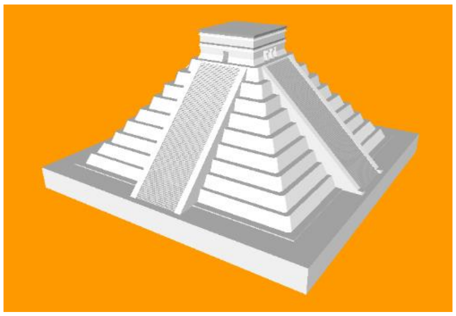

Fig. 8. Model of the Chichen Itza pyramid used in the complex shape case study.

Finally, it must be mentioned that although the 3D shapes used in the experiment may seem easy to teach to children with no visual disabilities, when dealing with visually impaired and blind children this process becomes a challenge, and conventionally relies on the use of physical objects or prototypes. However, when complex or large 3D shapes are mean to be taught, physical models or prototypes may be costly or inaccessible. In addition, if several subjects are taught, a large storage space may be required for all different models. In all these cases or situations, the use of the proposed virtual haptic learning approach becomes very useful since 3D models are accessible and free in many repositories. Moreover, virtual models can be zoomed in and out or rotated to feel and touch small or large details, which is not possible with physical models. Additionally, the computer and haptic system used in this investigation are not expensive, and do not require a large installation or storage space, so it can be used at any school or home.

V. Conclusions

It has been demonstrated that the new proposed virtual haptic perception approach to assist the education process of blind children is feasible and effective. Blind children are able to acquire knowledge and improve their performance by using the virtual haptic perception tool. It has been proved that the combination of haptic and virtual reality technologies allowed blind students to feel, touch and recognize virtual objects. The experimental results showed that the virtual haptic perception improved the skills and knowledge of blind children. Additionally, the regular use of the computer haptics helps to improve the blind children's ability and performance to recognize virtual objects. Future work includes the analysis and evaluation of the proposed haptic approach in other educational topics such as science and arts, including more advanced and complex virtual objects and a larger sample of participants.

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Raquel Espinosa-Castañeda completed her graduate studies in 2006 at the College of Humanities and Social Science in Visual Communication, Edinburgh College of Art, The University of Edinburgh. She is currently a senior researcher and lecturer at the Faculty of Communication Sciences of Universidad Autonoma de San Luis Potosí. Her research interests comprise information and communication technologies for accessible and inclusive education, multisensory perception for blind people, and social impact of new technologies.

Hugo I. Medellín-Castillo completed his PhD studies in Mechanical Engineering in 2005 at Heriot-Watt University, Scotland, UK. Since 2006 he is a Professor in the Mechanical and Electrical Engineering department at the Engineering Faculty of Universidad Autonoma de San Luis Potosí. He has authored more than 150 research publications. Dr. Medellin is member of the American Society of Mechanical Engineers (ASME), the Mexican Society of Mechanical Engineers (SOMIM) and the National System of Researchers (SNI) in México. His research interests include the development and analysis of virtual reality and digital tools to support engineering, medical and educational procedures, in particular inclusive education.