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ORIGINAL ARTICLE

Human factors and qualitative pedagogical evaluation of a mobile augmented reality system for science education used by learners with physical disabilities

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Abstract Technology-enhanced learning, employing novel forms of content representation and education service delivery by enhancing the visual perception of the real environment of the user, is favoured by proponents of educational inclusion for learners with physical disabilities. Such an augmented reality computer-mediated learning system has been developed as part of an EU funded research project, namely the CONNECT project. The CONNECT project brings together schools and science centres, and produces novel information and communication technologies based on augmented reality (AR) and web-based streaming and communication, in order to support learning in a variety of settings. The CONNECT AR interactive learning environment can assist users to better contextualize and reinforce their learning in school and in other settings where people learn (i.e. science centres and home). The CONNECT concept and associated technologies encourage users to visit science centres and perform experiments that are not possible in school. They can also build on these experiences back at school and at home with visual augmentations that they are communicated through web-based streaming technology. This paper particularly focuses on a user-centred evaluation approach of human factors and pedagogical aspects of the CONNECT system, as applied to a special needs user group. The main focus of the paper is on highlighting the human factors issues and challenges, in terms of wearability and technology acceptance, while elaborating on some qualitative aspects of the pedagogical effectiveness of the instructional medium that AR technology offers for this group of learners.

Keywords Augmented reality · Human factors · Science education

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1 Introduction

Current efforts in technology-enhanced learning, as employed in many fields of science, such as medicine [1], mathematics and geometry [2], attempt to enhance reality with synthetic (computer-generated) information, and thus improve the perspective of the learner's complex concepts understanding. The concept of augmented reality (AR) incorporates the use of technology applications that allow the use of 2D or 3D scenes of synthetic objects to enhance and augment the visual perception of the real environment [3, 4]. The co-existence of the computer-generated virtual objects and the real environment constitute a "mixed-reality", where users can interact with the environment, through appropriate input devices in real-time.

In recent years, the need to make a transition to a technology-enhanced classroom has been demonstrated through state-wide and international projects, in supplying computerized technologies to schools. While this ongoing effort is already taking place, there is also a need to immerse school students within rich contextualized learning settings. Museums and science centres present great learning opportunities in that direction. The CONNECT[1] project is a 3-year research effort, co-funded by the European Union's technology enhanced learning action line of the IST/6th Framework Programme and the National Science Foundation, proposing to use AR technologies in order to support science education both in the formal and informal learning environments. The project creates a network of museums, science centres and schools across Europe, to develop, apply and evaluate learning schemes that build on the strengths of formal and informal strategies [5]. It explores the integration of physical and computational media for the design of interactive learning environments to support learning about complex scientific phenomena in physics. The overall objective is to create learning environments, which allow students to interact physically and intellectually with instructional materials, through "hands on" experimentation and "minds on" reflection.

The CONNECT project creates a learning environment that links effective informal learning strategies with exemplary formal curricular activities in an attractive learning environment that utilizes cutting edge information and communication technologies in science education. In particular during the project lifecycle an advanced learning environment has been developed, the CONNECT Virtual Science Thematic Park (VSTP) that incorporates all resources available in the CONNECT network of science parks, science museums and research centres. The VSTP is the entry point of information for interested teachers, educators and/or organizations, in the form of a web portal. The system provides a fruitful environment for innovative use of educational technology and also interconnects the members of the network. In addition, the VSTP organizes the procedure of students' virtual and conventional visits to the science museums and thematic parks. These visits fulfil (through an informal but yet structured way) not only main pedagogical aims of the official curriculum but also estimate costs and efforts for museum staff and teachers as well as provide information regarding usability and wearability issues of the technology.

The VSTP includes two major components:

1. the CONNECT platform (CP), a web-based portal which facilitates pre- and post-visit activities as well as the remote visits to the museums and science parks (through web streaming), and
2. the mobile AR system which the students wear during their visit.

The CP is a web-based application whose aim is twofold. It serves as a central hub distributing the resources available through the project, thus creating a network of science parks, science museums and research centres. It also distributes information and organizes educational activities; it coordinates teachers, students and museum staff in the use of the innovative technology. The CP supports the mobile's AR system specifications and functionalities as well as materializes the VSTP's requirements and procedures. It supports the management of educational pathways, the authoring tool (CONNECT Visual Designer, CVD), allows science museum and classroom communication and provides collaborative tools for teachers and students (see Sect. 2 for the context of use).

Technology-enhanced learning that employs such new forms of content representation and education-service delivery has been favoured by proponents of inclusion in special needs education [6]. Educational inclusion expresses the commitment to educate each learner to the maximum extent appropriate, involving the use of appropriate support services to the learner. There is a lot of research in the field of special needs education and virtual/augmented reality environments, focusing on novel ways in which the new technology can provide and support inclusive education [7].

This paper discusses the elements of a user-centred evaluation of human factors and pedagogical aspects of the CONNECT project, as observed during the use of the system by learners with physical disabilities. The main focus of the paper is on highlighting the human factors issues and challenges, in terms of wearability and technology acceptance, while elaborating on some qualitative aspects of the pedagogical effectiveness of the instructional medium that AR technology offers for this group of learners. Both human factors and pedagogical effectiveness affect the re-design process, implementation and deployment of this type of educational technology for special needs learners.

[1] Designing the classroom of tomorrow by using advanced technologies to connect formal and informal learning environments.

2 Augmented reality in science education: the connect approach

The CONNECT project [5] uses a mobile AR technology-based system (whereby the user wears a head mounted display—HMD) and an associated computer-mediated learning platform, in order to support a learner in visualizing non-typically tangible physical phenomena, when interacting with real objects in the context of formal and informal science learning settings (e.g. interacting with exhibits during a visit at a science museum and recording/transmitting this interaction for reflecting about the experience in the classroom). The rationale behind this approach is based on the argument that graphics and multimedia tools capitalize on the students need for more interactivity, that has shown to aid the student's beliefs of enhanced learning [8]. The CONNECT backpack mobile AR wearable system consists of an i-glasses SVGA 3D Pro HMD, which overlays virtual images onto real world vision. These virtual images are streamed video, captured from a high resolution web cam mounted on the HMD. The mobile processing unit consists of a Dell Precision M60 laptop computer mounted on a backpack (Fig. 1).

The physical dimensions of the CONNECT backpack mobile AR wearable system components are shown in Table 1.

In adding virtual content, such as airflow, magnetic fields or force variables (usually "invisible"), to the user's real world view of a science museum exhibit or experiment, the CONNECT platform provides a mixed reality solution to science teaching that can be used both in formal and informal settings (see Fig. 2).

To assure maximal usability of the new tools, optimal adaptation to the local environments and realistic evaluation of the pedagogical effects in learners with physical disabilities, the project has adopted a student-centred approach where a special needs group of students have participated

Fig. 1 CONNECT wearable system

Table 1 Physical dimensions of the CONNECT backpack mobile AR wearable system

Component	Sub parts	Mounting location	Dimensions $h \times w \times d$ (cm)	Weight (g)
Mouse		Handheld	$3 \times 6 \times 11$	100
Headset		Head	$11 \times 17 \times 10$	650
	Cables	Back		400
	Battery pack	Back		150
Laptop		Back	$4 \times 36 \times 27$	2,300
	Battery packs	Back		850
Backpack		Back	$68 \times 37 \times 22$	1,650
			Total on back	5,350
			Total	6,100

during the trial runs of development cycle of the CONNECT system, in order to provide feedback to the design and implementation of the technology. In particular, students of "Special Lyceum of Athens" consented to support the user trials and a-testing of the system in order to help towards the best implementation and integration of the AR technology to the concept of the "school of the future", where the inclusion and the amalgamation of formal and informal learning are important components of it.

3 Methods

In order to evaluated the usability and the pedagogical effectiveness of the system for learners with physical disabilities, we have concentrated in:

(1) a wearability assessment of the mobile AR CONNECT system and its measurable effects to the physically disable students. The details of assessing wearability are provided below;

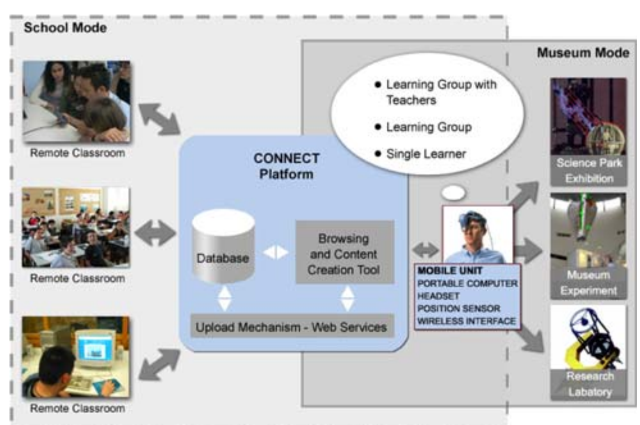


Fig. 2 High-level conceptual diagram of the CONNECT system for both formal and informal science education settings

Table 2 Participant details

Participant	Age	Sex	Disability
1	16	M	MD
2	15	F	MD
3	18	F	CP
4	16	M	MD
5	18	M	Arthogryposis

All subjects were constraint by different levels of mobility difficulties and were using a wheelchair. The subject with the arthrogryposis condition used the system with the help of the teacher, because of the bad condition of the shape of their body (stark shoulders and hands)

MD muscular dystrophy, *CP* cerebral palsy

(2) a qualitative comparative assessment between physically disable and able-bodied students groups on understanding science concepts, together with quasi-quantitative measurements on changes in self-esteem, following the use of the system.

The following selection criteria were applied to compose the group of participating disable students, which is shown in the Table 2.

- All subjects had a good level of cognitive functioning, to be able to reflect upon certain physics concepts and knowledge tests, comparable to that of individual similar-aged able-bodied students.
- A minimum degree of learning disability was present.
- The age of the subjects was between 15 and 18 years (comparable to the able-bodied students' ages).
- They were positive on alternative ways of learning.
- Appropriate consent for participation has been received by both parents and the subjects themselves.

The wearability evaluation of the CONNECT system assesses the effect of the wearable on three aspects. The physiological aspect assesses the energy expended due to the load attached to the body. Assessment of the biomechanical aspect focuses on musculoskeletal loading as the device is attached to the body. This may manifest itself in sensations of pain and discomfort, which may be localized to a specific region of the body [9, 10].

An overall sense of well-being is determined with an assessment of comfort. Measuring comfort across six dimensions, the comfort rating scales (CRS) were developed specifically for the assessment of wearable computers [11]. The six dimensions are Emotion (concerns about appearance and relaxation), Attachment (comfort related to non-harmful sensation of the device on the body), Harm (physical sensation conveying pain), Perceived change (non-harmful indirect physical sensation making the wearer feel different overall with perceptions, such as being awkward or uncoordinated, may result in making conscious compensations to movement or actions), Movement (conscious awareness of modification to posture or movement due to direct impedance or inhibition by the device), and Anxiety (worries as to the safety of wearing the device and concerns as to whether the wearer is using it correctly or it is working appropriately). By measuring across these six dimensions, the CRS attempts to develop a comprehensive assessment of the comfort status of the wearer.

Using physiological, biomechanical and comfort assessments, the wearability of a device can be determined, based on a "level of effect" rating. For a discussion of the metrics used to measure the level of effect see Knight et al. [12]. Table 3 gives five levels of effect from which five wearability levels (WL) can be suggested:

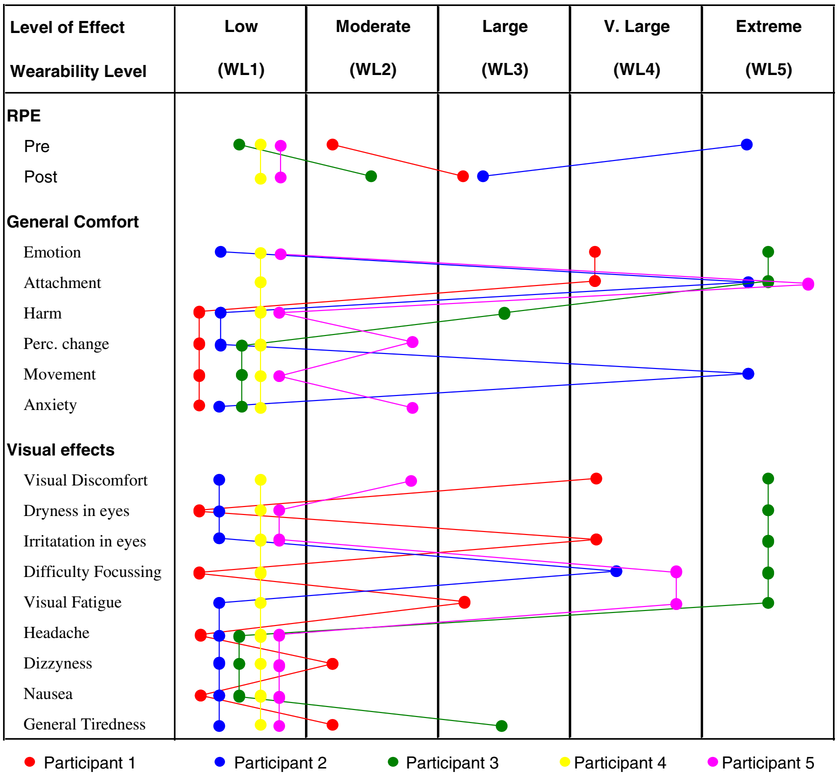
WL1—system is wearable.
WL2—system is wearable, but changes may be necessary, further investigation needed.
WL3—system is wearable, but changes are advised, uncomfortable.
WL4—system is not wearable, fatiguing, very uncomfortable.
WL5—system is not wearable, extremely stressful, and potentially harmful.

Suffice it to say that the tools used rely on subjective rating on a scale and were employed, as they are non-invasive,

Table 3 Levels of effect for wearability

	Metric	Units	Level of effect				
			Low WL1	Moderate WL2	Large WL3	Very large WL4	Extreme WL5
Energy cost	Heart rate	Beats per minute	Upto 90	91–110	111–130	131–150	>151
	Relative perceived exertion	Borg RPE score	6–9	10–11	12–13	14–15	16–20
Biomechanical	Localised pain and discomfort	Borg-CR10 score	0–1	2–3	4–5	6–7	8–10
Comfort	General wearable	CRS score	0–4	5–8	9–12	13–16	17–20
	Vision	VES score	0–2	3–4	5–6	7–8	9–10

Table 4 Relative perceived exertion (RPE), general comfort and vision effects rated by the five disabled participants



quick, and simple to implement without interfering with the users while interacting with the exhibit. All users were assessed for their initial energy cost while wearing the system and before interacting with the exhibit, while after finishing interacting with the science museum exhibit they were evaluated for energy cost, comfort, visual effects, and pain and discomfort.

4 Results

4.1 Assessment of wearability

The results of the wearability analysis are shown in Tables 4 and 5. Figures 3, 4, 5 show mean data and include able-bodied data ($n = 45$) from [13] for comparison. Of course, it should be noted that, due to the small sample size of the disabled student (wheelchair users) group, and hence the susceptibility for the data to be skewed by extreme individual responses, comparisons between the two groups, based on the average data, should be taken lightly. As it is, quantitative statistical analysis is not possible, and all analysis will be at the descriptive qualitative level.

For perceptions of physiological cost, through ratings of RPE, two participant's level increased from the pre- to post-test evaluation. This observation has also been found for able-bodied users (Fig. 3), suggesting that the wearable system was fatiguing to wear. For one participant the level decreased, however this was from an extreme level, and the final level was still rated as having a large physiological effect.

For perceptions of discomfort through ratings of general comfort, visual discomfort and sensations of pain, all the participants, except participant 4, perceived a very large or extreme level of effect for at least one variable. These participants perceived very large to extreme levels of effect for Attachment, which is probably due to the weight and fit of the HMD. For able-bodied users, Attachment is often the highest scoring comfort dimension (Fig. 4). However, the average Attachment score for wheelchair users was almost twice the average for able-bodied users, suggesting a significant difference between the two groups.

Two of the wheelchair users (participants 1 and 3) perceived a considerable emotional effect, suggesting that they were self-conscious or embarrassed wearing the CONNECT system, which is a response similar to able-bodied users. For the other comfort dimensions (harm, perceived change, movement and anxiety), able-bodied users have scored on average slightly higher than the wheelchair users, particularly for perceived change and

Table 5 Perceptions of pain and discomfort rated by five wheelchair participants

	Level of effect					
	Low (WL1)	Moderate (WL2)	Large (WL3)	Very large (WL4)	Extreme (WL5)	Total
Head	–	(6)	**1**(8)	(1)	–	**1**(15)
Face	–	(1)	(1)	–	–	(2)
Neck	–	(3)	(1)	(1)	–	(5)
Collar	–	(1)	–	–	–	(1)
Left shoulder	–	(1)	(1)	(2)	–	(4)
Right shoulder	–	(1)	(1)	(2)	–	(4)
Left upper arm	–	(2)	–	–	–	(2)
Right upper arm	–	–	–	–	–	–
Left lower arm	–	–	–	–	–	–
Right lower arm	–	–	–	–	–	–
Left hand	–	(1)	(2)	–	–	(3)
Right hand	–	(1)	–	–	–	(1)
Chest	–	–	–	–	–	–
Upper back	–	(3)	–	–	–	(3)
Mid Torso	–		–	–	–	–
Mid back	–	(2)	–	–	(1)	(3)
Waist	–	1	–	–	–	1
Lower back	–	(1)	–	–	–	(1)
Total	–	**1**(23)	**1**(14)	(6)	(1)	**2**(44)

Value in bold represents the number of participants reporting any sensation of pain value in brackets is able bodied data from Knight et al. [10], $n = 45$

anxiety. This suggests that wheelchair users feel less different due to wearing the CONNECT wearable system, and are less worried about the system.

For vision effects, visual discomfort, dryness in eyes, irritation in eyes, difficulty focusing and visual fatigue all scored very highly, indicating that the HMD system was considerably stressful on the visual system (Fig. 5). This was particularly so for participant 3 as well as for participants 1 and 5, who also felt generally tired after wearing the system. Although the average ratings for these effects were roughly double the average values generated by able-bodied users, they follow a similar pattern of responses reported by able-bodied users, in terms of being the most common symptoms experienced.

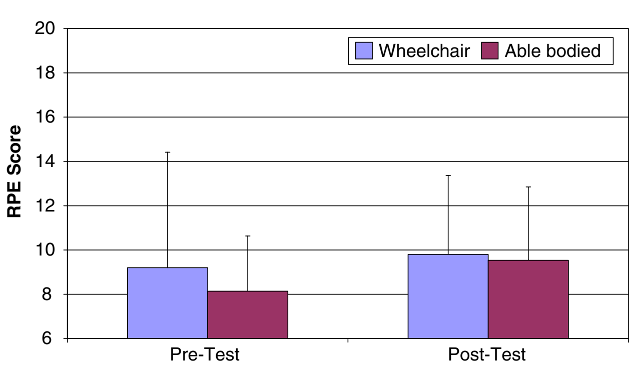


Fig. 3 Pre- and post-test RPE scores for disabled and able-bodied users

For musculoskeletal pain, only two participants rated any sensation, which were located on the head and around the waist, for participants 1 and 3, respectively (Table 5). For able-bodied users, head discomfort is common as is probably due to the weight of the HMD. However, able-bodied users also often experience discomfort around the shoulders, arms and back, which may be due to supporting the weight of the laptop unit in a backpack. The wheelchair users were not required to wear a backpack, which is why they did not experience any discomfort in these other areas.

Across the participants, participant 3 appeared to be particularly stressed wearing the CONNECT system, with increased RPE and extreme levels of effect for comfort and visual discomfort; whereas, participant 4 rated little effect. This suggests that there is considerable inter-individual difference in the wearabilty of the CONNECT system (Table 4). Indeed, Knight et al. [13] have shown that the level of effect for post-test relative perceived exertion (RPE) and the comfort dimension Harm are related body weight and duration of the trials, which also affects the level of visual fatigue. In addition, there also appear to be sex differences, specifically for the rating of RPE for able body users. Unfortunately, the limited sample size for wheelchair confound users means that similar relationships cannot be established or investigated, at this stage.

4.2 Assessment of pedagogical effectiveness

The qualitative evaluation methodology, which was developed to assess the impact of the proposed approach in the learning of the participants, focuses on locating evidence that proves the effectiveness of integrating informal learning methods to the curricular activities. All special needs participants had to follow the same routine as the able-bodied group that participated in other similar user trials. They had to study the physical concept (i.e. the concept of friction) and be evaluated with a knowledge questionnaire before the visit to a museum. They had then to follow-up with a visit and interact with an exhibit explaining the physics concept (i.e. an Airtrack exhibit, at Evgenidis Foundation in Athens), while being observed and evaluated on their understanding and motivation to complete an experimental scenario with the exhibit. Finally, they had to be re-examined on their knowledge post-visit, back in the classroom environment, and assess

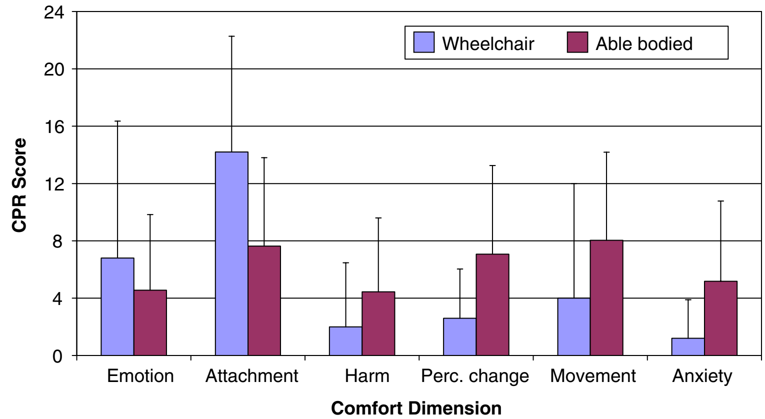


Fig. 4 Comfort scores for disabled and able-bodied users

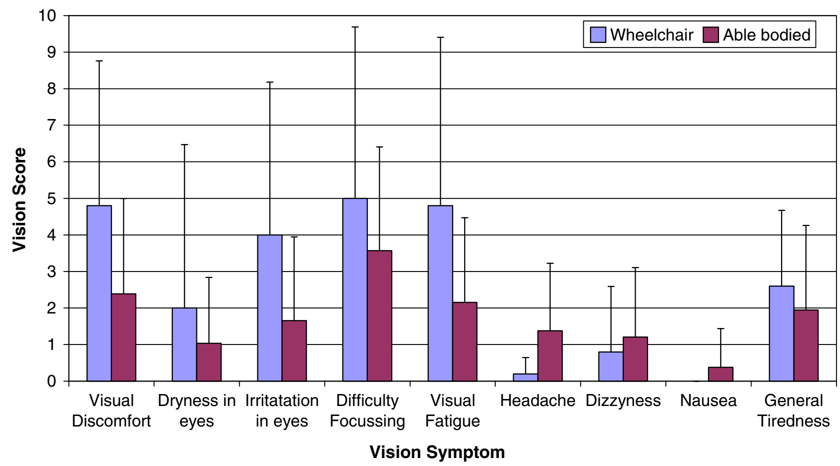


Fig. 5 Vision effect scores for disabled and able-bodied users

any improvement in their learning. Here we report some qualitative observations.

The disable students had almost the same results as the able-bodied students in the tests. The misconceptions as they came out from the wrong answers on the pre-visit tests were almost the same for both categories of the students. Moreover, the same was observed for the improvements on the post-visit tests. It is worth mentioned that one of the students couldn't understand the theme on the augmenting reality video (i.e. explaining the concept of friction by showing a hovercraft), the specialists consider it as a result of their limited spurs in their environment. This leads to the conclusion that any AR experimental scenario should be much more carefully designed and take under consideration the background of students (e.g. living conditions, previous experiences, etc.). Empirical measurements taken from the psychologist and a researcher at the end of the trials confirmed an increase of the self-esteem of the participants that had to do with the feelings of social acceptance and success (Fig. 6). After the experiments there was a change in the dynamics of team; the ties between the weakest students (participants 4 and 5) and the rest of the team became stronger.

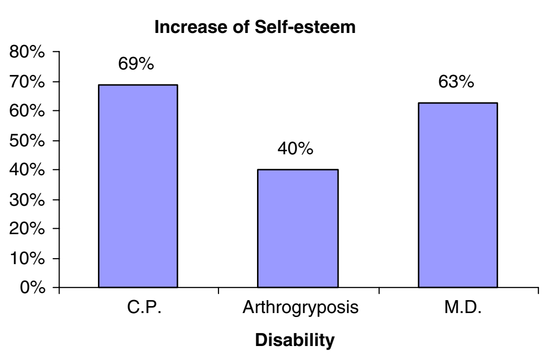


Fig. 6 Changes in self-esteem (empirical measurement during a post-visit evaluation)

5 Concluding remarks

The CONNECT project has an impact upon the fields of instructional technology, educational systems design, science education. Its aim is to integrate the use of physical objects that are computationally-augmented and to support and encourage face-to-face interaction between students and virtual objects. Although, in this paper, the sample size of the physical disabled users was limited for performing statistical analysis, the results are important, bearing in mind the new potential paths for further work that can be considered. Both the wearability and pedagogical evaluation trials have shown interestingly comparable results with able-bodied users, indicating the importance of inclusion in novel technology-enhanced learning approaches for science education. Future work should examine the importance of considering special needs education in the design of such technologies by looking at: (1) alternative ways that influence the education beyond the mere use of computers; (2) the contribution in the improvement of the students' life; (3) how technology can overcome the boundaries of disability; (4) how to alleviate isolation; (5) how to increase self-esteem; and (6) support integration.

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