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Using assistive robots to promote inclusive education

P. Encarnação¹¹, T. Leite², C. Nunes², M. Nunes da Ponte³, K. Adams^{4,5}, A. Cook⁴, A. Caiado³, J. Pereira³, G. Piedade¹, and M. Ribeiro¹

¹UCP - Católica Lisbon School of Business & Economics, Portugal

²School of Education, Lisbon Polytechnic Institute, Portugal

³Calouste Gulbenkian Rehabilitation Center for Cerebral Palsy, Lisbon, Portugal

⁴Faculty of Rehabilitation Medicine, University of Alberta, Edmonton, AB, Canada

⁵Glenrose Rehabilitation Hospital, Edmonton, AB, Canada

Abstract

Purpose This paper describes the development and test of physical and virtual integrated augmentative manipulation and communication assistive technologies (IAMCATs) that enable children with motor and speech impairments to manipulate educational items by controlling a robot with a gripper, while communicating through a speech generating device.

Method Nine children with disabilities, nine regular and nine special education teachers participated in the study. Teachers adapted academic activities so they could also be performed by the children with disabilities using the IAMCAT. An inductive content analysis of the teachers' interviews before and after the intervention was performed.

Results Teachers considered the IAMCAT to be a useful resource that can be integrated into the regular class dynamics respecting their curricular planning. It had a positive impact on children with disabilities and on the educational community. However, teachers pointed out the difficulties in managing the class, even with another adult present, due to the extra time required by children with disabilities to complete the activities.

¹ Corresponding author. Mail address: UCP - Católica Lisbon School of Business & Economics, Palma de Cima, 1649-023 Lisboa, Portugal. Tel: (351)214269781. Email: pme@ucp.pt

Conclusions The developed assistive technologies enable children with disabilities to participate in academic activities but full inclusion would require another adult in class and strategies to deal with the additional time required by children to complete the activities.

Keywords: augmentative manipulation, assistive robots, inclusive education

1. Introduction

Inclusive education systems in which children with and without disabilities participate and learn together in the same classes are the rule nowadays throughout the world. Research shows that children with disabilities in inclusive education settings are more likely to exhibit positive social and emotional behaviours, and have academic gains (please refer to [1] and the references therein). Inclusion also has positive effects on typically developing children. For example, they are more understanding of and develop positive attitudes toward children with disabilities, and by being able to model exemplary behaviours to their peers with disabilities, they are likely to show increased self esteem, confidence, autonomy, and leadership skills [1]. However, inclusive education carries the challenge of dealing with different learning needs. Educators need to employ effective teaching strategies, appropriate for all learners that can be accommodated and adapted to make the curricular content accessible for students with special education needs [2,3].

Drawing upon constructivism and social constructivism theories [4], teachers talk about and demonstrate new curricular content, but also give students the opportunity to experiment and make their own inferences, discoveries and conclusions. These hands-on activities may be inaccessible for children with neuromotor disabilities since they may not be able to manipulate the educational items and/or to verbalize their experience. Assistive technology may help to bridge the gap between the student's capabilities and the requirements of the activity [5,6].

Several studies addressed the use of augmentative and alternative communication (AAC) technology in educational contexts (e.g. [7,8,9,10]). It has been shown that AAC systems and appropriate strategies can contribute to the development of literacy by very young children with speech impairments [11,12,13]. However, there is a lack of studies on the acquisition by AAC users of other

curriculum content such as arithmetic skills [14,15]. Strategies for educational inclusion of AAC users are discussed in [16].

Industrial robots with an adapted interface have been used in schools by children with motor impairments to perform science, art and play activities [17,18,19,20,21]. In these studies teachers saw benefits from using the robot, and students, in general, liked to work with the robot. However issues with the integration of the robotic system into instruction, safety, cost, reliability, and the need for technical support were raised [22,23]. Additionally, Speech Generating Device (SGD) users had to put away their communication devices in order to use the robotic system making it harder to communicate while performing the robot-mediated activities.

Lego[®] Mindstorms[®] robots controlled through AAC devices have been used by students to manipulate educational items in math activities [24,25]. Studies have shown that the use of these robots is an effective way for students to demonstrate their knowledge of math concepts [26,27]. Moreover, students preferred to do the math activities by themselves, using the robot, rather than directing an adult to carry out the activity for them [26,25,28].

Simulated robots on a computer screen that can manipulate virtual objects in a virtual scene have the potential of overcoming some of the problems of physical robots. Safety is not an issue, they can be cheaper, reliable and easier to use. A software package including the virtual robot and a set of activities could be easily shared and deployed in a mainstream computer. Use of virtual robots has been compared to use of physical robots [29]. The study involved 20 typically developing children and nine children with neuromotor disabilities that used both a physical and a virtual version of a Lego[®] Mindstorms[®] robot to perform robot-mediated play-activities. Results showed no significant difference on the children's performance while using the virtual or the physical robots, thus opening the door for further investigation of the use of virtual robots as augmentative manipulation tools to enable participation in play and academic activities.

This article concerns the “UARPIE – Using Assistive Robots to Promote Inclusive Education” project aimed at developing and testing an Integrated Augmentative Manipulation and Communication Assistive Technology (IAMCAT) to enable students with neuromotor disabilities to

manipulate educational items while communicating about their experiences. With the developed system, children were able to use their preferred computer interface (e.g. trackball or eye tracking system) to access an AAC software that included programmable external commands to interact with robot control software. Through the AAC software they were thus able to communicate and control either a physical or a virtual robot to manipulate physical or virtual objects, respectively. Figures 1 and 2 illustrate the systems developed that are described in detail in Section 2.

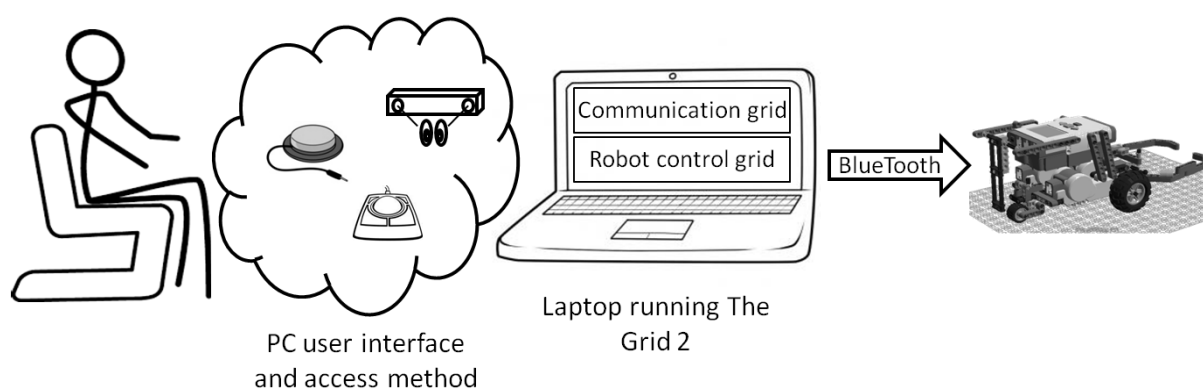


Figure 1 Physical IAMCAT

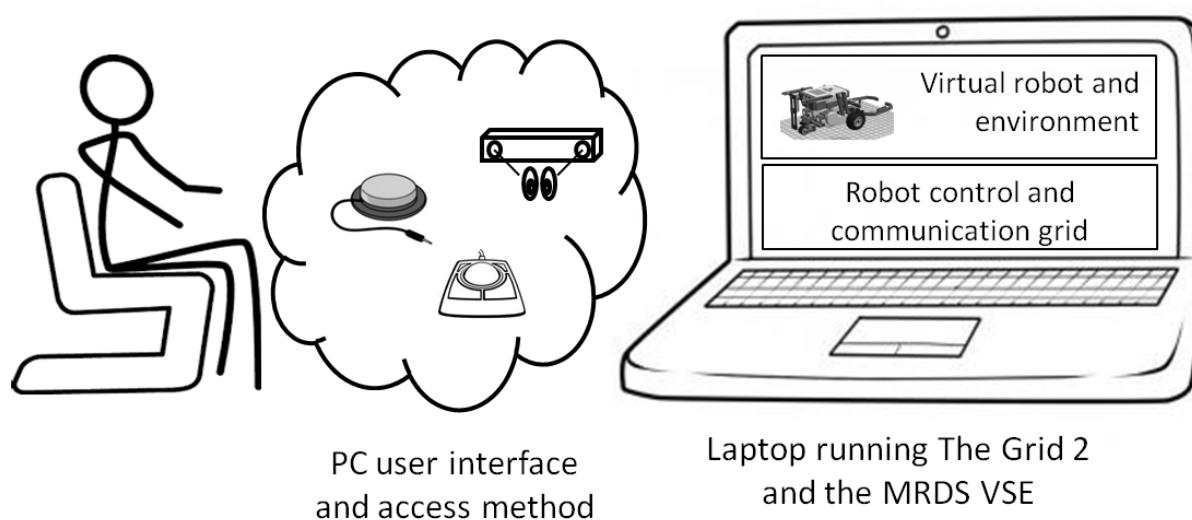


Figure 2 Virtual IAMCAT

Both the physical and the virtual versions of the IAMCAT were tested with children with disabilities integrated in regular schools to perform academic activities in the curricular areas of Language,

Mathematics, and Science & Social Studies, along with their typically developing peers, extending the works in [25,29]. The experimental objectives were:

1. Evaluate academic achievement when using the IAMCAT compared to performance before intervention;
2. Assess teachers' perceptions of the use of the IAMCAT and its impact on the student and in the classroom (e.g. student's engagement with activities, distractive and social inclusion factors);
3. Compare virtual and physical robotic systems in relation to 1 and 2.

Results from this descriptive case study research [30] are reported. Descriptive case study research, an approach for investigating phenomenon in depth in areas where prior research is limited [31], is particularly appropriate given the uniqueness of each student's abilities, and it recognizes the role that context plays in the phenomenon; frameworks used in assistive technology to evaluate outcomes always consider personal abilities and preferences, contextual factors, as well as task demands, and technology characteristics [32,33,34,35,36].

2. The IAMCAT

In this section the rationale behind the development and integration of the different IAMCAT components in figures 1 and 2 is described.

Children with communication limitations often utilize SGDs to communicate with others. These devices might be dedicated assistive technologies (e.g. the AccentTM series SGDs from PRC²) or they may be software running on mainstream hardware (e.g. The GridTM 2³). The latter option is more popular in Europe and is also becoming the choice of young North Americans with the advent of the iPad[®] [37]. Both options usually provide the possibility of controlling external devices through infrared or BlueTooth[®] ports. Since users invest a lot of time in training for the efficient use of their SGDs and these contain a large core vocabulary with which the users are already familiar, the IAMCAT development strategy was to add manipulation capabilities to each child's SGD. Since the UARPIE project took place in [Country] where the AAC software The GridTM 2 is widely used, a

² <https://www.prentrom.com/>

³ <http://sensorysoftware.com/>

mainstream computer running The Grid™ in a Microsoft® Windows operating system was the starting point for the development. This option also had the advantage of solving accessibility issues since The Grid™ 2 is compatible with virtually all computer access technologies. The IAMCAT is therefore accessible through any computer interface and any access method [5] which enabled the participants in this study to use the computer interfaces and access methods on which they were trained.

Robots to support manipulation for use by children with disabilities should be flexible enough to allow for a wide range of activities, robust, reliable and accurate, safe, accessible and easy to use and program, appealing to children, and with a relatively low cost [23]. Lego® Mindstorms® robots are among the commercially available robots that basically meet these specifications, despite some robustness, reliability and accuracy issues [23]. For the UARPIE project, a Lego® Mindstorms® NXT truck-like robot was built (see figure 3).

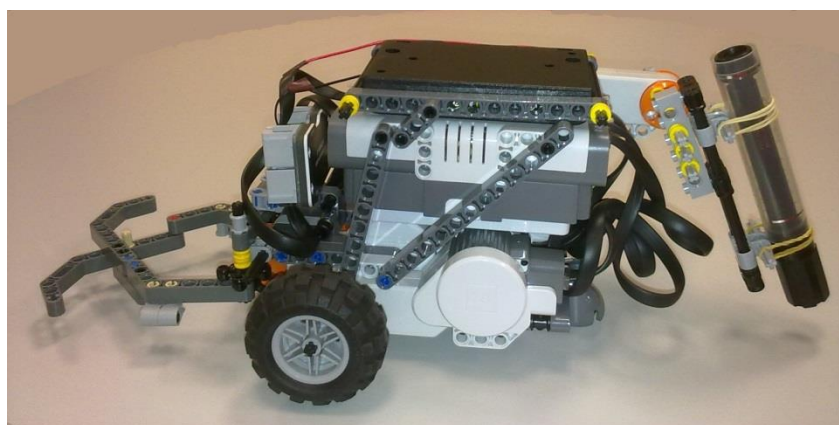


Figure 3 Physical Lego® Mindstorms® robot

Two independently controlled wheels and a free spherical wheel on the back allow for the robot to turn on itself and move forward and backward. A gripper actuated by another motor was added for manipulation of objects. With the designed gripper the robot is able to grasp and drag objects. Finally, a pen was attached to the robot such that the robot can trace its path on the travelling surface. Since the Lego® Mindstorms® NXT intelligent brick is only able to control up to three motors, it was necessary to use a NXTMMX-v2 motor multiplexer from Mindsensors⁴ to enable the control of the

⁴ <http://www.mindsensors.com>

motor for the robot pen. Instructions for assembling the robot are available at the UARPIE project website www.uarpie.anditec.pt.

A virtual version of the robot (figure 4) was designed using the Visual Simulation Environment (VSE) included in Microsoft® Robotics Developer Studio 4 (MS-RDS). VSE enables simulation and testing of robotic applications using a 3D physics-based simulation tool. In this study the VSE allowed for the comparison between physical and virtual versions of the IAMCAT through the implementation of robot-mediated academic activities in a virtual environment.

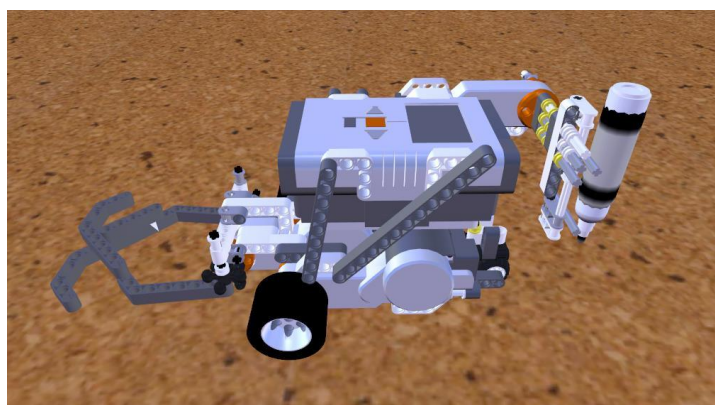


Figure 4 Virtual Lego® Mindstorms® robot

A software application to control the robot (physical or virtual) was also developed using the Microsoft® Robotics Developer Studio 4. All robot functions are available through the computer keyboard. Commands are sent to the robot via BlueTooth®. A list of commands is presented in table 1. A graphical user interface – the Command Manager - was created to manage the robot control application. Figure 5 shows the Command Manager window with numbers on the sides that will be used for reference to zones of the window in the following description.

Table 1 Robot control keyboard commands

Class of commands	Key	Command
Robot orientation	I	Sets the internal orientation variable to "Forward"
	L	Sets the internal orientation variable to "Right"
	K	Sets the internal orientation variable to "Backward"
	J	Sets the internal orientation variable to "Left"
Robot movement	T	Short step forward
	Y	Short rotation/step to the right
	G	Short step backwards
	R	Short rotation/step to the left
	H	Long step forward
	M	Long rotation/step to the right
	N	Long step backwards
	B	Long rotation/step to the left
Robot accessories	P	Enable/disable robot pen
	C	Open/close robot gripper
Virtual scene control	-	Previous scene
	+	Next scene
	.	Reset the actual scene
	0	Move the robot to the initial position
	1	Blocks sound
	2	Load blocks
	DEL	Clear drawing
General control	\	Enable robot control keys
	Z	Disable robot control keys
	U	Reset robot control

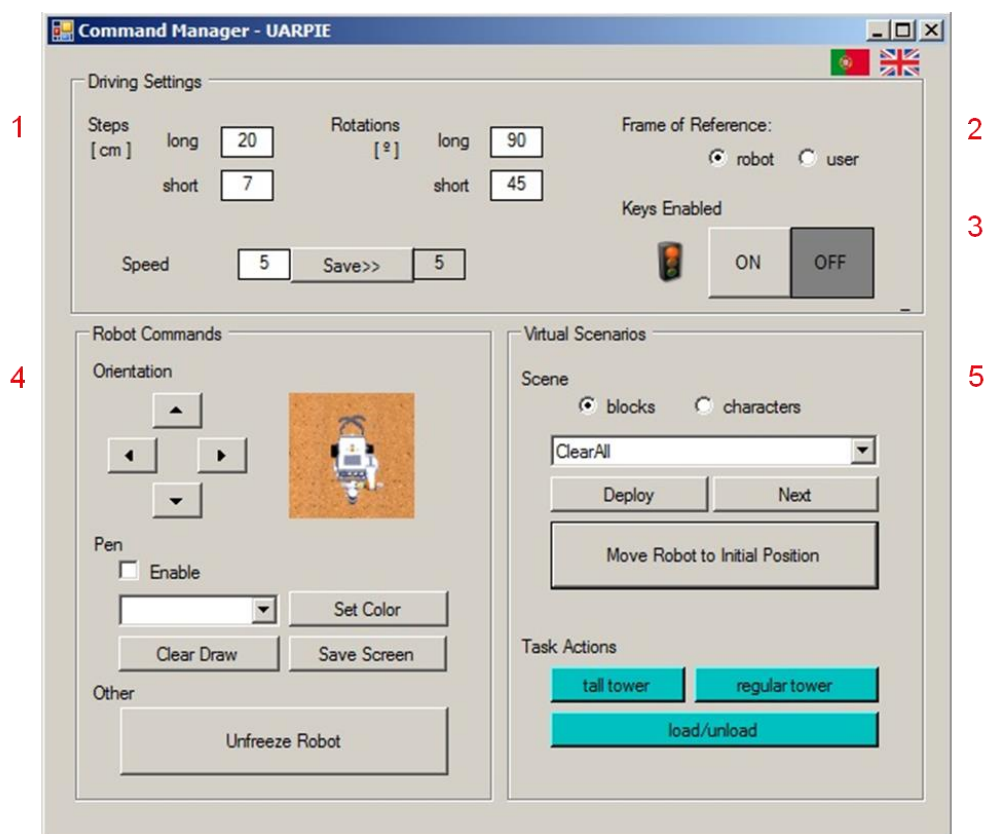


Figure 5 UARPIE robot Command Manager

The robot can be driven by moving it forward/backward and turning it left/right. Selecting any of these commands makes the robot move for a predetermined linear or angular displacement in the corresponding direction. Multiple movements in the same direction require the user to select the same command multiple times. To allow for fine positioning of the robot and also to expedite its control in activities where there is a need to move the robot for relatively long distances, predefined short and long linear and angular displacements can be set in Zone 1 of the Command Manager. It is also possible to set the robot speed from 1 (slower) to 10 (faster) in this zone of the Command Manager.

Robots can be controlled in their own frame of reference or in the user frame of reference. When controlling the robot in the robot frame of reference, the user needs to take into account that the commands forward, backward, left or right are relative to the actual orientation of the robot. For example, if the robot is facing the user, the forward command will make the robot move closer to the user, and the left command will make the robot turn to the right of the user. This control mode can be challenging, especially for younger children. In that case, one can opt for controlling the robot in the user frame of reference where all displacements are done relative to the user orientation. For example,

the forward command will always make the robot move away from the user, even if the robot was facing the user, i.e. the robot will turn 180 degrees on itself before moving forward; the left command will always make the robot move to the left of the user, even if it is necessary to rotate prior to moving forward. The type of control frame of reference can be selected in Zone 2 of the Command Manager.

In Zone 3 of the Command Manager it is possible to disable the robot control keys to prevent user key presses from making the robot move, which can be useful, for example, while explaining an activity.

A subset of internal robot commands is grouped in the Command Manager Zone 4. Here it is possible to synchronize the actual robot orientation and the orientation assumed internally by the program.

That is needed when someone is controlling the robot in the user frame of reference since the robot does not relay its orientation to the computer. If, for example, the robot is rotated by hand, the computer does not perceive that rotation and subsequent commands are executed taking into consideration the previous robot orientation. It is thus necessary to use one of the orientation commands in Zone 4 in order to align the robot represented in the Command Manager with the actual robot. The commands related to the robot pen are also in Zone 4. It is possible to activate the pen and, for the virtual robot, to select its colour from the list of available colours. Options “Clear Draw” and “Save screen” respectively erase the virtual drawing made by the virtual robot pen and save the drawing in a file. Finally, still in Zone 4, there is an “Unfreeze Robot” button that enables recovery from situations where the robot is not reacting to the user commands.

Command Manager Zone 5 is only for the virtual robot. Here it is possible to choose the virtual sceneries and the activities. There are two groups of activities, one involving knocking over stacks of blocks, another involving activities with characters (e.g. princess, farmer) – options “blocks” and “characters”. In each group there is a list of activities available. Activities are selected by choosing one in the drop down menu and pressing “Deploy”. The option “Next” allows for moving directly to the next activity in the list. The button “Move Robot to Initial Position” places the robot in its initial position. This is useful for an adult to quickly reposition the robot when the user moved the robot to a position from which it is difficult to recover or simply to speed up the task execution when it is necessary to take the robot back to the original position. For the activities that involve stacks of

blocks, the button “tall tower” resets the virtual environment and creates a high tower (6 blocks) in front of the robot, the button “regular tower” resets the virtual environment and creates a smaller tower (4 blocks) in front of the robot, and the button “load/unload” allows for loading and unloading blocks to be transported by the virtual robot. More details on the implemented activities will be given in sections 4.1 and 4.2. Instructions for installing and use of the UARPIE Command Manager as well as the virtual version of the IAMCAT are available in [38].

To integrate robot control with the AAC software, The Grid™ 2, cells in communication boards should be created emulating the key presses in table 1. To facilitate this, two The Grid™ example users were created, one for the physical version of the IAMCAT, another for the virtual version. For installing these example users, available at http://uarpie.anditec.pt/images/docs/grid_boards.zip, please refer to the Grid™ Manual. After activating the desired user, depending on the robot that is being used, four different grids are presented, two for controlling the robot in the user frame of reference, and two for controlling the robot in the robot frame of reference. The difference between the two grids for each frame of reference is the number of commands available. One contains 6 options, including only one distance for the displacements, the other contains 10 options, including short and long displacements. These grids can be used as starting points to configure a grid more adapted to a particular user’s needs. All example grids contain a jump cell to a very simple communication grid. This cell can be edited to jump to a communication grid familiar to the user. Figure 6 shows example robot control and communication grids used by one of the participants when performing a math activity.

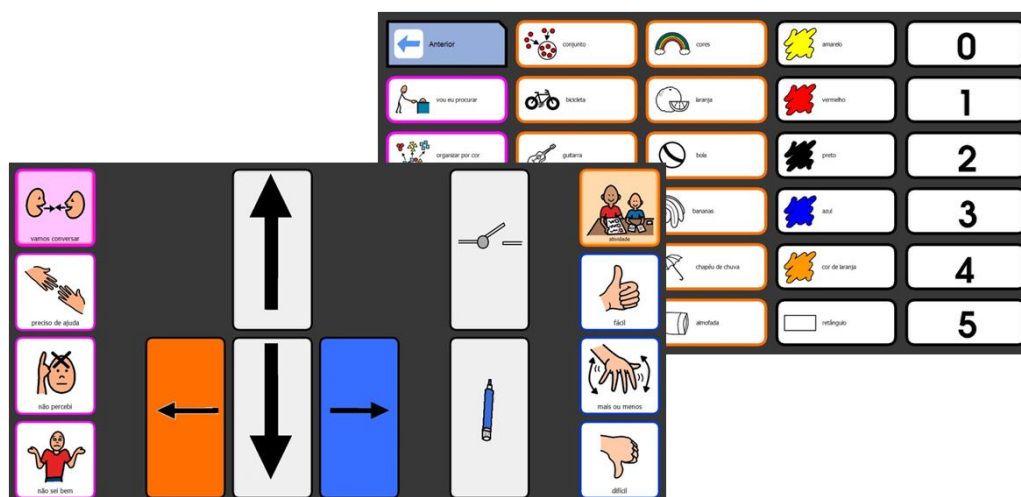


Figure 6 Robot control and communication grid example

The two versions of the IAMCAT were pilot tested with two children with disabilities: a 7 year old with bilateral spastic cerebral palsy trialled the virtual system, and a 9 year old with dystonic dyskinetic cerebral palsy trialled the physical system. Both participants had the opportunity to become familiar with the systems in one training session that took place approximately two weeks before the pilot test. They accessed the computer through a group-row-column scanning indirect method [5] controlled by a single switch activated by head movements. Children were invited to perform robot-mediated math activities, e.g. choosing the solid with only curved surfaces from a pyramid, a parallelepiped, and a sphere, “buying” objects with a limited budget, or choosing the correct result for an addition problem. The participants’ mothers reported that the children had already acquired the academic knowledge required by the activities, and thus possible mistakes should be attributed to difficulties using the IAMCAT. The pilot test was instrumental for identifying technical malfunctions in the original prototypes and for pointing out what should be modified in the virtual scene design and in The Grid™ communication boards to improve the system usability.

3. Participants

3.1. Child participants' selection

The study took place in two academic years: 2013/2014 and 2014/2015. Convenience samples were selected from the clients of the [Institution] ([Acronym]) in [City], one of the UARPIE project participating institutions. Inclusion criteria were: a) having neuromotor disabilities; b) being able to access a computer regardless of the interface used; and c) being included in a school in the greater [City] area. A total of nine children with neuromotor disabilities and chronological ages between three and six years old were recruited. Five of them participated in the 2013/2014 academic year, and the remaining four, along with one of the children from the 2013/2104 sample, participated in the 2014/2015 academic year.

Information packages were sent to parents, teachers, and school directors. Informed consent was obtained from the participants' parents and formal authorizations to conduct the tests in the participants' schools were obtained from the corresponding school directors.

3.2. Child participants' assessment

To characterize the child participants several instruments were used. Cognitive age was assessed through the Pictorial Test of Intelligence [39]. Motor skills were classified using the GMFCS - Gross Motor Function Classification System [40] and the MACS - Manual Ability Classification System [41]. Expressive and receptive language was assessed through the Reynell developmental language scales [42]. Communicative competence using AAC was evaluated using the protocol in [43]. Child participants were asked to re-tell a [Language] translation of the story "David the dinosaur" [44] to a familiar conversation partner. A subset of the InterAACtTM Framework Dynamic AAC Goal Grid items [45] which were applicable to the study was translated to [Language] for evaluating the level of AAC skills.

Semi-structured interviews of the participants' parents were conducted to collect further information on the strategies used by the participants to communicate and how they carried out activities that require the manipulation of objects. Additionally, parents' perceptions of their children's performance

in school were registered. Participants' previous experience on the use of robots or other remotely operated devices was also assessed through this interview. The level of detail obtained in the parents' answers was not uniform because the interviews were informally conducted and answers were registered by the researcher only after completing the conversation with the parents. This method was chosen to reduce the demands on parents when they were also taking their children to the rehabilitation interventions at the [Acronym].

Table 2 Characterization of the child participants in the 2013/2014 part of the study

	P1	P2	P3	P4	P5
Data					
Age	6y2mo	6y0mo	6y3mo	5y7mo	5y2mo
Gender	M	M	F	F	F
Diagnosis	Cerebral palsy (bilateral spastic, tetraparesis)	Cerebral palsy (bilateral spastic, tetraparesis)	Traumatic Brain Injury (hemiplegia and aphasia)	Cerebral palsy (bilateral spastic, tetraparesis)	Global Developmental Delay
School grade	1 st grade	1 st grade	Pre-school	Pre-school	Pre-school
PC access method (device)	Direct access through eye tracking (Tobii PCEye Go)	Direct access through a trackball (Kid-TRAC)	Direct access through a trackball (Kid-TRAC)	Direct access through a trackball (Kid-TRAC)	Direct access through a trackball (Kid-TRAC)
Assessment					
GMFCS	IV	III	II	IV	I
MACS	IV	II	III	IV	I
PTI - 2 Reynell	Low average	High average	Extremely low	Borderline	Low average
Expressive	Not evaluated	High average	Extremely low	Extremely low	Extremely low
Receptive	Low average	High average	Extremely low	Low average	Low average
InterAACt™					
Goal Grid					
Linguistic	Independent	Independent	Context dependent	Context dependent	Context dependent
Social	Context dependent	Independent	Context dependent	Context dependent	Context dependent
Operational	Context dependent	N.A. ^a	Context dependent	Context dependent	Context dependent
Strategic	Context dependent	Context dependent	Context dependent	Context dependent	Context dependent

^a Not applicable since P2 did not use any AAC device

Table 3: Characterization of the child participants in the 2014/2015 part of the study

	P4	P6	P7	P8	P9
Data					

Using assistive robots to promote inclusive education

Age	6y6mo	5y3mo	4y2mo	3y9mo	3y7mo
Gender	F	M	M	M	M
Diagnosis	Cerebral palsy (bilateral spastic, tetraparesis)	Cerebral palsy (dyskinetic)	Cerebral palsy (bilateral, spastic, with extrapyramidal component)	Cerebral palsy (bilateral, spastic, tetraparesis with dyskinetic component)	Cerebral palsy (dyskinetic)
School grade	1 st grade	Pre-school	Pre-school	Pre-school	Pre-school
PC access method (device)	Direct access through a trackball (Kid-TRAC)	Direct access through a trackball (Kid-TRAC)	Direct access through a trackball (Kid-TRAC)	Direct access through eye tracking (Tobii P15)	Direct access through eye tracking (Tobii PCEye Go) ^a
Assessment					
GMFCS	V	II	IV	IV	III
MACS	IV	III	IV	IV	III
PTI - 2	Borderline	Average	Average	Average	Extremely high
Reynell					
Expressive	Extremely low	Not Evaluated	Not Evaluated	Extremely low	High average
Receptive	Low average	Average	Low average	Low average	High average
InterAACt TM					
Goal Grid					
Linguistic	Context dependent	Context dependent	Context dependent	Context dependent	Context dependent
Social	Context dependent	Context dependent	Context dependent	Context dependent	Context dependent
Operational	Context dependent	Context dependent	Context dependent	Context dependent	Context dependent
Strategic	Context dependent	Context dependent	Context dependent	Context dependent	Context dependent

^a When the robot training started, P9 used an indirect row-column scanning access method through a switch operated by his left hand.

Table 3 Characterization of the child participants in the 2014/2015 part of the study

	P4	P6	P7	P8	P9
Data					
Age	6y6mo	5y3mo	4y2mo	3y9mo	3y7mo
Gender	F	M	M	M	M
Diagnosis	Cerebral palsy (bilateral spastic, tetraparesis)	Cerebral palsy (dyskinetic)	Cerebral palsy (bilateral, spastic, with extrapyramidal component)	Cerebral palsy (bilateral, spastic, tetraparesis with dyskinetic component)	Cerebral palsy (dyskinetic)
School grade	1 st grade	Pre-school	Pre-school	Pre-school	Pre-school
PC access method (device)	Direct access through a trackball (Kid-TRAC)	Direct access through a trackball (Kid-TRAC)	Direct access through a trackball (Kid-TRAC)	Direct access through eye tracking (Tobii P15)	Direct access through eye tracking (Tobii PCEye Go) ^a
Assessment					
GMFCS	V	II	IV	IV	III
MACS	IV	III	IV	IV	III
PTI - 2	Borderline	Average	Average	Average	Extremely high
Reynell					
Expressive	Extremely low	Not Evaluated	Not Evaluated	Extremely low	High average
Receptive	Low average	Average	Low average	Low average	High average
InterAACt™					
Goal Grid					
Linguistic	Context dependent	Context dependent	Context dependent	Context dependent	Context dependent
Social	Context dependent	Context dependent	Context dependent	Context dependent	Context dependent
Operational	Context dependent	Context dependent	Context dependent	Context dependent	Context dependent
Strategic	Context dependent	Context dependent	Context dependent	Context dependent	Context dependent

^a When the robot training started, P9 used an indirect row-column scanning access method through a switch operated by his left hand.

3.3. Child participants' characterization

Results of the child participants' assessment are summarized in tables 2 (for the 2013/2014 child participants) and 3 (for the 2014/2015 child participants). The nine children had different degrees of functional limitations, seven of them as a consequence of cerebral palsy, one as a consequence of a traumatic brain injury, and one as a consequence of a global development delay. Gross motor function for the nine children varied from levels I to V. Under the Manual Ability Classification

System participants were classified from levels I (being able to manipulate objects) to IV (being only able to handle a limited selection of easily managed objects in adapted situations).

Cognitive evaluation by the Pictorial Test of Intelligence revealed that general intelligence was extremely low for one participant, borderline for another, average for six participants (low average for two, average for three, and high average for one), and extremely high for the other participant. Therefore, though most of the participants had no significant concurrent cognitive impairments, two of them had cognitive limitations.

In regards to communication, receptive language level as evaluated by the corresponding Reynell developmental language scale, was below average for one participant and average for the remaining participants (low average for five, average for one, and high average for two). Reynell developmental expressive language levels were high average for two participants and below average for all the others. In the cases where the expressive language was not evaluated, it was due to the participants' limitations and thus these also correspond to participants with many expressive language limitations. With the exception of one participant that did not require any AAC device for communication, evaluation of the participants' communicative competency using their AAC showed that all participants were at a context dependent level [42].

The nine children were able to use the computer through a direct access method [5], six of them using a trackball and the remaining three a Tobii Dynavox⁵ PCEye Go eye tracking system. The two youngest participants had just started to use their eye tracking systems and thus they were still not competent users.

A summary of the information collected through the interviews to the participants' parents is presented in tables 4 (for the 2013/2014 child participants) and 5 (for the 2014/2015 child participants).

⁵ <http://www.tobiidynavox.com>

Table 4 Communication, manipulation and school participation from the parents' perspective (2013/2014 participants)

Parents interviews summaries		
P1	Communication	P1 uses his communication book through eye gaze. Parents ask for clarification when they don't understand and act as mediators in P1's communication with others.
	Manipulation	Sometimes P1 tries clay modeling and painting, but he needs a lot of help.
	School participation	P1 participates actively in all school activities. His academic knowledge is appropriate for his age and grade.
	Robots experience	None. He enjoyed remote control cars very much when he was younger.
P2	Communication	P2 speaks a lot, despite his disabilities. His mother says that everyone understands him.
	Manipulation	P2 has difficulties with small objects, but he doesn't need many adaptations. His mother only adapts his pencils. Painting is the only activity that he's not able to do by himself.
	School participation	P2 participates actively in all school activities. His academic knowledge is higher when compared to his classmates.
	Robots experience	None. He has only experience with remote control cars and with the TV remote.
P3	Communication	P3 looks and points to what she wants. She is a very expressive little girl, who laughs a lot. Her mother encourages her to speak, asking her to tell verbally what she wants.
	Manipulation	P3 plays with toys, she paints, she strings beads, and she plays with magnetic letters. She only needs adaptations to hold pencils.
	School participation	P3's teacher doesn't do anything with her. P3 only does things that don't need communication or manipulation. Only her special education teacher tries to do academic activities with P3. P3's academic knowledge is very poor for her age, but she has already progressed a lot.
	Robots experience	None. She knows how to use the TV remote and she always wants to push the elevator buttons.
P4	Communication	P4 uses her body and facial expressions a lot to communicate. She looks and points to what she wants. She only uses her communication book in the communication sessions, with her teacher.
	Manipulation	P4 does clay modeling, painting and puzzles. Her mother says that she doesn't need any adaptation.
	School participation	P4 is well integrated at school. She participates in the activities, although with some kind of adaptations. She is very shy with her peers and doesn't play with them. Her academic knowledge is very poor for her age.
	Robots experience	None. She had a remote control car when she was younger. She uses the TV remote.
P5	Communication	P5 is a very expressive little girl. She looks and points to what she wants. Her mother understands everything she says, but others don't. She only uses her communication book in the communication sessions, with her teacher.
	Manipulation	Every day, P5 plays with her father; she paints, and does puzzles. She doesn't need any adaptation. Her mother says that the only thing she needs is a lot of attention.
	School participation	P5 doesn't participate like the other children. She performs almost all activities, but separated from her classmates. In the majority of the situations, P5 is alone, she doesn't play with her peers. Her academic knowledge is poor for her age.
	Robots experience	None.

Table 5 Communication, manipulation and school participation from the parents' perspective (2014/2015 participants)

Parents interviews summaries		
P4	Communication	P4's mother said that P4's communication has not changed in the past year. She makes herself understood.
	Manipulation	[See Table 4]
	School participation	To P4's mother, she has progressed during the past year in school. This year she went for the first grade. Her mother said that at first it was difficult, but now she's doing better, despite their difficulties.
	Robots experience	[P4 participated also in the 2013/2014 experimental part of the study]
P6	Communication	P6 speaks with severe difficulties, but his mother insists on him using speech. He uses a lot of gestures to complement his speech and, to his mother that is very important. P6 has a communication book, but he doesn't use it.
	Manipulation	P6 needs some adaptations, namely in pens and small objects. He rips paper and peels fruit. His mother says that before they did many activities involving manipulation, but now they don't.
	School participation	P6 attends a new school and his mother was still not aware of how he participated in the activities. However, his academic knowledge is appropriate for his age.
	Robots experience	None. He had some remote control cars but not anymore since he broke them due to his manipulative limitations.
P7	Communication	P7 looks and points to what he wants. He is starting to make some sounds that sound like words, but his speech is not functional. P7 uses a communication book, but his father says that is difficult to use it all the time.
	Manipulation	P7 has severe difficulties in object manipulation. However, he manages to do puzzles (with big pieces) and to play with big objects. His father says that P7 doesn't need many adaptations or adapted toys or objects since usually they can find mainstream products that P7 is able to use (e.g., they always buy very thick pencils that P7 is able to grasp).
	School participation	P7 is well integrated at school and participates in all activities, without adaptations. P7's physical therapist is present at some of the classes and works with P7 at the same time he is attending the class. His academic knowledge appears to be appropriate for his age.
	Robots experience	None. Tried remote control cars but even with a joystick it was difficult for him. He has a small drone that he loves but it is very difficult for him to control it.
P8	Communication	P8 is a very expressive boy. He points and looks for what he wants. P8 uses his communication book every time. His parents insist for him to speak, namely the vowels sounds.
	Manipulation	P8 does a lot of manipulation activities. He draws, plays with puzzles, cars, modeling dough, sponges and many other objects with different textures. Her mother adapts some materials (e.g., pens and cards).
	School participation	P8 is well integrated at school and participates in all activities, requiring some adaptations provided by his mother or by his teacher (e.g., bigger sheets of paper or thick pencils). To his mother, P8's academic knowledge is appropriate for his age.
	Robots experience	None. He has some experience with remote cars but he can't control them, though he understands all the commands.
P9	Communication	P9's speech capability is evolving every day. Sometimes, he uses his communication book and gestures to complement his speech – that is not yet functional.
	Manipulation	P9 has severe difficulties in manipulation. At home, his mother provides him several activities like fitting pieces games, puzzles, modeling clay, painting, balls. Despite the difficulties, he only needs some adaptations on pencils and small objects.
	School participation	At school, P9 is well integrated and participates in all activities, without adaptations. He is a very bright boy and he is more advanced than his peers. His academic knowledge is far ahead of his classmates.
	Robots experience	None. He has a remote control car but he does not like it.

The above characterizations show that the participants in this study constituted a rather heterogeneous group. Therefore, comparisons between the results for different participants should always take into account the different characteristics of each participant. Generalizations from the nine case studies described cannot be made without reservation. The approach followed in this paper was to describe in

detail the nine case studies, providing all the information to the reader such that potential confounding factors can be identified and discussed.

3.4. Teacher participants

Nine regular teachers and nine special education teachers participated in the study. Data regarding their ages, teaching experiences and academic backgrounds are compiled in table 6.

Teacher’s pre-intervention interviews (see Section 4.2) included questions about the child participants. The results of that part of the interviews are presented in Section 5.2, and they provide the teacher’s perspective on the characteristics of the children that participated in this study.

To facilitate the exposition, hereafter the term participants will refer to the children that participated in the study.

Table 6 Characterization of the participating teachers

		Regular teachers (9 in total)	Special education teachers (9 in total)
Teaching experience (years)	0-9	2	1
	10-19	3	4
	20-29	3	2
	30-39	1	2
Academic background	Graduate / M.Sc. in Early Childhood Education	7	5
	Graduate in Primary Education	2	3
	Other degree	0	1
	Post-graduate in Special Education	2	9

4. Methods

Participants used either the physical or the virtual version of the IAMCAT as dictated by chance, trying to ensure an even distribution of the participants between the two versions.

The reference frame in which each participant controlled the robot was chosen initially according to the research team’s perception of the participants’ abilities. Then, if a participant started to make mistakes that could be connected to a misunderstanding of the frame of reference in which the robot

was being controlled, the frame of reference was changed. The number of robot controls that was made available to each participant also depended on the research team's evaluation of the participants' abilities. Initially participants had the possibility of using long and short steps for each robot displacement. If observation revealed that they didn't use both options appropriately, a simplified version of the robot controls, with only one travelling distance, was used.

4.1. Training sessions

Before using the IAMCAT to perform academic activities in class, children need to be trained on its use [46] so they are able to drive the robot to any workspace location, use the robot to pick and place objects, trace lines using the robot pen, and communicate using The Grid™ while controlling the robot. The robot training protocol in [47] was followed in this study. The protocol includes familiarization tasks that require the user to drive the robot into stacks of blocks placed in different positions with respect to the robot (to train basic robot driving), drive through slalom courses with different numbers of obstacles, pick and place objects around the work area, and use The Grid™ for communication. Tasks in the protocol are ordered by their level of difficulty. In general, a new task was proposed to the participant when (s)he mastered the previous one.

Training sessions took place in the [Acronym] except for the last one that took place in the participants' school in order for teachers and participants' peers to get acquainted with the IAMCAT. Regular session length was 45 minutes. The number of sessions was variable for each participant. The decision of ending the training with each child was taken by the research team supported by their qualitative evaluation of the participant's performance. When the team agreed that the child was not progressing anymore and that new training sessions would probably not help, the training was terminated. Sessions were videotaped for subsequent analysis.

The eleven robot skills in table 7 were observed and graded according to the level of prompting required by the child. The turn left/right skill was observed for children who controlled the robot in the robot frame of reference, while the move left/right skill applied for the children who controlled the robot in their own frame of reference. The prompting scale in table 8, borrowed from [45], was used. Grading was done by the research assistant who conducted the training sessions. The worst, the best

and the average performance (meaning the general impression that the research assistant retained from the session and after watching the session video) was recorded for all the applicable robot skills.

Table 7 Robot skills assessed during the training sessions

Move forward	Sequencing equal commands
Move backward	Sequencing different commands
Turn left/right or Move left/right	Drive the robot to the required location
Use long /short steps	Avoid obstacles
Pen up/down	Pick and place objects
Open/close gripper	

Table 8 Prompting scale to grade the robot skills

Score		Example for a knocking over blocks task
GM	Goal met	Child performs the activity after being told that he/she should knock over the stack of blocks
IC	Indirect cue	“Have you noticed that you may control the robot to knock over the stack of blocks?”
DVC	Direct verbal cue	“You need to drive the robot towards the stack of blocks”
DPC	Direct pointer cue	“You need to select this robot control cell”
PA	Physical assistance	Guiding participant’s hand in order to make the necessary selection

After the completion of the training protocol tasks, children were asked to perform the modified “Green Dot Test” [48] to assess their operational competence using the access method on the SGD (i.e. accuracy and time to select target items on the SGD). In this test, a green dot appears in a random position of the communication board and children are asked to select the corresponding cell. The total time t_{SGD} to complete the test, the number of selected cells s_{SGD} , and the number of green dot targets n_{SGD} is recorded. In this study, the SGD accuracy measure was taken to be

$$Acc_{SGD} = \frac{s_{SGD} - n_{SGD}}{n_{SGD}} \times 100\%$$

Thus, for example $Acc_{SGD} = 38\%$ means that the participant selected 38% more cells than needed. A perfect accuracy score would be 0%. The SGD time efficiency measure T_{SGD} was the average time to select the cells

$$T_{SGD} = \frac{t_{SGD}}{n_{SGD}} [s]$$

A robot operational accuracy test was also applied to the participants after the training protocol tasks. Placing the robot at the initial position, a target robot position was given to the child. The time t_{Robot} to reach the target position and the distance d_{Robot} travelled by the robot were recorded. These were compared with the minimum time t_{min} and with the minimum distance d_{min} for which it would be possible to reach the target through

$$\frac{t_{Robot} - t_{min}}{t_{min}} \times 100\%$$

and

$$\frac{d_{Robot} - d_{min}}{d_{min}} \times 100\%$$

These formulas give the percentage by which the time and the distance exceeded the minimum possible values. Taking the average of these comparative values for the n_{Robot} targets selected by the child provides measures of the time and distance efficiencies (T_{Robot} and D_{Robot} , respectively) when controlling the robot.

4.2. Academic activities design

A portfolio of activities in the curricular areas of Language, Mathematics, Science and Social Studies was developed to introduce the participants' teachers to the IAMCAT and show them what could be accomplished with the system. The activities in the portfolio have as background the story "The gigantic turnip" [49]. For each curricular area three activities with different degrees of difficulty were designed: one for 3/4 year olds, one for 4/5 year olds, and one for 6 year olds.

In an initial meeting with each of the participants' regular and special education teachers, the research team presented the IAMCAT and the portfolio of activities. Most teachers also had the opportunity to attend the last robot training session of their students that took place at their school. Teachers were then invited to think about the activities in the curricular areas of Language, Mathematics, and

Science & Social Studies that they were planning to do in class, that required the manipulation of objects and that could be adapted so the child with disabilities could also participate using the IAMCAT. Subsequent meetings with the research team were held to discuss the activities proposed by the teachers. After agreement on the activities to be performed by students, materials necessary for the activities, both for the study participant and for the rest of the class, were prepared by the research team. When the IAMCAT virtual version was being used, the activities proposed by the teachers were implemented in the virtual sceneries by the research team.

Annex 1 and Annex 2 contain tables describing the designed adapted activities respectively for the 2013/2014 and for the 2014/2015 participants. Figure 7 exemplifies the implementation of two of the listed academic activities: the first activity in the area of Science & Social Studies for participant P9 (cf. Annex 2) using the physical robot, and the fifth activity in the area of Language for participant P4, using the virtual robot (cf. Annex 1).



Figure 7 Implementation examples of two academic activities

Pre-intervention semi-structured interviews with the teachers were conducted to: a) assess teachers' previous knowledge of assistive technologies; b) collect their perspectives on the child's inclusion and participation in the class group, and on the child's academic, communicative and manipulative skills; c) learn which accommodations or adaptations to the curriculum they usually did, if any, to make it accessible to the child with disabilities; d) determine the teachers expectations regarding participation in the study; and e) understand the children's educational contexts, e.g. if there was support from a

special education teacher, psychologist, and/or therapist, and if they coordinated their interventions with other professionals and/or with the families.

4.3. Classroom sessions

In general, three sessions per participant, one per curricular area, conducted by the participants' regular teachers, took place in their regular classes. After completing the planned activities, typically developing children were invited to perform one of the activities using the IAMCAT. The special education teachers also attended the sessions, in most cases providing individual support to the child with disabilities. Three persons from the research team –the engineer that developed the IAMCAT, the psychologist from the [Acronym] that interacted with the children in all training sessions, and the early childhood educator that designed the activities with the teachers and prepared all the materials – were present in all classroom sessions focusing on the IAMCAT-adapted activities that were being done by the study participant. The psychologist from the research team provided individualized support to the study participants when the special education teacher did not. Classroom sessions were videotaped, one camera framing the participant from behind and the activity that was being conducted, and another framing the participant's face. Video framings were carefully chosen in order to not include the faces of the remaining children in class. Regular and special education teachers were interviewed after the last classroom session to collect their feedback on the use of the IAMCAT. A guide was prepared for the semi-structured interviews with groups of questions addressing: a) the inclusion of the child with disabilities in the class group during the sessions; b) the performance of the child with disabilities during the sessions, particularly the aspects of autonomy, participation, motivation, communication and demonstration of knowledge; c) the IAMCAT potentialities and limitations; and d) the impact of the IAMCAT on the child with disabilities and on the school community.

Pre- and post-intervention teachers' interviews were transcribed and a content analysis [50] was performed. Since there was not enough knowledge available in the literature about the use of robots to promote inclusive education, an inductive approach to content analysis [51] was taken. Interviews were read and open coded [51,52] by two members of the research team with experience in content

analysis. Validation of the coding was made through a dialogue between these two researchers [53]. The software ATLAS.ti⁶ was used for the content analysis. Regular and special education teachers' different backgrounds, and the closer connection that special education teachers often have with children with disabilities through their one-to-one interventions, may influence the way they assess the study. To take that possible bias into account, pre- and post-intervention interviews results were discriminated by regular and special education teacher. Post-intervention results were also discriminated by physical and virtual IAMCAT to allow for comparisons.

5. Results

Six participants used the physical IAMCAT and three used the virtual IAMCAT. Participant P8 was assigned to the virtual IAMCAT at first. However, since he was not motivated at all by the virtual robot, it was decided to change him to the physical robot in an attempt to gain his interest.

All 2013/2014 participants started by controlling the robot in the robot's frame of reference and three of them changed to the user frame of reference. All 2014/2015 participants started by controlling the robot in the user frame of reference (mainly due to the fact that they were in general younger than the 2013/2014 participants) and one of them changed to the robot frame of reference.

5.1. Training sessions

Following the protocol in [47], new activities with an increasing degree of difficulty were proposed to the participants when they were able to execute the previous task. However, sometimes it was decided to move to the next task when the lack of success in the previous one was attributed to a loss of motivation to perform it and not to specific difficulties in controlling the robot. Sessions were conducted in a playful environment to keep children engaged. That implied that sometimes activities in the protocol were changed on the fly, keeping the underlying goals, to motivate the participant. For example, a task that required the child to drive the robot forward until knocking over a stack of blocks

⁶ <http://atlasti.com/>

was sometimes replaced by a task that required driving the robot forward until meeting a princess to give her a flower, or until meeting an animal to give it food or water. Despite these strategies to keep participants engaged, in some cases it was necessary to end sessions before the scheduled 45 minutes due to lack of interest by the participant.

Tables 9 and 10 contain the SGD accuracy (Acc_{SGD}), the SGD time efficiency (T_{SGD}), the robot time efficiency (T_{Robot}) and the robot distance efficiency (D_{Robot}) measures obtained in the “Green Dot Test” and in the robot accuracy test (cf. Section 4.1) by the 2013/2014 and 2014/2015 participants, respectively. Due to their lack of motivation, it was not possible to apply the robot operational accuracy test to the participants P8 and P9. Neither this test, nor the “Green Dot Test” were repeated for P4 when she participated in the study again in the second academic year. Tables 9 and 10 also contain the qualitative evaluation of each participant’s performance when using the IAMCAT in the training sessions.

Results from the grading of the eleven robot skills in table 7 for each participant were plotted in graphs where the horizontal axis shows the training session and the vertical axis shows the level of prompting, from physical assistance to goal met (cf. scale in table 8). The absence of a point for a particular session indicates that the robot skill was not required in that training session. Each graph shows the best (in green), average (in yellow) and worst (in red) performance. Examples of such graphs are given in figures 8 to 10. The complete set of graphs can be found in Annex 3.



Figure 8 Level of prompting required to perform the robot skill “drive the robot to the required location” – participant P1 from the 2013/2014 experimental part. Best performance (BP) in green, average performance (AP) in yellow and the worst performance (WP) in red

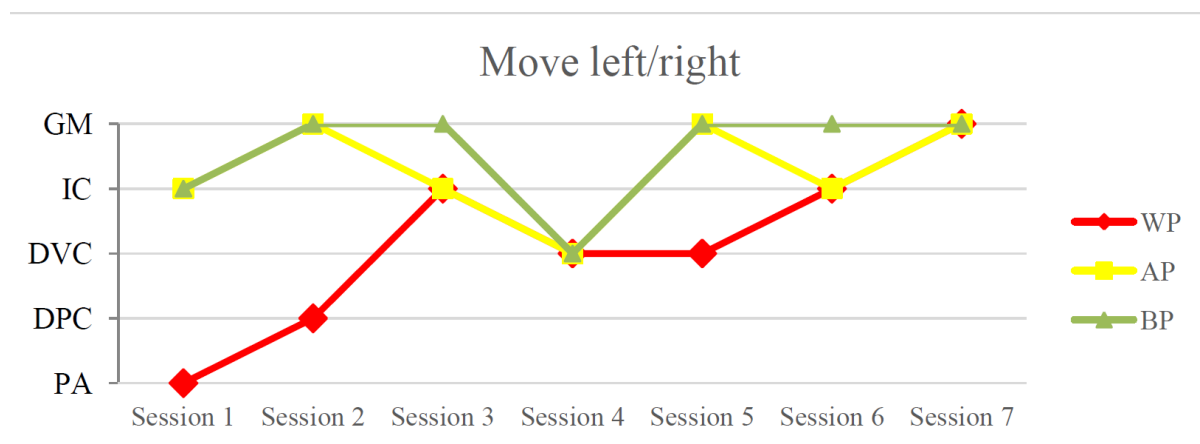


Figure 9 Level of prompting required to perform the robot skill “move left/right” – participant P7 from the 2014/2015 experimental part. Best performance (BP) in green, average performance (AP) in yellow and the worst performance (WP) in red

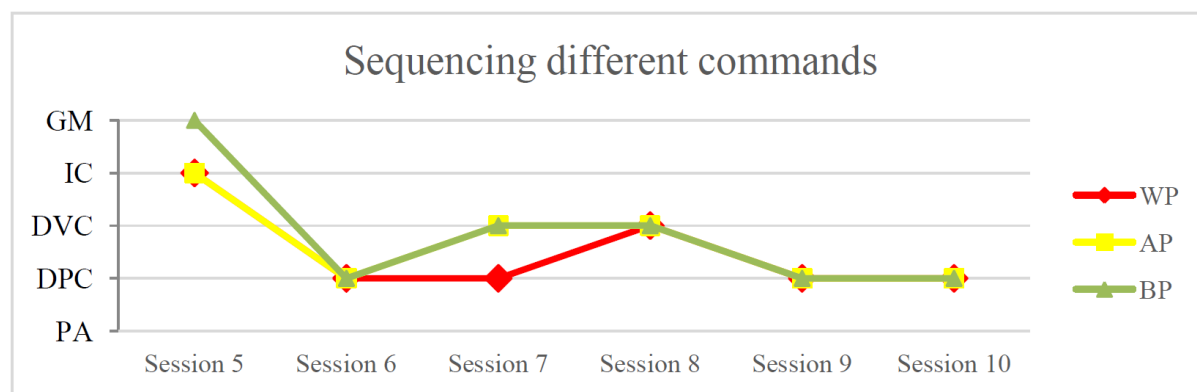


Figure 10 Level of prompting required to perform the robot skill “sequencing different commands” – participant P8 from the 2014/2015 experimental part. Best performance (BP) in green, average performance (AP) in yellow and the worst performance (WP) in red

Table 9 Training sessions results (2013/2014 participants)

	P1			P2			P3			P4			P5		
Robot	Physical			Virtual			Virtual			Virtual			Physical		
Operation Assessment															
Green dot test	Acc_{SGD}	T_{SGD} [s]		Acc_{SGD}	T_{SGD} [s]		Acc_{SGD}	T_{SGD} [s]		Acc_{SGD}	T_{SGD} [s]		Acc_{SGD}	T_{SGD} [s]	
	0%	1		0%	7		0%	10.5		38%	10.75		63%	6.5	
Robot accuracy test	n_{Ro}	D_{Rob}	T_{Ro}	n_{Ro}	D_{Rob}	T_{Ro}	n_{Ro}	D_{Rob}	T_{Rob}	n_{Ro}	D_{Rob}	T_{Rob}	n_{Ro}	D_{Rob}	T_{Rob}
	$_{bot}$ 8	$_{ot}$ 18%	$_{bot}$ 267 %	$_{bot}$ 8	$_{ot}$ 31%	$_{bot}$ 356 %	$_{bot}$ 4	$_{ot}$ 240 %	$_{ot}$ 413 0%	$_{bot}$ 6	$_{ot}$ 471 %	$_{ot}$ 178 4%	$_{bot}$ 4	$_{ot}$ 30%	$_{ot}$ 245 8%
Training	4 sessions			3 sessions			5 sessions			7 sessions			6 sessions		
Reference frame	Robot			Robot			Child			Child			Child		
Robot controls available	4 directions + large/small steps + pen + gripper			4 directions + large/small steps + pen + gripper			4 directions + pen + gripper			4 directions + pen + gripper			4 directions + pen + gripper		
Robot skills	For all skills, “Goal Met” was the P1’s most frequent performance.			For all skills, “Goal Met” was the P2’s most frequent performance.			P3 required “Indirect Cues” in the majority of cases and, occasionally, “Direct Verbal Cues”.			In many situations, P4 required “Indirect Cues” or “Direct Verbal Cues”. Her oppositional behavior conditioned the training.			P5 required, in almost every move, “Direct Verbal Cues”. Her behavior was very erratic and conditioned the training.		
Communication skills	P1 used the system to answer questions and to communicate beyond requested interactions. He used many non-verbal means of communication.			P2 used his speech to communicate in every situation. Only in one activity he used a virtual keyboard within The Grid™.			P3 used the system only to answer questions. She used many non-verbal means of communication.			P4 used the system to answer questions and, occasionally, to communicate beyond requested interactions. She used many non-verbal means of communication.			P5 used the system to answer questions and, occasionally, to communicate beyond requested interactions. She used many non-verbal means of communication.		

Table 10 Training sessions results (2014/2015 participants)

	P4			P6			P7			P8			P9		
Robot	Virtual			Physical			Physical			Physical ^a			Physical		
Operation Assessment															
Green dot test	Acc_{SGD}	T_{SGD} [s]		Acc_{SGD}	T_{SGD} [s]		Acc_{SGD}	T_{SGD} [s]		Acc_{SGD}	T_{SGD} [s]		Acc_{SGD}	T_{SGD} [s]	
	0%	6.4		200%	6.8		338%	15.4		0%	2.5		0%	3.9	
Robot accuracy test	n_{Rob}	D_{Rob}	T_{Rob}	n_{Rob}	D_{Rob}	T_{Rob}	n_{Rob}	D_{Rob}	T_{Rob}	n_{Rob}	D_{Rob}	T_{Rob}	n_{Rob}	D_{Rob}	T_{Rob}
	<i>bot</i>	<i>ot</i>	<i>bot</i>	<i>bot</i>	<i>ot</i>	<i>ot</i>	<i>bot</i>	<i>ot</i>	<i>ot</i>	<i>bot</i>	<i>ot</i>	<i>bot</i>	<i>bot</i>	<i>ot</i>	<i>bot</i>
	-	-	-	8	121%	178%	4	525%	660%	-	-	-	-	-	-
Training	1 session			3 sessions			7 sessions			6 sessions			3 sessions ^b		
Reference frame	Child			Robot ^c			Child			Child			Child		
Robot controls available	4 directions + pen + gripper			4 directions + pen + gripper			4 directions + pen + gripper			4 directions + pen + gripper			4 directions + pen + gripper		
Robot skills	For all skills, “Goal Met” was P4’s most frequent performance. Occasionally, she needed “Direct verbal cues” for using the gripper.			For all skills, “Goal Met” was the P6’s most frequent performance.			For most skills, “Goal Met” was the P7’s most frequent performance. He needed some “Indirect” or “Direct verbal cues” in more complex tasks.			For most skills, “Direct pointing cue” was the P8’s most frequent performance. For using the gripper, he needed most frequently “Direct verbal cues”.			For all skills, “Direct verbal cue” was the P9’s most frequent performance.		
Communication skills	P4 used the system to answer questions. She used many non-verbal means of communication.			P6 used the system to answer questions. He used many non-verbal means of communication.			P7 used the system to answer questions, ask for help, comment the activity and establish communication beyond requested interactions. He used many non-verbal means of communication.			P8 used the system, with “Direct pointing cues” to answer questions. However, he used many non-verbal means of communication.			P9 used his speech to communicate in every situation, as well as many non-verbal means of communication.		

Notes: ^a At the beginning of the study, P8 used the virtual system in his Tobii P15 eye tracker equipment.

However, given his lack of interest, it was decided to change to the physical robot. Here only the training sessions with the physical system were considered; ^b During the training sessions P9 changed his access method from scanning to eye tracking, for reasons unrelated with the project. Here only the training sessions with the eye tracking access method were considered. ^c P6 began the training using the child reference frame, however, given his capabilities, it was decided to change it. Here only the training sessions with this frame of reference were considered.

5.2. Classroom sessions

All participants had three classroom sessions except participant P1 who had an extra session where he used the physical IAMCAT to draw, and participant P9 who used the IAMCAT only in one session at school due to his difficulties in using the system. Classroom sessions were conducted by the participants' regular teachers, except for participant P2 where the special education teacher conducted the class, and for participant P3 where one member of the research team did it, since the regular teachers preferred not to do it.

The main, generic and sub-categories that were inferred in the inductive content analysis of the pre-intervention interviews are listed in table 11. Table 12 contains the main, generic and sub-categories inferred for the post-intervention interviews. Please refer to Annex 4 for the complete list of codes grouped under each category and for the number of times each code was mentioned by the teachers in the interviews.

Table 11 Inferred categories from the pre-intervention interviews

Main categories	Generic categories	Sub-categories
A) Characteristics of the participants	1) Means of communication	a) Non-symbolic means of communication
		b) Communication using low-tech AAC devices
		c) Communication using high-tech AAC devices
		d) Oral communication
	2) Potentialities	a) For development
		b) For learning
		c) For communication
	3) Difficulties	a) For development
		b) For learning
c) For communication		
B) Inclusion of the child	1) Inclusion and participation	a) Participation in the mainstream activities
		b) Positive inclusion in the group
	2) Interaction in the group	a) Infrequent interactions
		b) Frequent interaction
	3) Barriers to inclusion	a) Non-acceptance by children of other classes
		b) School constraints
		c) Family constraints
C) Pedagogical process	1) Teaching organization	a) Curriculum modifications
		b) Curricular planning
	2) Assessment process	a) Assessment adaptations

		b) Assessment techniques
	3) Therapeutic and educational support	a) Collaboration with professionals that provide specific support b) Personalized pedagogical support
	4) Coordination with the family	a) Information exchange b) Difficulties in coordination c) Positive coordination
D) Assistive Technology (AT) practices	1) AT in the educational context	a) Difficulties related to AT b) Skills developed by AT
	2) Knowledge and experience on AT and robots	a) Use of AT b) Use of robots
	1) Envisioned benefits	a) Improvement of inclusion
		b) Improvement of the learning experience
c) Support for manipulation and communication		
d) Autonomy and self-confidence improvement		
2) Envisioned disadvantages	a) Increased amount of work for the teacher	
	b) Need for training and human resources	
	c) Envisioned problems in managing the group in the classroom	
	d) Lack of conditions in school / kindergarten	
	e) Problems inherent to the project	

Table 12 Inferred categories from the post-intervention interviews

Main categories	Generic categories	Sub-categories
A) Appreciation of the project deployment	1) Pedagogical process	a) Selection and planning of strategies and activities
		b) Adaptation of activities and resources
		c) Inclusion of the activities in the class dynamics
	2) Inclusion of the participant in the group during the sessions	a) Interaction with peers during the activities
		b) Reaction of the group to the activities
		c) Attitude of the group towards the participant during the activities
	3) Difficulties experienced	a) Management of the group
		b) Work with the participant
		c) Use of the AT
B) Project results	1) Assessment of the participant given the objectives	a) Satisfactory academic performance
		b) Unsatisfying academic performance
	2) Relevance of the AT for the participant's performance	a) Autonomy
		b) Participation
		c) Motivation
		d) Communication
		e) Manipulation

		f) Learning
	3) Irrelevance of the AT for the participant's performance	a) General performance
		b) Autonomy
		c) Motivation
	4) Project impact on the school and on the class	a) On the group dynamics
		b) On the group learning
		c) On the teacher
		d) On the school community
C) Project sustainability	1) Support for teachers	a) Provision of human resources
		b) Need for training
	2) Suggestions for improvement	a) Of the AT
		b) Of the activities
	3) Continuation proposals	a) Forms of continuation

For each main category considered in the pre-intervention interviews, figures 11 to 15 show the number of times that each sub-category was mentioned, discriminated by regular and special education teacher. Please refer to the figures' captions and to table 11 to identify the sub-categories in each generic and main categories addressed by each figure. Note that the absolute frequencies shown refer to the number of times that each sub-category was mentioned in the teachers' responses and that one teacher could have mentioned one sub-category more than once. Thus it is possible that in a particular sub-category numbers add up to more than the number of teachers (18). The corresponding results for the post-intervention interviews are presented in figures 16 to 18. Once more, from the figures' captions, confronting with table 12, it is possible to identify which are the main, generic and sub-categories addressed by each figure. Representative statements made by the teachers that fall under the categories in figures 11 to 18 will be presented in the discussion section.

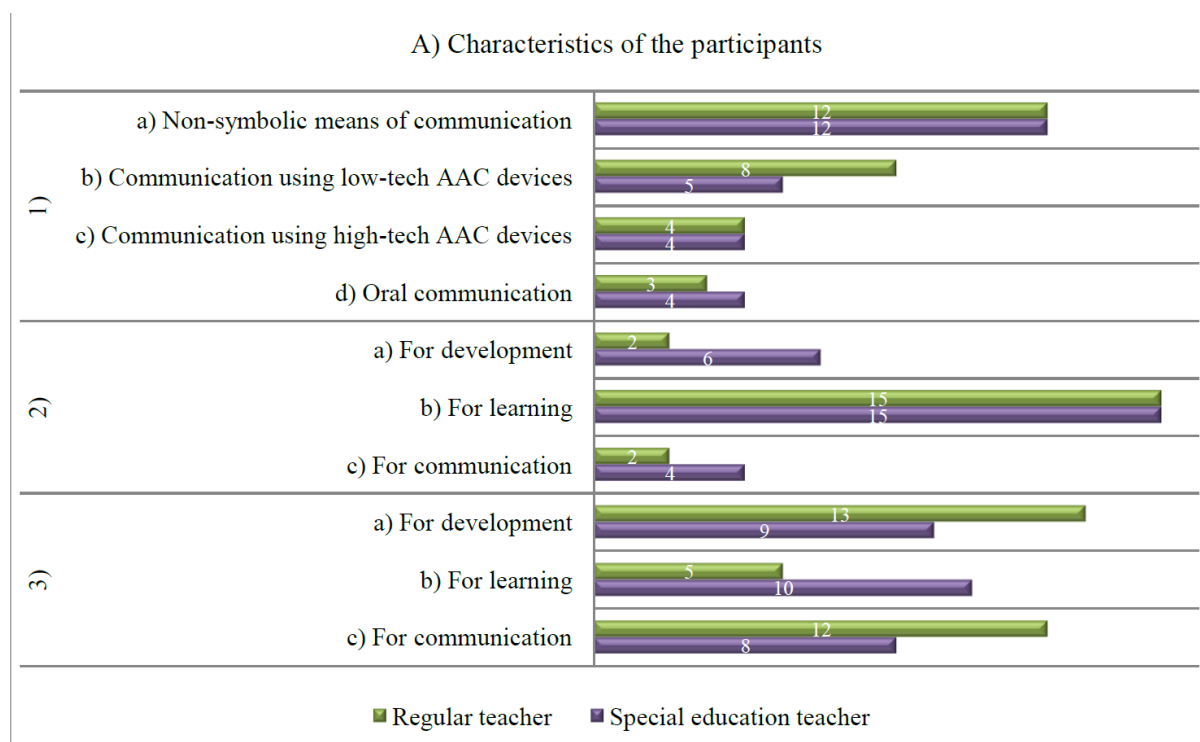


Figure 11 Pre-intervention interviews content analysis results: absolute frequencies, discriminated by regular and special education teacher, of the sub-categories in the main category “A) Characteristics of the participants”. Generic categories 1) to 3) in this main category are: “1) Means of communication”, “2) Potentialities”, and “3) Difficulties”

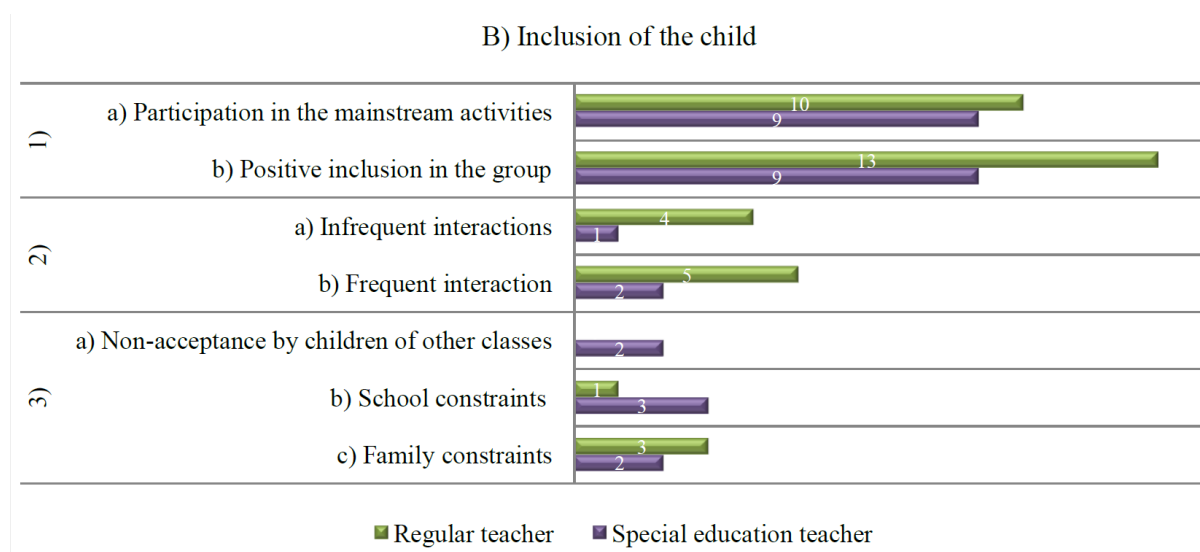


Figure 12 Pre-intervention interviews content analysis results: absolute frequencies, discriminated by regular and special education teacher, of the sub-categories in the main category “B) Inclusion of the child”. Generic categories 1) to 3) in this main category are: “1) Inclusion and participation”, “2) Interaction in the group”, and “3) Barriers to inclusion”

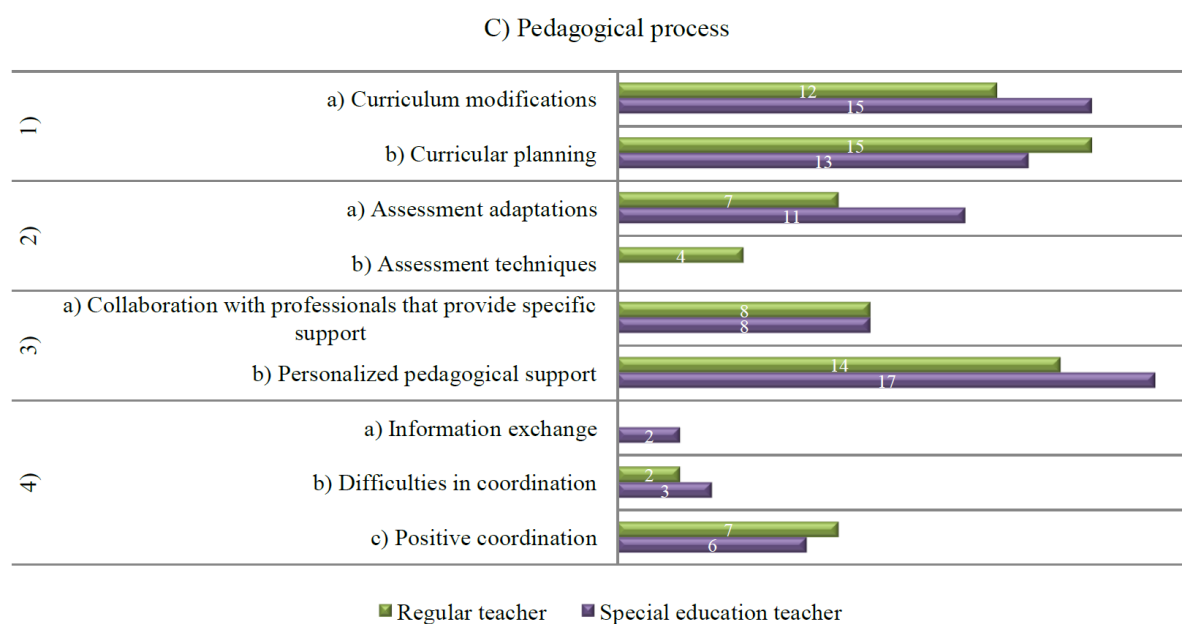


Figure 13 Pre-intervention interviews content analysis results: absolute frequencies, discriminated by regular and special education teacher, of the sub-categories in the main category “C) Pedagogical process”. Generic categories 1) to 4) in this main category are: “1) Teaching organization”, “2) Assessment process”, “3) Therapeutic and educational support”, and “4) Coordination with the family”

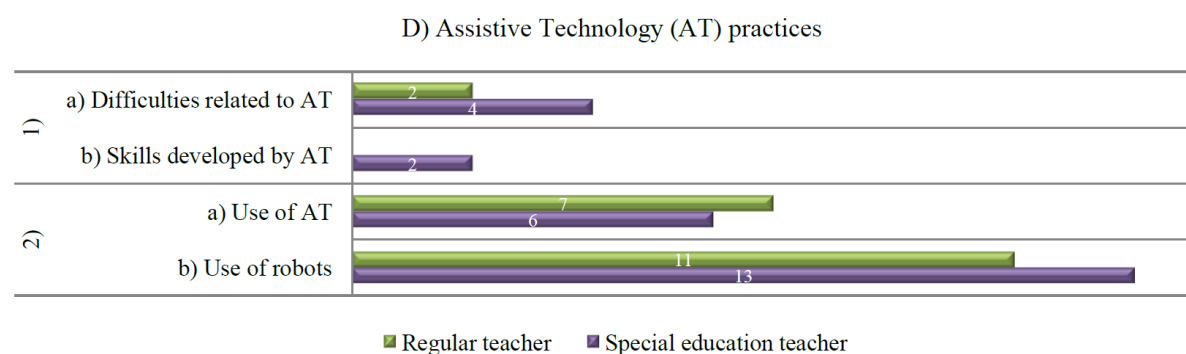


Figure 14 Pre-intervention interviews content analysis results: absolute frequencies, discriminated by regular and special education teacher, of the sub-categories in the main category “D) Assistive Technology (AT) practices”. Generic categories 1) and 2) in this main category are: “1) AT in the educational context” and “2) Knowledge and experience on AT and robots”

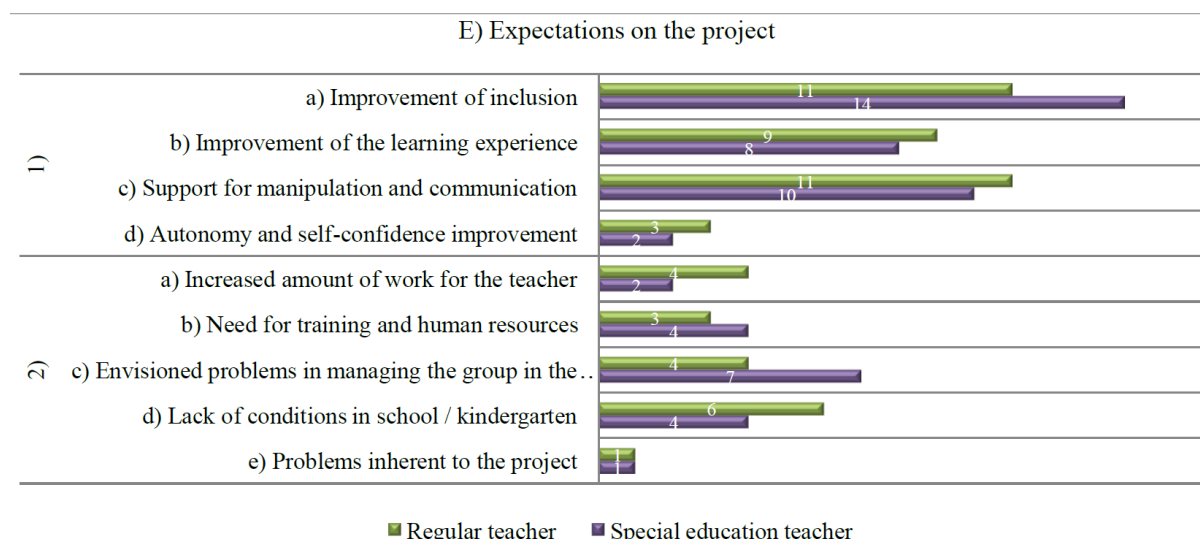


Figure 15 Pre-intervention interviews content analysis results: absolute frequencies, discriminated by regular and special education teacher, of the sub-categories in the main category “E) Expectations on the project”. Generic categories 1) and 2) in this main category are: “1) Envisioned benefits” and “2) Envisioned disadvantages”

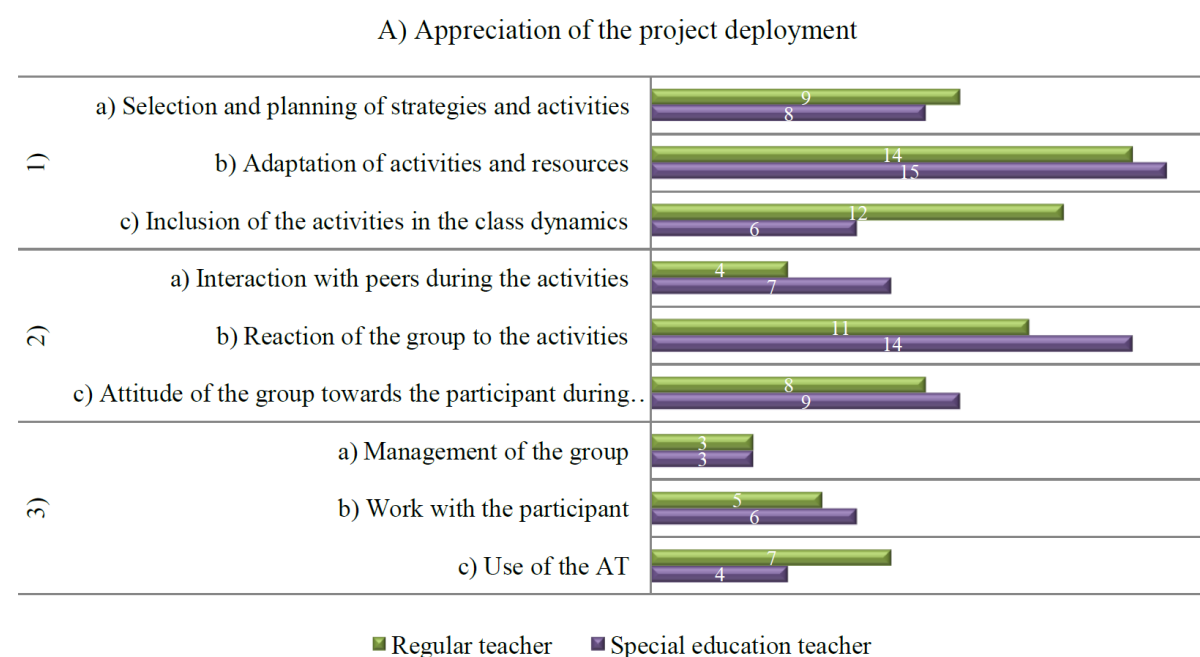


Figure 16 Post-intervention interviews content analysis results: absolute frequencies, discriminated by regular and special education teacher, of the sub-categories in the main category “A) Appreciation of the project deployment”. Generic categories 1) to 3) in this main category are: “1) Pedagogical process”, “2) Inclusion of the participant in the group during the sessions”, and “3) Difficulties experienced”

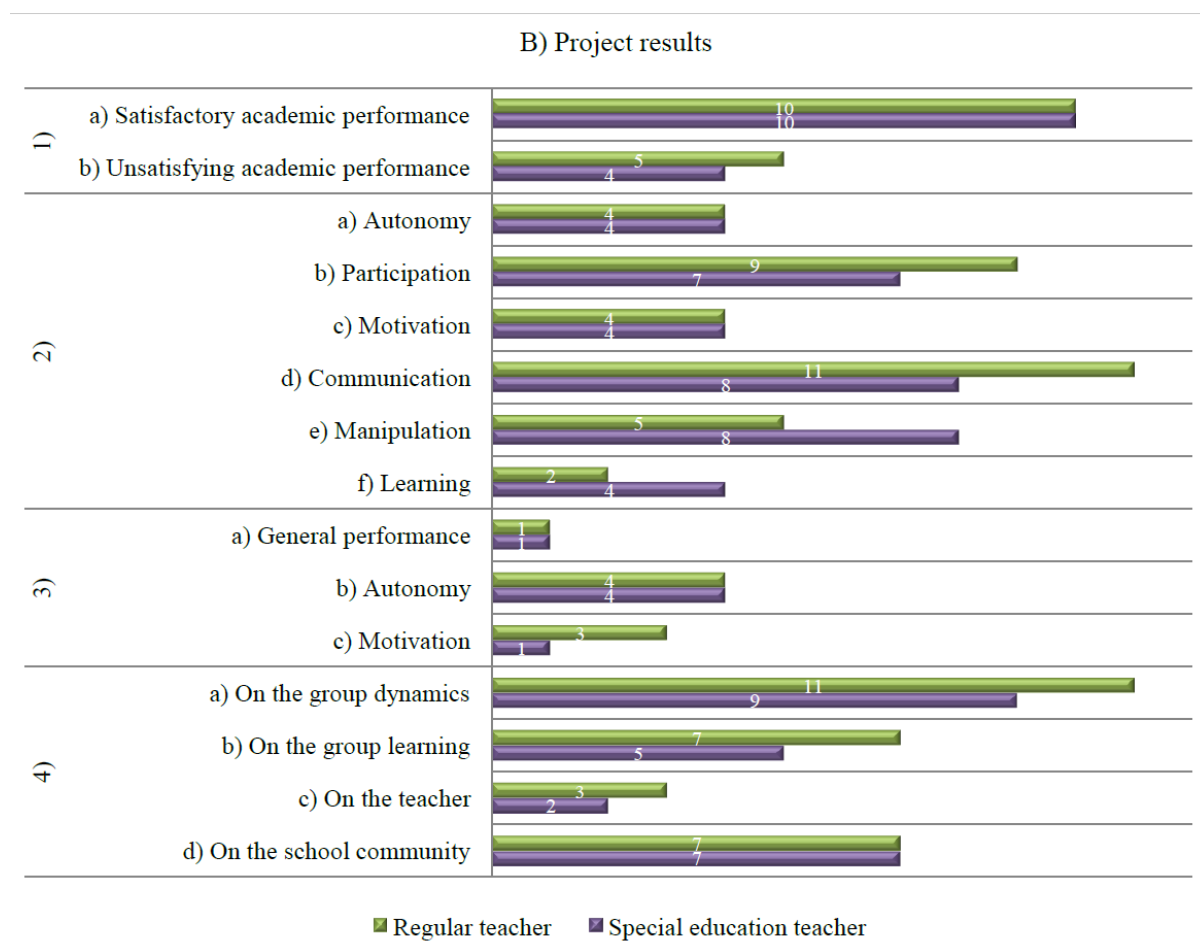


Figure 17 Post-intervention interviews content analysis results: absolute frequencies, discriminated by regular and special education teacher, of the sub-categories in the main category “B) Project results”. Generic categories 1) to 4) in this main category are: “1) Assessment of the participant given the objectives”, “2) Relevance of the AT for the participant’s performance”, “3) Irrelevance of the AT for the participant’s performance”, and “4) Project impact on the school and on the class”

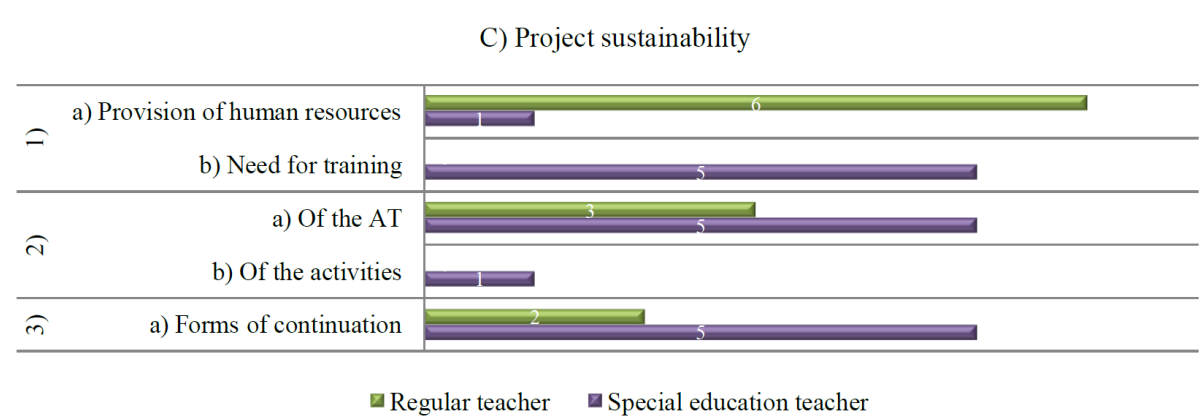


Figure 18 Post-intervention interviews content analysis results: absolute frequencies, discriminated by regular and special education teacher, of the sub-categories in the main category “C) Project sustainability”. Generic categories 1) to 3) in this main category are: “1) Support for teachers”, “2) Suggestions for improvement”, and “3) Continuation proposals”

To avoid bias in the results due to the unbalanced number of participants using each of the IAMCATs, comparisons between the physical and the virtual IAMCAT are done using the relative frequencies of each of the sub-categories with respect to the absolute frequency of the corresponding main category. For each sub-category, the relative frequency was obtained by dividing its absolute frequency by the absolute frequency of the corresponding main category. For example, referring to the table with the post-intervention interviews categories and content analysis results in Annex 4, the sub-category “a) Selection and planning of strategies and activities” was mentioned 9 times for the physical system. This is a sub-category of the main category “A) Appreciation of the project deployment” that was mentioned 93 times for the physical system. Therefore, the relative frequency for the sub-category “a) Selection and planning of strategies and activities” is $9/93 \times 100 = 9.7\%$ for the physical system. This means that 9.7% of the comments on the “A) Appreciation of the project deployment” for the physical system were about the “a) Selection and planning of strategies and activities”. This number can be compared to the 15.4% obtained for the virtual system, disregarding the fact that the sub-category “a) Selection and planning of strategies and activities” and the main category “A) Appreciation of the project deployment” could have been mentioned more times for the physical system because there were more teachers involved in the trials with this system. Figures 19 to 21 show the relative frequencies for the sub-categories in the three main categories considered in the post-intervention interviews. Figures’ captions and table 12 identify the sub-categories in each generic and main categories addressed by each figure.

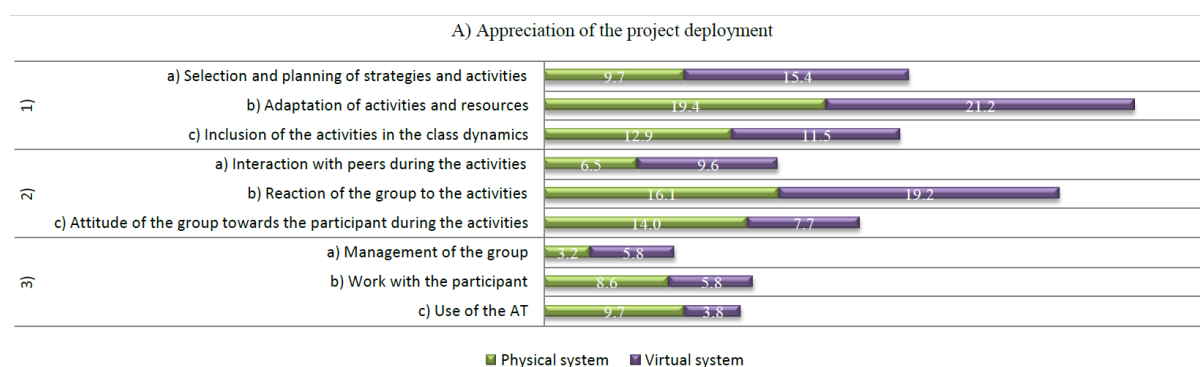


Figure 19 Post-intervention interviews content analysis results: relative frequencies, discriminated by physical and virtual system, of the sub-categories in the main category “A) Appreciation of the project deployment”. Generic categories 1) to 3) in this main category are: “1) Pedagogical process”, “2) Inclusion of the participant in the group during the sessions”, and “3) Difficulties experienced”

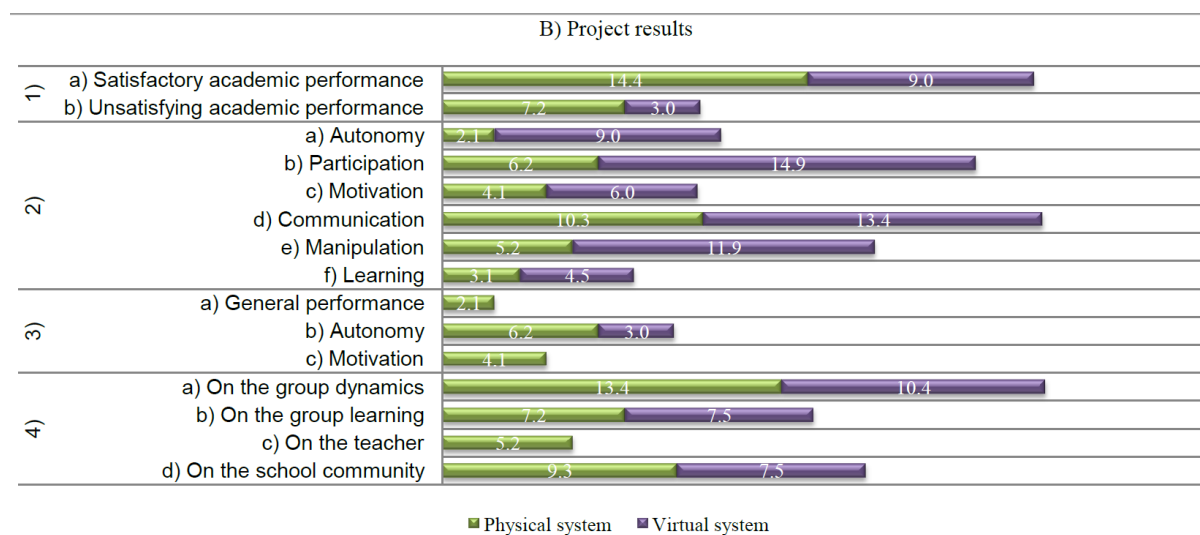


Figure 20 Post-intervention interviews content analysis results: relative frequencies, discriminated by physical and virtual system, of the sub-categories in the main category “B) Project results”. Generic categories 1) to 4) in this main category are: “1) Assessment of the participant given the objectives”, “2) Relevance of the AT for the participant’s performance”, “3) Irrelevance of the AT for the participant’s performance”, and “4) Project impact on the school and on the class”

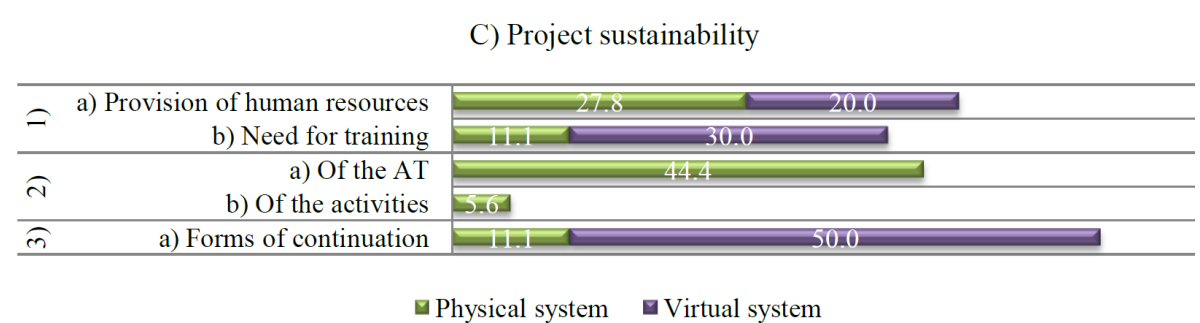


Figure 21 Post-intervention interviews content analysis results: relative frequencies, discriminated by physical and virtual system, of the sub-categories in the main category “C) Project sustainability”. Generic categories 1) to 3) in this main category are: “1) Support for teachers”, “2) Suggestions for improvement”, and “3) Continuation proposals”

6. Discussion

6.1. Training sessions

All participants went through a variable number of training sessions (from one, for P4 when she was participating for the second time, to seven). Training with each child was ended when, according to the qualitative assessment by the research team, the participant would not benefit from further sessions since (s)he was losing interest and not progressing anymore.

After the training sessions, three participants (P3, P5 and P4 in her first year of participation) required direct verbal clues for many robot actions. The two youngest participants (P8 and P9) had many difficulties in using the system. These were attributed to their lack of motivation and to problems with the control of the IAMCAT through eye gaze. When P8 changed from the virtual to the physical IAMCAT he became more interested but still only used the system when prompted. P9 was not at all engaged with the robot, supporting his mother's perception of his lack of interest in remotely operated vehicles (cf. table 5). Both P8 and P9 were novice users of eye tracking systems and unwanted selections of different robot controls made the robots behave erratically thus making it difficult for these participants to establish cause and effect relationships and thus understand how to control the robot. Moreover, controlling the robot through eye tracking poses an additional challenge: children need to look at the computer screen to select the robot control option and then look at the robot to check its effect. This forces the user to keep changing the focus of attention, adding another layer of complexity. Age could also have played a role here. In fact, in [54,29] authors report that children under five years old have more difficulties in understanding cognitive skills like sequencing actions, a cognitive skill that is necessary to use the IAMCAT.

The results of the "Green Dot Test" and of the robot accuracy test in tables 9 and 10 also reflect the different levels of competence of the participants at the end of the training sessions. The main reason for the wrong selection of target cells in the green dot test (and thus for values of Acc_{SGD} greater than 0%) was the accidental pressing of the mouse switch while manipulating the trackball. Only P1, who accessed the computer through eye gaze, could be considered a fast user of the SGD. Regarding the robot operational competence, values of T_{Robot} and D_{Robot} show that all participants required much more time and drove the robot through much longer paths when compared to minimum time and distance required to reach the targets. In particular, average time for the robot to reach the targets was between 2.7 and 66 times slower than the fastest possible time, thus clearly showing that, even when participants were able to successfully use the robot, they were not very efficient.

Participants' performance shown by coding of the level of prompting required to achieve each robot control goal did not stabilize for all participants along all goals (see for example figure 9). In some

cases, demonstrated skill level got worse throughout the sessions (cf. figure 10). This may be due to several factors. Task complexity increased along the sessions aiming at improving children's mastery over the system and this might have caused a deterioration of the participants' performance. Some participants started to lose interest after a few training sessions, performing below their true abilities and failing to improve. Moreover, for such young participants, performance measures may have a strong behavioural interference, reflecting not so much their abilities to control the robot but rather their motivation to perform. Supporting this hypothesis is the fact that some of the participants performed much better in class, when they were motivated by the presence of their peers, than in the training sessions.

Quantitative evaluation of the robot skills helped to identify robot control and communication goals that needed to be addressed in each training session and, when the training ended, which were the skills that were not mastered by the child and that needed to be addressed by reprogramming the robotic system or by appropriately designing the academic activities. For example, in the case of P8, due to his difficulties driving the robot, all classroom activities were prepared such that they could be performed just by moving the robot forward and backward and using the gripper to pick up objects.

6.2. Classroom sessions

Evaluation of academic achievement when using the IAMCAT (experimental objective 1) and assessment of teachers' perceptions of the use of the IAMCAT and its impact on the student and in the classroom (experimental objective 2) were performed through the content analysis of the participants teachers' post-intervention interviews. This analysis also provided information on the teachers' opinions about the integration of the IAMCAT in the pedagogical process and about how the project ideas could be implemented in the academic practices.

Academic achievement when using the IAMCAT

From the nine participants in this study, six were enrolled in pre-school, two in the first grade, and the child that participated in both academic years was first in pre-school and then in the first grade. For such young participants, learning is a continuous process and academic achievement is usually not

assessed by tests but rather by a qualitative evaluation of how children progressed through the academic year. The same curricular content is often addressed several times, using different perspectives and/or materials. Worksheets that are used in classes are often completed with the help of the teachers, giving students the opportunity to revise their answers if something was not correct. In this study, the activities prepared by the teachers to be performed by the participants in class were all framed in each teacher's curricular planning and focused on content that was already addressed in each class. Therefore, teachers' opinions on academic achievement refer more to the learning process than to the acquisition of new knowledge by the participants. In figure 17 it is possible to see that there were many references to the participants' satisfactory academic performance. However, teachers also reported difficulties in some curricular areas for some of the participants. For example, in the case of P9, an unsatisfactory performance in the activities was reported. Due to P9's poor performance in the first classroom session and his complete lack of motivation to perform, it was decided not to run the second and third classroom sessions.

Teachers' perceptions of the use of the IAMCAT and its impact on the student and in the classroom

Regarding the inclusion of the participant in the group during the activities, many teachers considered that the IAMCAT contributed positively (figure 16). However, many also referred to difficulties in managing the group since doing the activities with the IAMCAT required more time (figure 16).

In the opinion of many teachers, the IAMCAT positively contributed to the participation, motivation and autonomy of the children with disabilities who participated in the study (figure 17). It promoted manipulation, communication, and learning. Teachers of the participants P8, P9, P6, P3, P2, and P7 reported that the IAMCAT did not affect these children's performance. In the case of P8 and P9, the two 3-year old participants, their difficulties in using the system might have prevented it from having an impact on the child's performance. Participants P6, P3, and P2 didn't have severe manipulation limitations and that can explain why teachers did not see a significant impact of the IAMCAT on these participants' performance. However teachers reported that, for these participants, the IAMCAT facilitated the access to new curricular content, communication, and/or task control. Teachers reported that the IAMCAT did not change P7's autonomy and that P7's motivation decreased through the sessions. The comments about autonomy may be because of P7's difficulties using the trackball.

While P7 was doing the activities, all the other students were watching him and the activities were demanding in terms of robot control. P7 became tired of controlling the robot in front of everybody and he only wanted to use the IAMCAT to communicate with the others. That may also explain the decrease in motivation reported by the teachers. Nevertheless, the IAMCAT was considered relevant for P7 in terms of participation, communication, manipulation, access to new curricular content, self-esteem and self-confidence. Many teachers evaluated the impact of the IAMCAT on the group and on the school community very positively. The project raised awareness of the need for assistive technology in classes. One teacher said ‘If we had this system always available in the classroom, classes would be prepared taking into account the system and she [P4] could always participate in the activities’. The project also changed the way the participants were perceived. The initial expectations of the children’s performance were exceeded after watching them using the IAMCAT: ‘...and we managed to overcome all the difficulties in the three sessions, she [P4] became involved in a way that exceeded my expectations’. Perceptions of the typically developing peers also changed: ‘the group realized that P7 is able to do things and that he can communicate and participate effectively’; ‘the children thought she [P5] was playing with the robot, but then they realized that she was carrying out the activities and they saw the difficulties that she has to overcome’. Additionally, the project motivated the exploration of different inclusive experiences. With one of the study participants, the physical scene for the robot-mediated activity was prepared in class with the collaboration of all students.

Children’s opinion on the use of the system was not formally assessed. However, informal observation by research team members who knew well the participants from AAC interventions revealed that even children who were usually more reserved were clearly very happy to see that they were doing the same activities as their typically developing peers. One of the participants, when asked about what he liked the most in the classroom session, answered that it was seeing the others trying to use the robot as he did. In some cases the child with disabilities was given the central role in class, all the others observing how (s)he was doing the activity with the IAMCAT or using his/her example to correct the activity for the other children. This completely reversed the often observed situation in which children with disabilities are mere observers of what is happening in class. In one case the way

that the child with disabilities performed the activity was taken as the model for the others to follow. Having to complete a worksheet requiring them to connect two points, typically developing children drew a broken line imitating the robot movements forward, 90 degrees turn, forward, 90 degrees turn, forward, instead of drawing a diagonal line connecting the points. On that occasion, children commented that it was easier to complete the activity using a pencil but that it was more fun to do it with the robot. Teachers also reported that the IAMCAT contributed to the improvement of the participants' self-esteem, self-confidence, and self-valorisation by the success in performing the activities along with their typically developing peers: '... the fact that she [P4] noticed that she could do the exact same activity as other colleagues contributed to raise her self-esteem'. The experience of having the typically developing children trialling the system gave an opportunity for children with disabilities to help and teach their typically developing peers how to use the robot. Note that the children with disabilities were trained on its use, while the other children were not. Interestingly, many times they were not very patient with the difficulties their typically developing peers were showing.

Conducting pre-school and first grade classes with about 20 children is a very challenging task. Often teachers concentrate on keeping order while conducting the academic activities designed to meet the curricular goals defined for each school year. When a child with disabilities is present, it is very hard for the teacher to give the special support or allow for the extra time that he or she might need to complete the activity. This often results in teachers using the fastest communication strategies with children with speech impairments, relying on facial expressions and on yes and no answers. Participation in this project gave teachers an opportunity to give more attention to the child with disabilities. In one session, one of the children used the IAMCAT to access a communication grid with more vocabulary (instead of only the vocabulary needed for the task) and maintained the following dialog with her teacher:

Teacher: 'Did you ever ride a bicycle?'

Child: 'Yes'

Teacher: 'With whom?'

Child: 'Father'.

Using assistive robots to promote inclusive education

In that occasion, the teacher commented that it was the first time she knew something from child's life outside school.

Integration of the IAMCAT in the pedagogical process

From figure 16 it is possible to see that several teachers commented on the pedagogical process that led to the preparation of the academic activities. They considered that it was possible to select, plan, and adapt activities framed in the class-planned activities taking into consideration the participants' capabilities. It is worth noticing that all the preparation was done with the support of the research team.

Implementation of the project ideas in the academic practices

Despite the general positive appreciation of the assistive technology, teachers' pointed out the need for technical improvements in the IAMCAT (speed, for example). Many referred to the need for training on the use of assistive technology and also the need of at least another adult in class to support the child with disabilities using the system (figure 18).

6.3. Comparison of the perceptions of the regular and the special education teachers

Differences between the perspectives of regular teachers and special education teachers were mainly observed in the evaluation of the project sustainability (figure 18) and, to a lesser extent, in the assessment of the potentialities and difficulties of the children's participation in the project (figure 11). While regular teachers emphasized the need for other adults in class, special education teachers put the focus on the need of training for using assistive technology. Special education teachers also had more reservations about the difficulties related to the use of assistive technology in the educational context, when compared to the regular teachers (figure 14). Figure 15 shows that both regular and special education teachers had positive expectations for the IAMCAT, but envisioned difficulties in managing the group. Proposals to implement the project ideas in day-to-day school practices came

more from special education teachers than from regular teachers (figure 18). In regard to the characterization of the participants, regular teachers gave more attention to the potential difficulties and were less optimistic about the participants' potentialities (figure 11).

6.4. Physical and virtual IAMCAT comparison

Results of the post-intervention interviews content analysis were discriminated by both the physical and virtual IAMCAT to assess the experimental objective 3: compare physical and virtual systems in relation to the other experimental objectives (evaluation of academic achievement and teachers' perceptions of the use of the IAMCAT and its impact on the student and in the classroom). Potential differences regarding teachers' opinions about the integration of the IAMCAT in the pedagogical process and about how the project ideas could be implemented in the academic practices were also analyzed. Children's views were not assessed.

Academic achievement when using the IAMCAT

References to unsatisfactory academic performance were more common for the physical IAMCAT (figure 20). This bias may be due to the fact that the two younger participants used the physical IAMCAT. In fact, when assessing the participant given the objectives, teachers referred to a satisfactory academic performance more often for the physical than for the virtual system.

Teachers' perceptions of the use of the IAMCAT and its impact on the student and in the classroom

Difficulties in the use of the assistive technology were more common for the physical IAMCAT (figure 19). It is interesting to note, from figure 20, that teachers reported the impact of the physical system on them, considering that using it was a formative experience, while they do not attribute the same conclusion to the virtual system. The impact on the group dynamics was more often cited for the physical than for the virtual system. In general, the relevance of the assistive technology for the participants' performance was reported more in the case of the virtual IAMCAT, and its irrelevance to the participants' performance was reported more for the physical IAMCAT (figure 20).

Integration of the IAMCAT in the pedagogical process

From figure 19 one can see that there were no clear differences regarding the appreciation of the pedagogical process with the physical and the virtual robot. The physical materials needed for the activities with the physical IAMCAT and the virtual objects and scenes for the virtual IAMCAT were primarily prepared by the research team.

Implementation of the project ideas in the academic practices

Suggestions for the improvement of the assistive technology and of the activities were only given for the physical IAMCAT (figure 21). Teachers involved with the virtual IAMCAT made more suggestions for continuation of the project, which included having the robot in class for longer period of time and commercialization of the prototype. These results corroborate the rationale for testing virtual tools to promote the participation in academic activities, namely their potential to overcome technical difficulties present in the physical systems, ease of use, and potential for being less disruptive in classes. However, teachers also referred more often to the need for specific training when the virtual IAMCAT was involved. Additionally, the virtual IAMCAT is less flexible in the long term. In fact, to design new academic activities to be performed with the virtual IAMCAT, it is necessary to develop the corresponding virtual scenes and objects which requires programming skills. In contrast, new activities can be designed for the physical IAMCAT requiring only the use of different objects to be manipulated by the physical robot, possibly constructing a new physical activity scene.

7. Conclusions

Both the physical and the virtual IAMCAT proved to be useful technologies to allow children with neuromotor disabilities to actively participate in academic activities. Before the classroom sessions, children need to go through training sessions to learn how to manipulate objects using the robotic tool and to communicate using the AAC feature. Training should end when the child acquires all the necessary robot and communication skills or when the child starts to lose motivation. To fight disengagement, play time with the IAMCAT should be included in every training session. Additionally, activities that match each child's preferences should be proposed. Quantitative

assessment of the training sessions is useful to inform the subsequent training sessions, possible robot reprogramming, and the adaptation of the academic activities. However, the end of training should be decided mainly based on the qualitative perception of the child's performance.

Teachers considered that the system allowed for adapting activities in their annual curricular planning, without the need for drastically changing what was planned. After conducting the classes where the system was used, they reported that it was possible to integrate it into the regular class dynamics and that it contributed to the inclusion of the child with disabilities, fostering participation and access to the curriculum content. However, they pointed out the difficulties in managing the different times required for typically developing children and for the IAMCAT user to perform the same activity. Additionally, they referred to the need for at least another adult in class to give dedicated support to the child with disabilities in performing the IAMCAT mediated activities.

The facts that: a) only teachers' opinions on the systems were collected, while the learning experience from the children's point of view or from the long term academic achievements was not assessed; and b) the physical system presents a bigger challenge to the teachers in using it; do not allow for final conclusions regarding which version of the IAMCAT is preferable. However, this project encourages further studies with virtual tools to support participation in academic activities.

The IAMCAT was not useful for the two three-year-old participants. This might be related to the difficulties these children had accessing the computer through their eye tracking system. Additionally, the tasks required cognitive skills (e.g. sequencing) that typically younger children do not master [54,29].

Project limitations include: a) each participant used the IAMCAT only in a small number of classroom sessions and thus it was not possible to evaluate long term effects of the system, in a less experimental context; b) children's and parents' opinions on the system were not collected; and c) as in many studies with children with disabilities, the small number and the heterogeneity of participants makes it hard to generalize conclusions. Extending the use of the IAMCAT to more children with disabilities, on a regular basis during the entire academic year, will be the next step in this research to obtain more evidence on the usefulness of these assistive technologies to promote the participation of children with neuromotor disabilities in regular classroom activities.

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