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Using virtual robot mediated play activities to assess cognitive skills

Abstract

Purpose To evaluate the feasibility of using virtual robot mediated play activities to assess cognitive skills.

Method Children with and without disabilities utilized both a physical robot and a matching virtual robot to perform the same play activities. The activities were designed such that successfully performing them is an indication of understanding of the underlying cognitive skills.

Results Participants' performance with both robots was similar when evaluated by the success rates in each of the activities. Session video analysis encompassing participants’ behavioural, interaction and communication aspects revealed differences in sustained attention, visuospatial and temporal perception, and self-regulation, favouring the virtual robot.

Conclusions The study shows that virtual robots are a viable alternative to the use of physical robots for assessing children’s cognitive skills, with the potential of overcoming limitations of physical robots such as cost, reliability, and the need for on-site technical support.

Keywords: Cognitive skills assessment, virtual robots, augmented manipulation

Introduction

The assessment of cognitive understanding of children with neuromotor disabilities raises concerns. In fact, cognitive ability may be confounded by the nature of the physical disability itself [1]. Traditional tests rely on motor or verbal responses that children might not be able to provide due to their disability. Adapted tests (e.g. the PTI - Pictorial Test of Intelligence[2]), where children only need to choose from a set of possible answers through a pointing method, for instance eye gaze, are available, but these require sustained attention on questions that may be meaningless and uninteresting to the children. As a consequence, children’s cognitive abilities might be underestimated, leading to reduced expectations on the part of parents, teachers, and clinicians. Reduced expectations can lead to providing fewer opportunities for children to develop and demonstrate their cognitive skills, thus entering a vicious cycle that prevents children from developing to their full potential [3].

The use of robot mediated activities has been proposed as an alternative method for assessing cognitive skills of children with disabilities [4]. In these applications, robots are used as augmentative manipulation tools to perform play activities that elicit particular cognitive skills. The performance of a child with disabilities can then be compared to the performance of typically-developing children when executing the same robot mediated play activities as a proxy measure of his or her cognitive development. The main advantage over other cognitive assessment tests is that children are playing while their cognitive skills are being tested, thus increasing children's motivation to perform the activities. Robots can be controlled using different access methods (e.g. single switches or a joystick) making them accessible to potentially every child. Additionally, robots can be programmed to perform complex tasks upon a simple command from the child. For example, a robot can be programmed to go to a particular location and load food to be given to an animal upon a single switch press. This feature allows the design of activities that appeal to the children and that do not require high level cognitive skills (in the example, only cause and effect needs to be understood to press the switch that makes the robot go and load the animal's food). Or, robots can require more input from the child in order to accomplish tasks. For example, the robot could move forward, backward, left or right based on which of four switches the child presses. In this way children are challenged to use more skills. Lego® Mindstorms® robots have been used in the work reported in Cook et al. [4]. These are relatively inexpensive robots (~$300) that are perceived by children as toys. Different robots can be built with the Lego parts and robot programming is facilitated through graphical programming software. For an in-depth discussion on the characteristics that a robot should have for being used as an augmentative manipulation tool for play and academic activities, please refer to Cook et al. [5].

From several studies (a survey of those studies can be found in Cook et al. [4]) it is now clear that the use of robotic systems can provide a window into children's cognitive skills, avoiding dependence on standardized test administration [4]. Children as young as 8 months are able to use a robot as an augmentative manipulation tool to perform different activities [6]. Children's performance on robot mediated activities designed to elicit particular cognitive skills varies with cognitive age[*] [7,8,4], thus showing the potential of the method to discriminate children by cognitive age.

Potential barriers to the use of robot mediated activities to assess cognitive skills are: Lego robots are still expensive in some contexts (e.g. under resourced countries), they are not very reliable (e.g. when programmed

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[*] In this paper, cognitive age refers to the age equivalent provided by a standardized cognitive and developmental abilities test (e.g. the PTI [2]).

to do a right angle turn they may not turn exactly 90 degrees thus compromising the direction of subsequent movements), and they require technical skills for assembling and troubleshooting. Virtual robots have the potential of overcoming these limitations. A software package including different activities to be performed using virtual robots that could have different visual features to match the child's preferences could be developed and easily shared. Standard assistive technologies for computer access [9] could be used to make the software accessible for all. But in order to take advantage of these benefits, it is necessary to establish the equivalence between the virtual and the physical robots when used in activities to assess children's cognitive skills.

In this paper a study is reported aiming at comparing the experiences of children with and without disabilities using a physical robot and a matching virtual robot to perform the same tasks respectively in a physical and in an on-screen simulated environment. The objectives of the study were:

1) To determine if the tasks successfully completed by typically-developing children using physical robots are also successfully completed using computer simulations of robots.

2) To determine if the tasks successfully completed using physical robots by children with disabilities are also successfully completed using computer simulations of robots.

3) The potential for the tasks to discriminate children by cognitive age.

Robot mediated activities and underlying cognitive skills

Robot mediated activities to assess cognitive skills were proposed in Cook et al. [7]. This was the basis for the robot mediated tasks designed for the study with typically-developing children reported in Poletz et al. [8]. The same tasks were utilized in the study described in this paper, building on the acquired experience. The tasks are briefly explained here in the sequence in which they were presented to the children in our study. Names for the tasks reflect the major cognitive skill they aim to elicit[†].

Task 1—Cause and effect

The child is required to press and hold a switch to make the robot drive forward to knock over a stack of blocks (figure 1).

Task 2—Inhibition

The child is required to drive the robot forward (by pressing and holding the same switch as for task 1), stop beside a pile of blocks (by releasing the switch when the robot reaches the pile) where blocks are loaded onto

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[†] In previous publications we have used different terms for cognitive skills: task 1 (causality), task 2 (negation), and task 3A (binary relations).

the robot, and then drive the robot to the location at which they were stacked for the first task (by pressing and holding again the switch to make the robot move to the end of the table and by releasing the switch at the end of the table to make the robot stop). This is illustrated in figure 2.

Task 3A—Laterality

In task 3 two stacks of blocks are located one to the left and one to the right of the original stack, and the robot is placed at the end of the table between these two new stacks. In task 3A the child is required to choose a stack of blocks to knock over and then turn the robot towards that stack using one of two new switches (figure 3). Each of these new switches makes the robot turn 90 degrees left or right upon a switch hit (pressing and holding the switch has exactly the same effect of turning 90 degrees; for additional turns it is necessary to release the switch and hit it again).

Task 3B—Sequencing

After turning the robot in 3A in the appropriate direction, the child is required to press and hold the forward switch to knock over the desired stack of blocks (figure 4).

---- Insert figure 1 about here ----

---- Insert figure 2 about here ----

---- Insert figure 3 about here ----

---- Insert figure 4 about here ----

These robot mediated activities were designed to be play activities that are able to discriminate children by their cognitive age, meaning that being able to perform each of the tasks is an indication of cognitive understanding of a set of skills. Even though several other skills are required to successfully complete the proposed robot tasks, each task described above aims to elicit a particular major cognitive skill that can provide information regarding the child's current cognitive understanding. The following is a list of these major cognitive skills and the operational definition under which they have been explored in this study. These skills are presented with reference to childhood development and tool-use literature. Tool use refers to the ability of the child to use an object to act on the environment to accomplish a goal [10] and develops within the second year of life

[11,10,12,13]. Tasks 1 to 3 require that children understand that they can use the robot as an augmentative manipulation tool to interact with the environment, namely with the blocks.

Cause and effect

In order for a child to understand a causal relation between objects or events, the child must be able to make causal inferences. A causal inference is the ability to detect a difference between initial and final states in an event, and infer a cause as a result of tracking this event over time [14]. In the robot task 1, the child is not given explicit information about the switch controlling the robot and the subsequent relation between them (i.e. a continued press of the switch causes the robot to keep moving). In order to successfully carry out the task the child needs to be able to identify how the robot moves while the switch is being pressed, therefore inferring the cause and effect relation. This kind of very simple cause and effect relationship was understood by children with the cognitive age of 8 months in controlling a robot arm to bring a cookie closer [6]. Causal knowledge changes with age and children are able to progressively understand more complex causal relations as they get older and are exposed to different objects and interactions [15]. Gopnik et al. [16] found that two, three and four year olds were able to make causal judgements when exposed to a new machine, a “blicker detector”, but only three and four years olds could use this information to make the machine stop when requested. The robot in this study was controlled via infrared signals, hence, there was no direct contact between the switch and the robot, potentially making the task more complex than in Stanger and Cook [6].

Inhibition

Inhibition or inhibitory control, is the ability of the child to actively inhibit a predominant response in order to achieve a certain goal [17], especially when this response has been previously successful and as a result a positive reinforcement has been associated with it [18]. In the second task, the child is required to release the switch in order to stop the robot at specific places. The child is thus required to inhibit the response that was previously successful in completing task 1, i.e. continued switch activation to complete the task. Inhibition emerges towards the end of the first year of life and matures rapidly in the toddler and pre-school years, allowing children to progressively regulate their behaviour [17].

Laterality

The ability of the child to orient in terms of left and right depends on right- left discrimination and recognition [19]. Right- left discrimination can be defined as the ability of the child to differentiate between two identical symmetrical stimuli shown simultaneously in relation to the body sagittal symmetry [20]. This ability also allows the child to compare objects regarding their location in space. For example, when applied to objects or images, this ability allows the child to differentiate the object as being left or right and compare it with an image previously seen or use its location to make a choice [19]. In task 3A, the child faces two identical options (one on the left and the other on the right) that he/she needs to differentiate in order to choose one or the other. Then, the child is required to recognize which of the two symmetrical identical switches relates to the chosen side. Some of these aspects are mastered by the fourth year, but the appropriate use of the labels "right" and "left" can continue up to the eleventh year [19]. The robot task does not require the child to label the side correctly but rather discriminate one side and then relate it to the same side switch, therefore making the task more appropriate for pre-schoolers.

Sequencing

A child’s learning process is largely underlined by the ability to segment actions into sequences and determine which small sequences of action are necessary or useful for a particular outcome and why [21]. The ability to understand and perform a sequence of actions to achieve a goal has been related to imitation and critical dimensions such as cultural and social knowledge [22]. Children around the end of their second year of life can plan sequences prospectively to achieve a goal even when there is no contact visually available between the tool and the target [10]. Three year old children were able to complete a two-step sequencing task, but not a three-step sequence in Stanger and Cook [6]. In task 3B the child is required to plan and perform a certain sequence of switch presses in order to accomplish the goal of knocking over the desired stack of blocks.

Cognitive skills mature with age and thus it is not possible to precisely state the ages at which each skill is attained. However, it is possible to indicate the age intervals at which typically cognitive skills are acquired. This is done in table 1 from which one can infer the potential of the proposed tasks to discriminate children by cognitive age. The degree to which such discrimination is possible will also be analyzed using data gathered from the study.

---- Insert table 1 about here ----

Methods

A convenience sample of twenty typically-developing children and nine children with cerebral palsy was obtained at day cares and institutions that support children with cerebral palsy within greater Lisbon (Portugal). Children were recruited in three cognitive age brackets: 33-39, 45-51 and 57-63 months. Table 2 shows the distribution of participants by cognitive age group. Cognitive age was assessed through the Pictorial Test of Intelligence (PTI) [2]. The PTI is an adapted test of general intelligence comprising three subtests: verbal abstractions, form discrimination, and quantitative concepts. Scores in each subtest are combined to provide a global score that gives an age equivalent for the subject. Having participants in relatively narrow cognitive age brackets allowed for the evaluation of the discriminating potential of the different robot mediated tasks by comparing the average performance of typically developing children in each cognitive age group when executing the same task. A video analysis was also conducted in order to compare the utilization of the two robots beyond the task success rates analysis. To increase sample size, in the video analysis of the participants with cerebral palsy four additional participants were added that were not considered in the task success rates analysis since their cognitive age did not lie in any of the defined cognitive age brackets: one child 40 months old, two children 41 months old, and one child 43 months old (n = 13 in total). The necessary institutional ethics board approval was obtained. Informed consents were obtained from the parents for each child.

---- Insert table 2 about here ----

Participants were seen in two sessions approximately one week apart. Sessions took place in quiet rooms at the day cares or at the institutions participants were recruited from and were videotaped for subsequent analysis. In each of the sessions children were required to perform the robot mediated tasks 1 to 3B using a Lego® Mindstorms® TriBot physical robot and a matching virtual robot, with a 20 minutes recess between robots. Robot order was randomized ensuring a balanced number of participants starting with each robot and it was changed for the second session with each child. Tasks with both robots were presented to participants following the protocol in table 3. In this study, task 1 played the role of a familiarization task as children with cognitive ages of 33 months and more should all master cause and effect. The protocol for presenting this task to the participants thus included stages of modelling and exemplification since failure in executing task 1 reveals a resistance by the child to use the robot (e.g. from being afraid of using the robot or due to shyness). Modelling and exemplification stages were not included for the other tasks since the goal of the study was to evaluate participants' cognitive skills using the robot mediated tasks, and not to teach those cognitive skills.

---- Insert table 3 about here ----

The virtual robot was developed using Microsoft® Robotics Developer Studio[‡] (MS-RDS). MS-RDS is a widely available at no cost programming environment for building robotics applications. It includes a Visual Simulation Environment (VSE) to simulate and test robotic applications using a 3D physics-based simulation tool, thus allowing for the creation of robotic applications without the hardware. Moreover, robot control programs can be used either with the physical or the corresponding virtual robot. User-defined 3D virtual environments can be designed using VSE, and a scenario with a table inside a classroom with piles of blocks on it was created mimicking the physical scenario. Physical properties and sounds were added such that behaviour of the virtual objects matched the behaviour of the physical objects as closely as possible. For more details on the development of the virtual robot please refer to Encarnação et al. [23,24]. Figure 5 shows the experimental setups with the physical and the virtual robots. Participants controlled both robots through the same set of switches. The scenarios and the activities were similar in both cases, the only difference being that with the virtual robot action took place on a computer screen with virtual objects instead of on the table with physical objects, as with the physical robot.

--- Insert figure 5 about here ---

Participants with cerebral palsy were all able to access the three single switches used for robot control (they were all in levels 1 or 2 of the Gross Motor Function Classification System [25]).

Success rates in each task were registered by the investigator through a command console which controlled the robots and the switch inputs.

Videos from the experimental sessions were coded with i) behavioural markers: behavioural changes (out of context laughing or irritation), child rejects the activity, fatigue, stereotypes (repetitive movements or sounds), and echolalia; ii) interaction and communication markers: search for support, additional guidance, child's

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[‡] http://www.microsoft.com/robotics/

comments (referring to the activity), verbal and non-verbal expressions of displeasure and of pleasantness; and iii) cognitive construct markers: sustained attention, association of ideas, visuospatial and temporal perception, eye-hand coordination, and self-regulation/impulsivity. Table 8 describes how these markers were operationalized in the context of the proposed tasks. For the typically-developing participants' video analysis, only the cognitive construct markers, except for eye-hand coordination, were considered in the robot comparison. This is because the main goal of the study was to assess children's cognitive skills through the use of robot mediated tasks, while behavioural, interaction and communication, and eye-hand coordination aspects were not expected to be critical for this population. The use of behavioural analysis such as this has also been reported by Cook et al. [26], and by Dautenhaun and Werry [27] who called them "micro-behaviours".

Results—typically-developing children

Typically-developing participants' success rates in tasks 1 to 3B with both robots are plotted in figure 6. The three cognitive age groups are identified at the three vertical stripes corresponding to the age brackets 33-39, 45-51, and 57-63 months. Participants' success rates between 0 and 100% in each of the four tasks are presented on the same plot. A vertical comparison informs on the success rates for the different activities for a given cognitive age, while a horizontal comparison provides a task success rate analysis across ages. The two plots in figure 6 refer to the physical (top) and the virtual (bottom) robot.

--- Insert figure 6 about here ---

Despite having only a convenience sample, the small sample size, and the unbalanced design (different sample size in each sample group), a statistical analysis was conducted to get indicative answers to the following questions: i) Are success rates influenced by the robot? ii) Are success rates influenced by participant's cognitive age? and iii) Are success rates influenced by the task? A three-way main-effects repeated measures ANOVA [28] to assess the dependency of the success rates on the independent variables robot, cognitive age group, and task was conducted using SPSS®. In this analysis, task 1 success rates were not considered since, as expected, all participants had 100% success rates in this familiarization task. The within-subjects variables were the robot (physical or virtual) and the task (2, 3A, or 3B) and the between subjects variable was the cognitive age group (3, 4, or 5 years old). The p-values obtained are listed in table 4, showing that the factors cognitive age and task influence the success rates, while the robot factor does not. The p-values shown for the within-subjects effects (robot and task) hold assuming sphericity or not [28]. The p-value computed for the between-subject effect (cognitive age) assumes equality of error variances while Levene's test [28] does not support this assumption for the success rates in task 3A using the virtual robot (p=0.022), thus it should be interpreted with caution.

---- Insert table 4 about here ----

In order to refine the analysis, a-posteriori multiple comparisons were conducted computing 95% confidence intervals for the estimated marginal means with Bonferroni adjustment [28]. Table 5 shows the confidence intervals obtained. If a confidence interval contains the null value, one cannot reject the hypothesis that the group means are different at the confidence level of 95%, and the interval amplitude is indicative of the confidence one can have that the group means are in fact equal [29]. From table 5 one can thus conclude that the success rates are similar for the two robots, that the means across cognitive age groups only achieved significant differences between the three and the five years groups, and that the average success rates on tasks 2 and 3B and on tasks 3A and 3B were significantly different

Regarding the video analysis, Wilcoxon matched-pairs signed ranks tests [28] were used to compare the number of occurrences of the cognitive construct markers sustained attention, association of ideas, visuospatial and temporal perception, and self-regulation/impulsivity in the two environments. Significant differences for the markers sustained attention (better in the virtual environment, p=0.002), visuospatial and temporal perception (better in the virtual environment, p=0.014), and self-regulation/impulsivity (also better in the virtual environment, p=0.007) were found.

---- Insert table 5 about here ----

Results—children with cerebral palsy

Figure 7 shows the success rates of participants with cerebral palsy when performing tasks 1 to 3B using the physical (top) and the virtual (bottom) robots. Since the number of participants in each cognitive age group does not allow statistical assessment of the influence of cognitive age on the success rates, as was possible with the typically-developing sample, a two-way main-effects repeated measures ANOVA analysis was performed having the robot (physical or virtual) and the task (2, 3A, or 3B) as the within-subject variables. The p-values obtained are listed in table 6. A significant effect of the task factor is observed, while the robot factor had no significant effect on the success rates.

A-posteriori multiple comparison 95% confidence intervals with Bonferroni adjustment are shown in table 7. Again, there is evidence that the robot has no effect on the success rates, and the differences between the success rates in task 3B were significantly different from the success rates in tasks 2 and 3A.

---- Insert table 6 about here ----

---- Insert table 7 about here ----

In the video analysis, Wilcoxon matched-pairs signed ranks tests [28] for all the markers in table 8 revealed only one significant difference between utilization of the two robots for the marker visuospatial and temporal perception (one tailed p-value of 0.000, better with the virtual robot).

---- Insert table 8 about here ----

Discussion

Results show that participants' performance assessed by the success rates in each task as well as by the video analysis is similar or better with the virtual robot when compared to a matching physical robot. For the typically-developing participants, the video analysis conducted showed significant differences for the markers visuospatial and temporal perception, sustained attention, and self-regulation/impulsivity, with children performing better with the virtual robot. Visuospatial and temporal perception might be enhanced by the onscreen view of the virtual play environment, while the children's perspective of the physical environment may induce parallax errors (when objects appear in a different position due to the line of sight). The virtual environment has less distracting factors, which can promote sustained attention and self-regulation. However, only significant differences for the visuospatial and temporal perception marker were found for the participants with cerebral palsy. In spite of the fact that children's visual acuity was not assessed in this study, it is important to take into account that up to 70% of children with cerebral palsy have visual acuity problems which may affect perception [30].

Another important consideration is that 25% of children with cerebral palsy have behavioural and psychosocial problems [30] which can interfere with self-regulation. This study showed no significant differences between the physical and virtual robots regarding self-regulation. It was measured by observing if participants waited until the task explanation ended or the blocks were loaded onto the robot before performing an action. However, if only waiting until the blocks were loaded in task 2 was considered, significant differences would be found (p=0.031) for the participants with cerebral palsy. This might be a consequence of the fact that, with the physical robot, four blocks were loaded, two at a time, and participants were not informed of how many blocks would be loaded and thus they might have thought that they should take the two first blocks right away to the end of the table. With the virtual robot, loading of four blocks was done instantaneously.

The experimental data supports that children with cognitive ages above three years old are able to use a virtual robot to perform play activities. Task 1, which mainly requires the understanding of cause and effect, something that typically-developing children start mastering at approximately 8 months of age [26], had 100% success rates both with the physical and the virtual robot. Success rates in the other tasks varied with cognitive age, as predicted.

Though success rates in task 2 were not significantly different from success rates in task 3A, a visual inspection of figures 6 and 7 shows that there are performance differences in these activities for the three and four years cognitive age groups. Having participants in a continuum of cognitive ages, instead of only in relatively narrow age brackets, could have helped to capture the maturation of the cognitive skills.

The cognitive skills that can be potentially mapped through the use of these tasks allow children with disabilities to reveal understanding of important concepts often associated with more complex global skills such as problem solving. Problem-solving is a sequence of cognitive and perceptual actions and processes required to achieve a certain goal [10]. It includes acting prospectively, monitoring problems in performance that need to be solved in order to achieve the goal and changing strategies that are judged to be inefficient for achieving success. All of these skills can be assessed and adapted as needed when using robot tasks. Another part of problem-solving is to use spatial concepts to control the robot in multiple dimensions. The successful completion of the robot tasks requires that the child is able to transition from an egocentric frame of reference, i.e. the child needs to be able to place him/herself on the robot’s frame of reference in order to be able to control the robot since the switches make the robot move forward, left, or right relatively to the robot’s frame of reference.

Conclusions

The paper reports a study where typically-developing children and children with cerebral palsy utilized a physical robot and a matching virtual robot as tools to perform play activities. One basic conclusion from the study is that children with cognitive ages of three years and above are able to use a virtual robot to perform play activities in a simulated environment on a computer screen, as previous studies have shown they were able to do with physical robots. Additionally, the study revealed that the performance was similar for both the physical and the virtual robot. The proposed robot mediated activities were designed to require increasingly complex cognitive skills such that success rates in each activity would be an indicator of children cognitive understanding. The study results show that participants' performance varied with age thus validating this proxy measure of cognitive development within the context of the skills associated with tasks 1, 2, 3A and 3B. Limitations of the study include the small sample size and the limited number of cognitive skills encompassed in the tasks. Other aspects of virtual versus physical robots should also be addressed:

- Would teachers' and parents' perceptions that child is more skilled after seeing them use a virtual robot be the same as they have been with physical robots [7]?
- The use of physical robots by children with disabilities in classroom contexts, for example, has shown to promote children's integration [31]. Will that be the case for virtual robots?
- Would virtual robots motivate children to participate like the physical robots did?
- Are children's play experiences similar with both robots?
- Virtual robots cannot be used to explore children's own toys or their own room or house, or any real physical environment unless those objects and environments are included in the virtual scenarios.

It is also necessary to evaluate virtual robots use by children with severe motor impairments to assess if the absence of manipulation experiences or the need for different access methods (e.g. scanning) influences the results. Furthermore, the economic value of using virtual robots instead of physical robots may not have a great impact in countries where personal computers are not widespread (like in Colombia).

However, the study opens the doors to the investigation on the use of virtual robots as augmentative manipulation tools for cognitive development through the participation in play and academic activities.

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Declaration of interest

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References

1 Johnson M, Wilhelm C, Eisert D, Halperin-Phillips H. Assessment of children with motor impairments. In: Simeonsson R, Rosenthal S, editors. Psychological and developmental assessment. New York: Guilford; 2001. p. 205-224.

2 French J. Pictorial Test of Intelligence. 2nd ed. Austin: Pro-Ed; 2001.

3 Jennings K, MacTurk R. The motivational characteristics of infants and children physical and sensory impairments. In: MacTurk R, Morgan G, editors. Mastery motivation: Origins, conceptualization and applications. New Jersey: Ablex Publishing Corporation; 1995. p. 201-220.

4 Cook A, Adams K, Encarnação P, Alvarez L. The role of assisted manipulation in cognitive development. Developmental Neurorehabilitation. 2012;15(2):136-148.

5 Cook A, Encarnação P, Adams K. Robots: assistive technologies for play, learning and cognitive development. Technology and Disability. 2010;22(3):127-145.

6 Stanger C, Cook A. Using robotics to assist in determining cognitive age of very young children. In: Proceedings of the 12 Annual International Conference of the IEEE Engineering in Medicine and Biology Society; 1990; Philadelphia. p. 1911-1912.

7 Cook A, Adams K, Volden J, Harbottle N, Harbottle C. Using Lego robots to estimate cognitive ability in children who have severe physical disabilities. Disability and Rehabilitation: Assistive Technology. 2011;6(4):338-346.

8 Poletz L, Encarnação P, Adams K, Cook A. Robot skills and cognitive performance of preschool children. Technology and Disability. 2010;22(3):117-126.

9 Cook A, Polgar J. Cook & Hussey's Assistive Technologies: Principles and practice. 3rd ed. Philadelphia, PA: Elsevier Inc.; 2008.

10 Keen R. The development of problem solving in young children: A critical cognitive skill. Annual Review of Psychology. 2011;62:1-21.

11 Haywood K, Getchell N. Life span motor development. 5th ed. Illinois: Human Kinetics; 2009.

12 Buttelman D, Carpenter M, Call J, Tomasello M. Rational tool use and tool choice in human infants and great apes. Child Development. 2008;79(3):609–626.

13 Berger S, Adolph K, Lobo S. Out of the toolbox: Toddlers differentiate wobbly and wooden handrails. Child Development. 2005;76(6):1294–1307.

14 das Gupta P, Bryant P. Young children's causal inferences. Child Development. 1989;60(5):1138-1146.

15 Sobel D, Tenenbaum J, Gopnik G. Children's causal inferences from indirect evidence: Backwards blocking and Bayesian reasoning in preschoolers. Cognitive Science. 2004;28:303-333.

16 Gopnik A, Sobel D, Schulz L, Glymour C. Causal learning mechanisms in very young children: Two-, three-, and four-year-olds infer causal relations from patterns of variation and covariation. Developmental Psychology. 2001;37(5):620-629.

17 Morasch K, Bell M. The role of inhibitory control in behavioral and physiological expressions of toddler executive function. Journal of Experimental Child Psychology. 2011;108(3):593-606.

18 Barkley R. Behavioral inhibition, sustained attention and executive functions: Constructing an unifying theory of ADHD. Psychological Bulletin. 1997;121(1):65-94.

19 Rigal R. Right- left orientation: Development of correct use of right and left terms. Perceptual and Motor Skills. 1994;79:1259-1278.

20 Corballis M, Beale I. The psychology of left and right. Hillsdale, NJ: Erlbaum; 1976.

21 Buchsbaum D, Gopnik A, Griffiths T, Shafto P. Children's imitation of causal action sequences is influenced by statistical and pedagogical evidence. Cognition. 2011;120(3):331-340.

22 Williamson R, Jaswal V, Meltzoff A. Learning the rules: Observation and imitation of a sorting strategy by 36-month-old children. Developmental Psychology. 2010;46(1):57-65.

23 Encarnação P, Piedade G, Cook A, Adams K, Gil I, Maya C, Azevedo L, Londral A, Rodrigues S. Virtual robot and virtual environments for cognitive skills assessment. In: Gelderblom G, Soede M, Adriaens L, Miesenberger K, editors. Everyday technology for independence and care - AAATE 2011, Assistive Technology Research Series; 2011; Maastricht. p. 508-516.

24 Encarnação P, Piedade G, Cook A, Adams K. Virtual assistive robot for play. In: Proceedings of AT 2012 - 2nd IASTED International Conference on Assistive Technologies; 2012; Innsbruck. p. 842-848.

25 Palisano R, Rosenbaum P, Bartlett D, Livingston M. Gross Motor Function Classification System - extended and revised. CanChild Centre for Childhood Disability Research; 2007.

26 Cook A, Hoseit P, Liu K, Lee K, Zenteno-Sanchez Z. Using a robotic arm system to facilitate learning in very young disabled children. IEEE Transactions on Biomedical Engineering. 1988;35(2):132-137.

27 Dautenhahn K, Werry I. A quantitative technique for analyzing robot-human interactions. In: Proceedings of the 2002 IEEE International Conference of Intelligent Robots and Systems; 2002; Lausanne. p. 1132-1138.

28 Sheskin D. Handbook of parametric and nonparametric statistical procedures. 5th ed. Chapman & Hall/CRC; 2011.

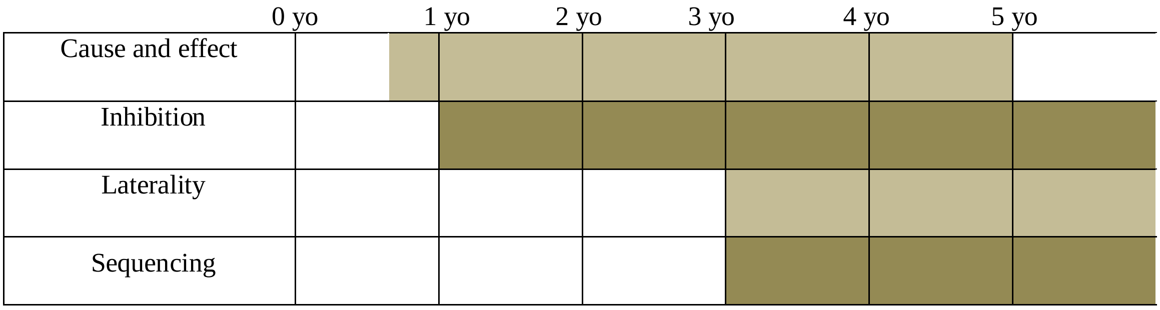
29 Hoenig J, Heisey D. The abuse of power: The pervasive fallacy of power calculations for data analysis. The American Statistician. 2001;55(1):19-24.

30 Imms C, Dodd K. What is cerebral palsy? In: Dodd K, Imms C, Taylor N, editors. Physical and occupational therapy for people with cerebral palsy: A problem based approach to assessment and management. London: MacMeith Press; 2010.

31 Adams K, Cook A. Using an augmentative and alternative communication device to program and control Lego robots. In: Proceedings of the RESNA Annual Conference; 2009; New Orleans.

List of tables

Table 1: Ages intervals at which the main cognitive skills underlying the proposed robot tasks are acquired



	0 yo	1 yo	2 yo	3 yo	4 yo	5 yo
Cause and effect	░	░	░	░	░	
Inhibition		▓	▓	▓	▓	▓
Laterality				░	░	░
Sequencing				▓	▓	▓

Table 2: Study participants by cognitive age group

	[33, 39] months	[45, 51] months	[57, 63] months	Total
Typically-developing participants	5	8	7	20
Participants with cerebral palsy	5	2	2	9

Table 3: Experimental sessions' protocol

	Instruction		
Level of Prompting	**Task 1 – Cause and effect**	**Task 2 - Inhibition**	**Task 3 – Binary Choice & Sequencing**
A - No prompting	Let's see what we have here for you to play with. Look: there we have a pile of blocks, here a truck (the robot) and here a switch. *(pointing to each).* In a little while, you get to drive the truck. *(physical robot)* Would you like to press this *(pointing to the orange button on the truck)* to turn on the truck? Ok! Well-done! Are we ready to start? Can you drive the truck right down here (*pointing out the route*) and knock that pile of blocks? *Give the child 15seconds before prompting.* *If task is completed: repeat task (2nd trial) and, if completed again, move to 2A.* *If in need of further prompting, move to 1B.*	Ok. Now how about you help me build the stack of blocks? Can you help me take these blocks from here (*pointing*) to there (*pointing*)? Ready? Ok. So now we're going to drive the truck, and we need to stop here *(pointing to where the blocks are)*, so I can put these blocks on the truck. *If the child stops the truck at the correct place (beside the blocks), place the blocks on the truck and provide the child with the instruction for the next step:* Well done! Now let's drop off the blocks at the end here *(point to exactly where they should stop)* *Give the child 15seconds before prompting.* *If in need of further prompting, move to 2B.*	Now we have a pile of blocks here (*pointing*) and another over there (*pointing*). Which would you like to knock over first? *Make sure the choice is clear for both the child and the investigator.* OK! Now you have three switches *(pointing to the switches so as to ensure the child is aware of them).* Go ahead! *Give the child 15seconds before prompting* *If in need of further prompting, move to 3B.*
B - Prompting by clarifying steps and/or explicitly referring to the switches	Do you think this button will do something? *Give the child 15seconds before prompting.* *If task is completed: repeat task (2nd trial) and, if completed again, move to 2A.* *If in need of further prompting, move to 1C.*	*1. If the child does not stop the truck by the blocks, and it drives to the end of the table: Place the truck at the starting position and provide the child with the cue:* Good try! Remember we have to stop right here *(pointing to where the blocks are).* *2. If the child stops, but too far behind:* Good try! That was close. Do you think you can stop even closer? – right here (*pointing to where the blocks are*). *3. If the child stops, but too far ahead:* Good try! That was close. Now let's try again and see if we can get even closer. *(Place the truck back at the starting position).* Do you think you can stop even closer? – right here (*pointing to where the blocks are*). *If task is completed: repeat task (2nd trial) and, if completed again, move to 3A.* *If task is not completed, stop, and move onto 3A.*	*1. If the child does not decide upon a switch to turn the truck or presses the wrong button (thus, not demonstrating binary choice):* *Place the truck in the starting position of this task and say:* Remember you have three buttons you can use *(pointing to all three, so as to ensure that by looking, the child becomes more aware of all three buttons).* *2. If the child succeeds in the binary logic task (turns in the right direction), but persists with the same switch for the sequencing task:* *Place the truck in the starting position of this task and say:* Well done! You turned the right way. Now, remember you have three buttons you can use *(pointing to all three, so as to ensure that by looking, the child becomes more aware of all three buttons).*
C - Modelling	*If the child does not press the switch, the investigator should model the task by pressing the switch and then have the child try the task.* *If task is completed: repeat task (2nd trial) and, if completed again, move to 2A.* *If in need of further prompting, move to 1D.*		
D - Exemplification using hand-over-hand support)	*If the child continues not pressing the switch, exemplify using child's hand to press the switch.* *If there is no collaboration on the child's part, end the activity. After an interval, attempt with the other robot.*		

Table 4: Typically-developing participants' data—Three-way main-effects repeated measures ANOVA results

	Cognitive age group	Tasks	Robot
p-value	0.023	0.000	0.962

Table 5: Typically-developing participants' data—A-posteriori multiple comparison 95% confidence intervals for the mean differences

Robot (physical/virtual)
]-0.075, 0.072[

Cognitive age groups	4 yo	5 yo
3 yo	]-0.435, 0.120[	]-0.614, -0.044[
4 yo		]-0.424, 0.080[

Tasks	3A	3B
2	]-0.138, 0.278[	]0.158, 0.622[
3A		]0.137, 0.503[

Table 6: Participants with cerebral palsy data—two-way main-effects repeated measures ANOVA results

	Task	Robot
p-value	0.000	0.454

Table 7: Participants with cerebral palsy data —A-posteriori multiple comparison 95% confidence intervals for the mean differences

Robot (physical/virtual)
]-0.079, 0.160[

Tasks	3A	3B
2	]-0.087, 0.500[	]0.284, 0.805[
3A		]0.027, 0.648[

Table 8: Video analysis—markers operationalization

	Marker	Operationalization
Behavioural markers	Behavioural changes (out of context laughing or irritation)	Self-explanatory
	Child rejects the activity	Self-explanatory
	Fatigue	Yawning, resting head on arms, and alike where taken as fatigue indicators
	Stereotypes (repetitive movements or sounds)	Self-explanatory
	Echolalia	If participant automatically repeated vocalizations made by the researcher
Interaction and communication markers	Search for support	Participant asked for help and asked or looked for approval
	Additional guidance	If additional guidance was given to the participant
	Child's comments (referring to the activity)	If participant made a verbal comment
	Verbal expression of pleasantness	Self-explanatory
	Non-verbal expression of pleasantness	Self-explanatory
	Verbal expression of displeasure	Self-explanatory
	Non-verbal expression of displeasure	Self-explanatory
Cognitive constructs markers	Sustained attention	Number of times the participant looked away from the task stimuli for more than 3 seconds
	Association of ideas	Intentionally looked at the switch after the task explanation
	Visuospatial and temporal perception	Stopped right beside the stack of blocks
	Eye-hand coordination	Pressed the switch after looking at it
	Self-regulation/Impulsivity	Pressed switches before or during the instruction or while the researcher placed the blocks on the robot

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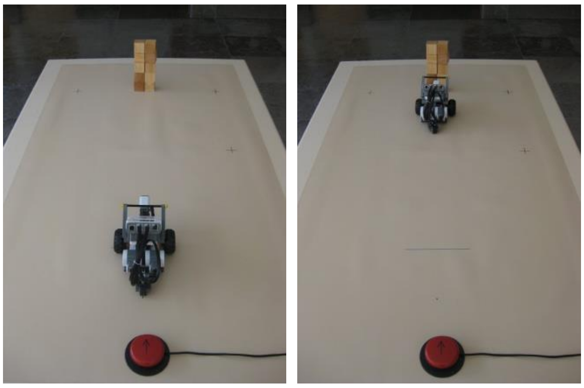


Figure 1: Task 1 – Cause and effect

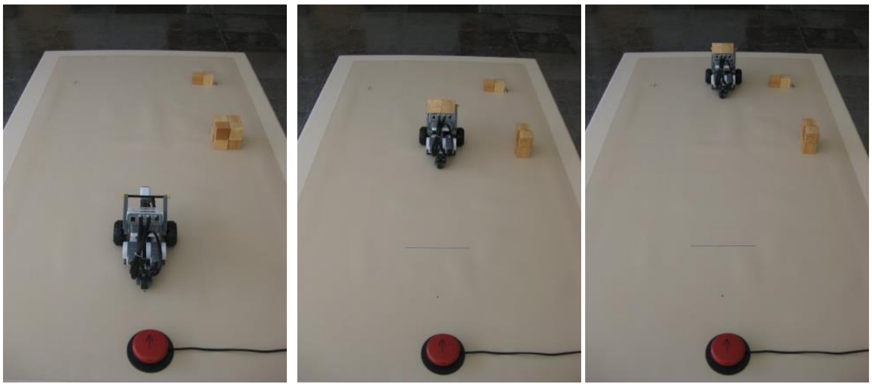


Figure 2: Task 2 – Inhibition

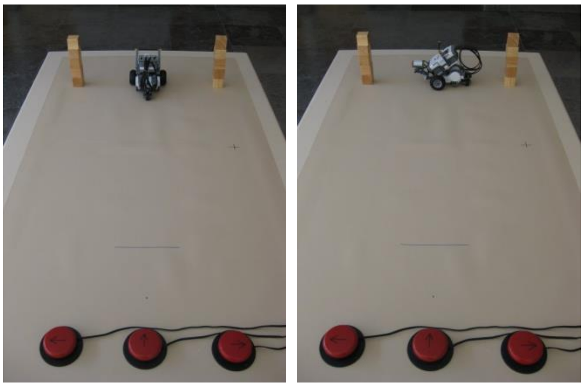
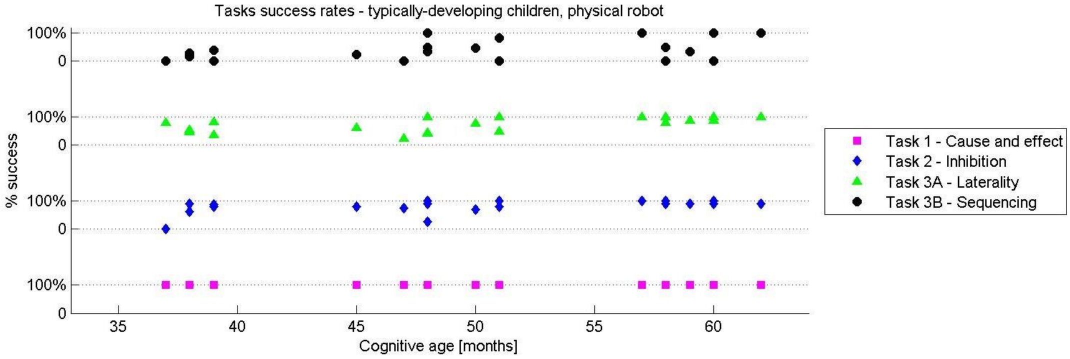


Figure 3: Task 3A – Laterality

Figure 4: Task 3B – Sequencing

Figure 5: Experimental setups with the physical and the virtual robots



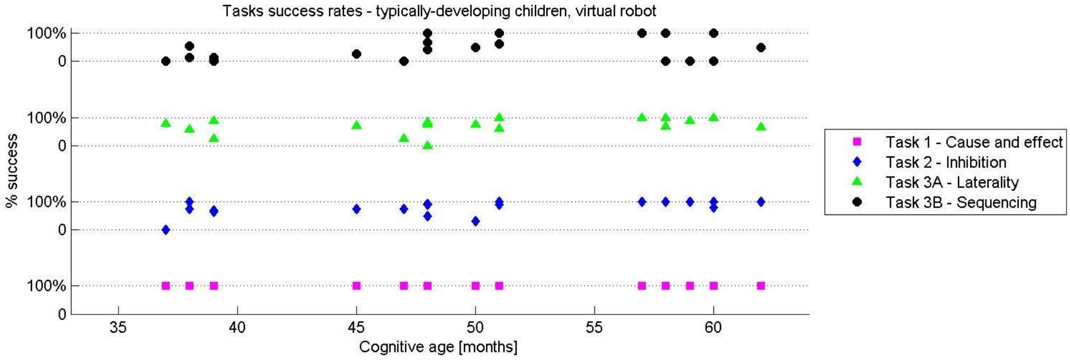


Figure 6: Typically-developing participants' success rates in tasks 1 to 3B

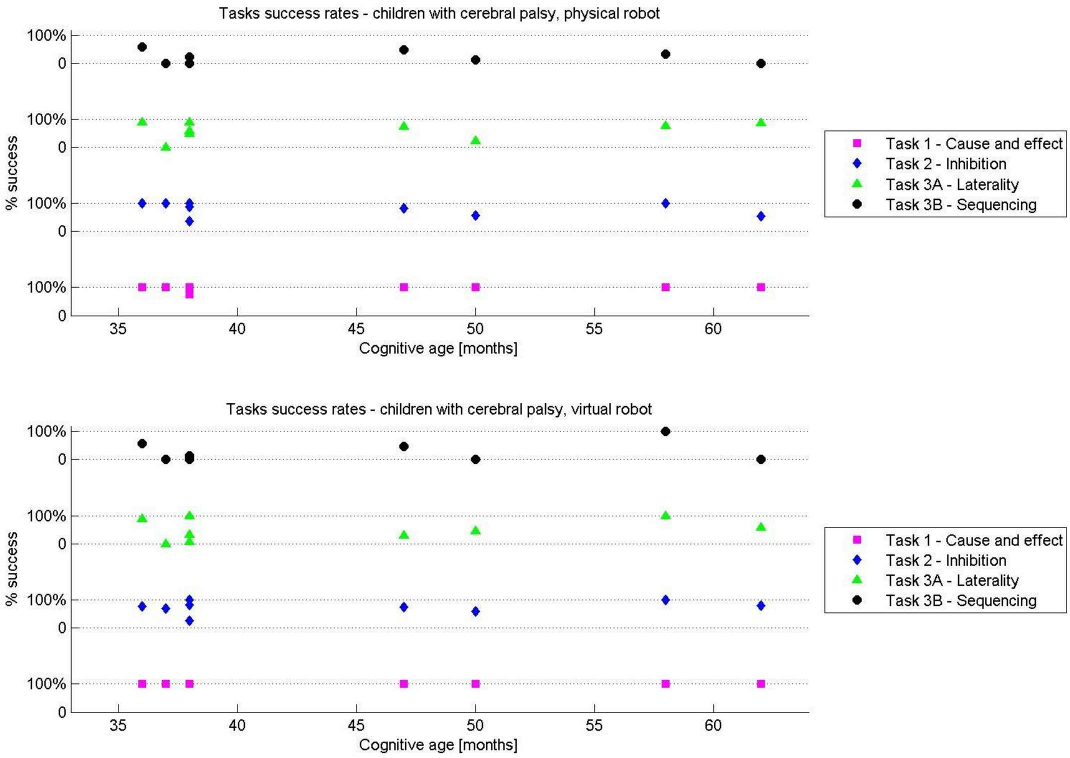


Figure 7: Participants with cerebral palsy success rates in tasks 1 to 3B