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Multi-touch gestures for pre-kindergarten children ☆

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ABSTRACT

The direct manipulation interaction style of multi-touch technology makes it the ideal mechanism for learning activities from pre-kindergarteners to adolescents. However, most commercial pre-kindergarten applications only support tap and drag operations. This paper investigates pre-kindergarteners' (2–3 years of age) ability to perform other gestures on multi-touch surfaces. We found that these infants could effectively perform additional gestures, such as one-finger rotation and two-finger scale up and down, just as well as basic gestures, despite gender and age differences. We also identified cognitive and precision issues that may have an impact on the performance and feasibility of several types of interaction (double tap, long press, scale down and two-finger rotation) and propose a set of design guidelines to mitigate the associated problems and help designers envision effective interaction mechanisms for this challenging age range.

1. Introduction

Multi-touch technology has made great advances in recent decades, since its initial steps in the eighties, even before the adoption of graphical user interfaces, to its widespread acceptance today (Buxton, 2013). It now offers new sophisticated input and processing mechanisms that enable users to interact in a more natural and intuitive way (Smith et al., 2012). In fact, they are so natural and intuitive they have triggered a new approach to developing applications for children even younger than was previously thought possible. Rideout (2011) pointed out that even very young children (between 0 and 8) are frequent digital media users in the USA. For instance, her study showed that 38% of them had used a Smartphone, iPad or similar device at least once. Among this group, 10% were between 0 and 23 months and 39% between 2 and 4 years old. The Horizon report (Johnson et al., 2012) supports this evidence and identifies mobile devices (smartphones and tablets) as one of the two emerging technologies suitable for children under two years old.

In order to provide users with natural and intuitive multi-touch systems, the direct manipulation interaction style and direct-touching are used. As Shneiderman and Plaisant (2004) pointed out, there are three ideas behind the concept of direct manipulation: (1) visibility of objects and actions of interest; (2) replacement of typed commands by pointing-actions on objects of interest; and last but not least, (3) rapid, reversible and incremental actions that help to keep children engaged, give them control over the technology and avoid complex instructions. On the other hand, direct-touch, as Hourcade (2007) stated, is preferred over mediated pointing devices like the mouse, as it provides a more direct way of selecting options on the screen. Moreover, as Couse and Chen (2010) stated, young children became totally engaged in their learning activities, even though they have to overcome certain technical difficulties.

This inherent ability of touch systems to engage children's attention is being widely exploited to promote learning activities from pre-kindergarteners to adolescents. For example, Mansor et al. (2009) have shown that tabletops can be operated by children as young as three and that there is no significant difference between learning in a real or virtual environment. Other studies (Sluis et al., 2004; Khandelwal and Mazalek, 2007; Tyng et al., 2011) have shown that this technology can be used by children between three and seven to learn to read, solve mathematical problems, develop a sense of space, etc. Other studies have demonstrated that the technology can also be used to promote collaboration between peers (Rick and Rogers, 2008; Fleck et al., 2009; Rick et al., 2010; González et al., 2001; Alessandrini et al., 2014) and to foster creativity (Helmes et al., 2009; Catala et al., 2012).

However, the increasing interest in multi-touch technology has not as yet given rise to studies on the design of multi-touch systems for the youngest age range, as Hourcade (2007) has pointed out. Ingram et al. (2012) also concluded that although the set of multi-touch interactions that users and developers instinctively and unanimously agree upon is small (consisting of

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only one-finger touch for selection and one-finger drag for movement, and other fundamental tasks), the lack of standardized and universally accepted interactions makes the need for well-designed multi-touch interactions even more crucial.

In addition, such studies should be carefully designed as, according to Wolock et al. (2006), knowledge of children's developmental abilities is particularly important when designing software for the very young. This is especially relevant because, as these authors found, children between 18 and 30 months of age can use touch-screens under supervision. Therefore, studies that focus on pre-kindergarteners and older pre-school children must be carried out in order to provide them with technology specially tailored to their needs.

This paper thus addresses the fundamental question of the ability of pre-kindergarteners to perform gestures other than basic tap and drag operations on multi-touch surfaces. We also aim to identify any issues that would require bespoke solutions specifically tailored to the needs of the very young.

The contributions of this work are manifold. The first contribution is a review of 100 commercial applications of multi-touch devices for pre-kindergarteners which reveals that most existing educational applications for these users only support tap and drag interactions. The second contribution is the experimental confirmation that pre-kindergarteners' abilities are by no means limited to these two basic actions, but they can also perform one-finger rotation and two-finger scale up and scale down, with equivalent success rates to those observed for the tap and drag gestures, despite gender and age differences. The third contribution is the identification of cognitive and precision issues that may have an impact on the performance and usability of several types of interaction. Finally, the fourth contribution is a set of design guidelines to mitigate the cognitive and precision-related issues identified in the course of this work, aimed at helping designers to envision effective interaction mechanisms for this challenging age range.

2. Related work

Interesting studies can be found in the literature that focus on the direct manipulation interaction style and have children as target population. For instance, Donker and Reitsma (2007) analyzed whether 6–7 year-old children made more errors while using a mouse to drag and drop than university students, and concluded that children were less skillful than adults, although most of their mistakes were due to the size of the destination area and the direction of the movement and not to the need to keep the mouse button pressed. The most frequent cause of these errors was their less developed fine motor abilities and eye–hand coordination. The shape of the mouse, which had been designed with adults in mind, was also identified as another cause of error.

Other interesting studies have examined the use of a tablet stylus for direct manipulation-interaction. For instance, Terra et al. (2009) worked with children aged from 9 to 11, and Couse and Chen (2010) with subjects between 3 and 6, in tests to see whether they could use a stylus for learning activities. These studies concluded that the stylus interaction learning period was relatively short and that the stylus had advantages over the alternatives.

Finally, still other studies focused on schoolchildren using both direct manipulation interaction and direct touching. For instance, Kharrufa et al. (2010) presented a design process, grounded on both collaborative interaction and learning theories, for a collaborative learning application for 10–13 year-old children on tabletops. Their study shows the overwhelming superiority of tabletops for creating collaborative learning tools and gives some interesting guidelines for their development. Harris et al. (2009) analyzed the differences between single-touch and multi-touch interaction in 7–10 year-old children's groups and found that although touch did not affect the interaction in terms of frequency or equity, it did influence their communication and encouraged them to talk to each other about their joint actions. Yu et al. (2010) assessed the design of the interaction aspect of touch screens in order to develop digital educational games. They tested the effectiveness of 5–6 year-olds in four game prototypes while dragging, clicking, rotating and zooming in and out. Their results indicated that pre-school children were not familiar with rotating and zooming and that they needed at least six minutes of training time. They also found that the main cause of the problem was the gap between the sensitivity of the device and the precision of the action required for the game. One of their negative findings was that more than half of the children rested their non-operational hand on the screen while using the interface.

Other studies have focused on pre-school children. For instance, Shoukry et al. (2012) defined a set of guidelines applicable to designing educational games for this group. Mansor et al. (2008) compared the interaction of 3–4 year-olds on a tabletop and in a physical setting. They concluded that children found it difficult to drag objects on the surface, mainly due to bad posture and suggested they should remain standing during these operations.

Other meaningful approaches, such as Rubio et al. (2014), (Hourcade et al. (2011), Weiss et al. (2011) and Piper et al. (2006), focused on the use of touch-screens by children with some type of cognitive disorder. They showed that it is possible to obtain significant results, especially in promoting collaboration and motivation, although these studies cannot be taken as a reference for normal children's behaviour with touch-screens.

It can be seen from the above that touch-screen technology opens up a whole new world of possibilities for pre-school learning applications. This technology solves the problems inherent in other interaction devices, such as those involving mouse or keyboard, as it enables them to take advantage of both the direct manipulation interaction style and direct touch. Unfortunately, as far as we know, studies to date have only tested children over 3 years old, probably because age is a limiting factor; younger children do not have the verbal and cognitive skills to express their likes and preferences (Kremer, 2012), nor are they able to carry out tasks for long periods and are easily distracted (Egloff, 2004). However, according to Piaget (1973), children nowadays are in a preoperational stage from 2 years old onwards, i.e., they begin (1) to think in terms of images and symbols, and (2) develop symbolic play with imaginary objects, which means they could be candidates for multi-touch technology.

This led us to the main research question of this work: What multi-touch gestures are children between two and three years of age able to utilize? This paper provides an answer to this question by analyzing the most suitable gestures for pre-kindergarteners in terms of completion time and success.

2.1. Commercial perspective on multi-touch technology

The previous section carried out a review of some of the most interesting studies from a research perspective. However, it is also worth considering the commercial perspective of multi-touch technology and describing the two most popular currently available operating systems supporting multi-touch interaction: Android (Google, 2013) and iOS (Apple, 2013).

Regarding Android, we analyzed 100 educational applications,[1] available to download from the Android AppStore, to determine the types of gestures used in these applications. The applications were

[1] Analysis of 100 Educational Applications http://issi.dsic.upv.es/Members/fjaen/ijhcs/RevisedGames.pdf.

randomly selected from the collection of pre-school educational applications. Some of our most interesting conclusions are the following:

- There are three recurrent learning topics in these applications: *numbers and math*, 35 applications revolve around this topic; *words and language*, 35 applications focus on this topic; and *colors and shapes*; with 20 of the applications involving this topic. Some of the applications focus on other learning activities, such as types of animals or fruits.
- Regarding the learning methods (see Fig. 1); 55 applications use *learning by reinforcement* or *repetitive* methods, which consist of the repetition of the desired behavior with a positive or negative reinforcement according to the learner's performance (Laird, 1985); 48 applications use receptive methods in which learners have to understand the content but do not discover anything new; and only five applications use active methods in which children have an active role in discovering the concepts and their relationships and adapting them to their cognitive schema (Michel et al., 2009). An example of the active method is the “Kids basic patterns” application, developed by Fun4Kids in which a shape appears following a pattern, a space and three options; the kids should choose the correct shape that fits the pattern.
- Gestures: only three types of gestures are currently used (Fig. 2). The *one-finger tap* is used in 99 of the analyzed applications, and the *one-finger drag* in 56. Only three applications use an accelerometer for interaction. It is worth noting that only two of the analyzed applications, “Animals Memory Game” and “KidMath”, enable multiplayer mode (two players). These are also the only ones that allow the simultaneous interaction of two hands (one per participant).

A detailed analysis of iOS can be found in Shuler (2012). One of this study's most interesting conclusions is that 72% of the top-selling apps developed for iOS are aimed at children, with toddlers/pre-schoolers being the most popular age group (58%). This category has also experienced the greatest growth (23%), even higher than that of apps designed for adults, which shows the market importance of this target population and the potential to offer new solutions to these users. The report also highlights the need for a research agenda that guides developers and researchers towards creating effective, high-quality products.

Two main conclusions can be drawn from these results: firstly, there is clear confirmation of an important commercial trend in developing apps for children with touch-screen technology, mainly for learning activities. This highlights the need for empirical studies to help in the design of apps that adequately support children's development, as other authors have pointed out (Shuler, 2012). Secondly, but no less important, the results of the analysis of the Android Store (Fig. 2) show that this technology is not being fully exploited for pre-school learning, as the supported gestures involved are too limited. Defining design guidelines that enable infants to take full advantage of multi-touch technology would make it possible to develop attractive new applications and eventually could also aid children's cognitive and motor development. We should highlight that designers and developers will make the final decision about the most appropriate gestures for their future apps according to other factors, such as cost or time to market, no matter what the results of this study are. Hopefully, the design guidelines proposed in this work will empower them to take a step forward in their developments.

3. Experimental study

The overall goal of our experimental study was to identify gestures suitable for pre-kindergarten children and to determine those best suited to future tablet applications targeted at children. Therefore, using the Goal Question Metric (GQM) template (Basili et al., 1994), our goal can be defined as follows: *analyze* a set of multi-touch gestures *for the purpose* of evaluating their suitability *from the viewpoint* of usability in multi-touch technologies *in the context of* pre-kindergarten children. For this study we used children of both genders of between 2 and 3 years of age. We were interested in finding out whether certain gestures should be focused on a specific target gender, leading to further study on gender-based market segmentation. A specific age range was considered for the purposes of developmental issues. According to developmental theories, children are continuously developing and refining their motor skills between 2 and 7 years of age (Piaget, 1973). As we were more interested in exploring how gestures are learned and performed by very young children, we put the upper age limit at three years old. *Gender* and *the 2–3 age group* were thus the two main independent variables considered. Completion time and success rate were the two measured dependent variables for each task (tap, double tap, long pressed, drag, scale up, scale down, single rotation, one-finger rotation, two-finger rotation). Consequently, the hypotheses to be statistically tested, which were defined for each task performed (type of gesture), were formulated as follows:

- H_1: Completion time of task k is not affected by gender.
- H_2: Completion time of task k is not affected by age group.
- H_3: The degree of success for task k is independent of gender.
- H_4: The degree of success for task k is independent of age group.
  We also defined another hypothesis related to the homogeneity of the success rates of the different tasks:
- H_5: The degree of success is independent of the task.

In order to test these hypotheses, we measured the manipulation time of each gesture as well as its success, with the ultimate goal of obtaining a set of guidelines specifically focused on designing touch-enabled applications for very young children.

3.1. Participants

Thirty-two children aged between 24 and 38 months took part in the experiment (Mean (M)=31.34, Standard Deviation (SD)=4.24). The genders of the children were balanced, with 16 males and 16 females. Parental authorization was obtained before carrying out the study. The children were divided into two age groups: 24–30 months and 31–38 months, with 8 males and 8 females per group. We involved participants in the 2-to-3 age range from two Spanish nursery schools in order to explore how gestures are acquired and performed by children in the earliest stage of development. This age range corresponds to the first Spanish early education program for children between one and three. The starting age of our study is considered to be the start of the development of fine-grained motor skills (Piaget, 1973).

3.2. Apparatus

The interaction framework for the experiment was implemented in Java using JMonkeyEngine SDK v.3.0beta. The devices used for deployment and the experiment were a Motorola MZ601 and a Samsung Galaxy Note 10.1 tablet with Android 3.2 both with capacitive multi-touch screens.

3.3. Procedure

For each task, the children were given a 5-minute learning phase with an instructor. The experimental platform then asked

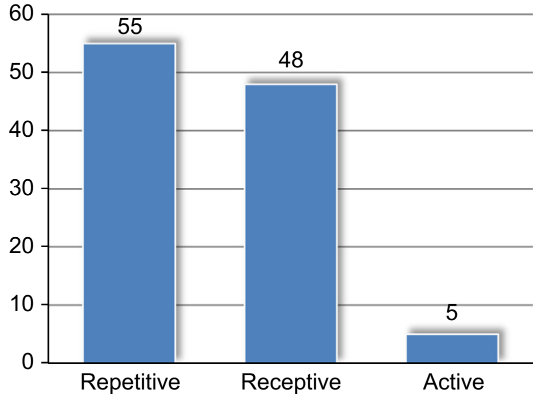

Fig. 1. Learning methods.

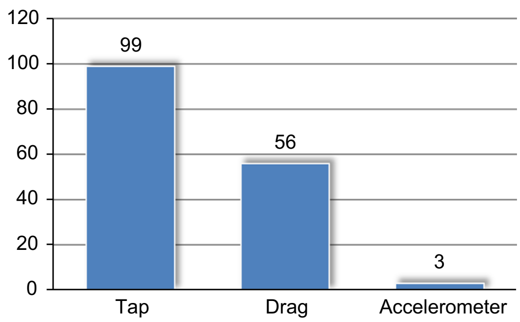

Fig. 2. Supported interactions.

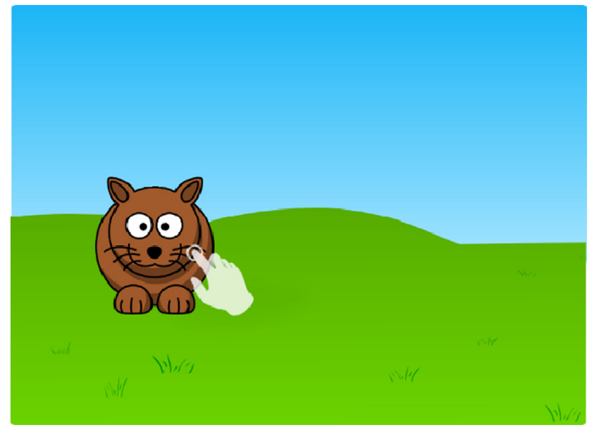

Fig. 3. Example of a simple tap, double tap or long pressed test.

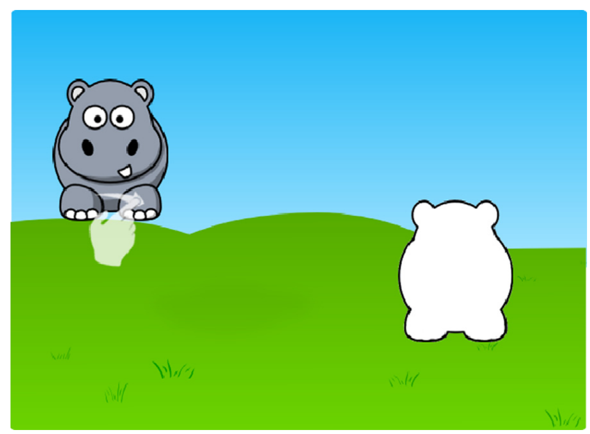

Fig. 4. Example of a drag test.

them to perform the task without any assistance. They had to perform three repetitions of each gesture under specific conditions (see Section 4). When the gesture was completed successfully, the platform gave a positive audiovisual feedback. If the instructor saw that the participant did not carry out the task in a given time, it was marked as undone and the child went on to the next one.

For each interaction, the system recorded the start time (seconds needed to go into action after the visual stimulus was shown), completion time, success (performed correctly or incorrectly), and the number of contacts with the surface (in order to know in an unsuccessful action whether the user had made any attempt to interact). A qualitative analysis was also carried out from the notes taken by an external observer during the experimental sessions.

4. Tasks

4.1. Task 1: tap

A static image of an animal appears in a random position on the screen (see Fig. 3). Participants are requested to tap on the target image in order to pass the test.

4.2. Task 2: double tap

A static image of an animal appears in a random position on the screen (see Fig. 3). Participants are requested to double tap on the target image with one finger in order to pass the test. The task will succeed when the participants perform two taps in under 300 milliseconds, which is Android's default time interval for this gesture.

4.3. Task 3: long pressed

A static image of an animal appears in a random position on the screen (see Fig. 3). Participants are requested to carry out a long pressed gesture on the target image until the target disappears. The task will succeed when the participants put their finger on the target image and hold it for at least 500 ms, which is Android's default time interval for this gesture.

4.4. Task 4: drag

A static image of an animal appears in a random position on the screen and the same (reference) image appears in a white profile in another random position, always at a distance of 378 pixels so as to be able to compare execution times among the different subjects (Fig. 4). The random position of the reference image is subject to some geometric restrictions, to make sure that it is completely visible on the surface. Participants are requested to drag the target to the reference image with one finger. The task will succeed when the target image reaches the location of the reference image with a precision of less than 10 pixels on each X and Y axis. It is not necessary for the subject to lift his/her hand to reach success.

4.5. Task 5: scale up

A static image of an animal appears in the center of the screen within a similar but 1.5 times larger reference shape (see Fig. 5a). Participants are requested to scale up the target image to the size of the reference shape. This can be done by expanding the distance

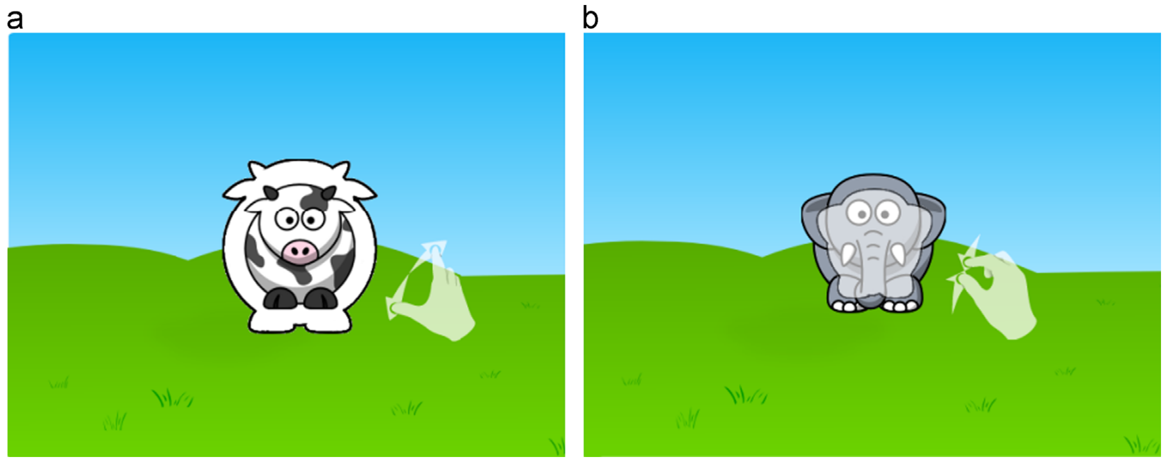

Fig. 5. Example of a scale test: (a) scale up and (b) scale down.

between two fingers of either one hand or two hands. The fingers do not have to be in contact with the reference image and the scaling factor applied is the incremental value returned by the JMonkeyEngine runtime for this gesture. If more than two contacts are made on the surface, JMonkeyEngine considers only the two most recent ones for communicating scaling events. The task will succeed when the target image reaches the size of the reference image, not being necessary for the subject to lift his/her hands when the size of the target image is reached.

4.6. Task 6: scale down

A static image of an animal appears in the center of the screen superimposed on a similar reference shape half its size (see Fig. 5b). Participants are requested to scale down the target image by making the target object shrink until it reaches the size of the reference image with two fingers of either one or two hands. The task will succeed when the target image reaches the size of the reference image as in the previous case.

4.7. Task 7: one-finger rotation

A static image of an animal appears in the center of the screen in front of a blank profile of the same image in a different orientation. Rotation is always clockwise to a fixed position so as to be able to compare interaction execution times among subjects (see Fig. 6). Participants are requested to rotate the target image to the position of the reference image by dragging one finger around the center of the target image. Pressure can be applied on the target image itself or anywhere around it. The task will succeed when the target image reaches an angle larger than the specified goal which is automatically detected by the system to produce the positive audiovisual feedback.

4.8. Task 8: two-finger rotation

A static image of an animal appears in the center of the screen in front of a blank profile of the same image but always rotated clockwise to a fixed position, so as to be able to compare interaction execution times among subjects (see Fig. 7). Participants are requested to rotate the target image with two fingers until it reaches the position of the reference image. The task will succeed when the target image reaches the orientation of the reference image. The system detects this situation and produces the visual reward, it not being necessary for the subject to lift his/her hands.

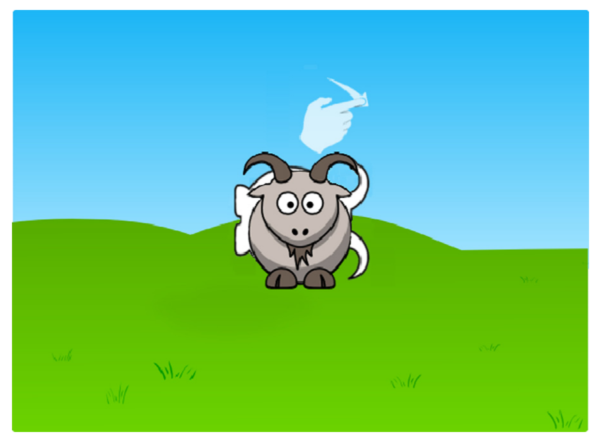

Fig. 6. Example of a one-finger rotation test.

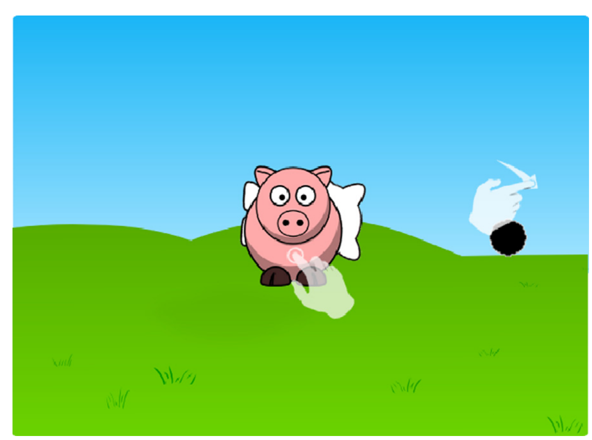

Fig. 7. Example of a two-finger rotation test.

The children were initially asked to use two fingers in pilot tests, although this was soon discarded because they were found to touch the screen with the whole hand, not just the fingers, producing multiple contacts on the surface. As the task thus became unfeasible, this led us to ask the children to touch and hold one finger on the target image, at which point a black spot appeared on the right of the screen. They then had to rotate one finger around the black spot until the image reached the orientation of the reference shape. If the finger was not kept on the target before the correct position was reached, the black point disappeared and the rotation was disabled until the participant again touched the target object.

5. Results

This section presents the results of the experimental tests, according to each of the analyzed independent variables. Completion time is dealt with in Section 5.1 and the success rate in Section 5.2. The tasks are compared in Section 5.3 and the qualitative results are presented in Section 5.4.

5.1. Completion time

The three trials carried out by each participant were combined to perform the subsequent analysis. The average of each subject's successful tasks is used to obtain the average completion time value per task and user. If the test is not performed successfully it is not included in the completion time analysis, resulting in different statistical degrees of freedom for each task. Mean completion time for each task is presented in Tables A1 and A2 (see Appendix A) by age group and gender. The results are also shown graphically in Figs. 8 and 9.

Table 1 shows the tested hypotheses in relation to completion time. The application of a two-way between-subject ANOVA with the independent variables *gender* and *age group* and dependent variable *completion time* demonstrated that it is not significantly influenced by gender (see Table 2), so that Hypothesis H_1 cannot be rejected for any of the tasks. The analysis also showed that completion time is not significantly influenced by the interaction of the gender and age group factors, meaning that H_{12} cannot be rejected either (Table 2).

The analysis also demonstrated that the double tap, drag, scale down and one-finger rotation tasks are significantly influenced by the age group factor (p-value<0.05), so that Hypothesis H_2 is rejected for these tasks. The participants in the second age group (31–38 months) performed these gestures faster than those in the first group (24–30 months).

On the other hand the tap, long pressed, scale up and two-finger rotation tasks are not significantly influenced by the age group factor and, consequently, H_2 cannot be rejected for them. Nevertheless, on average, these gestures are performed faster by the second age group, as can be seen in Fig. 8. The results therefore show that, in the analyzed age range, the older participants are faster at performing the tasks.

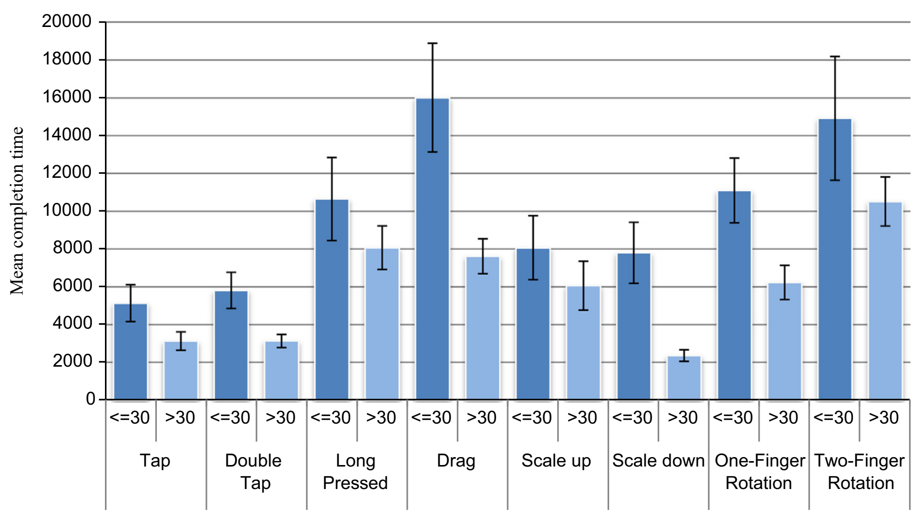

Fig. 8. Mean completion time by task and by age group.

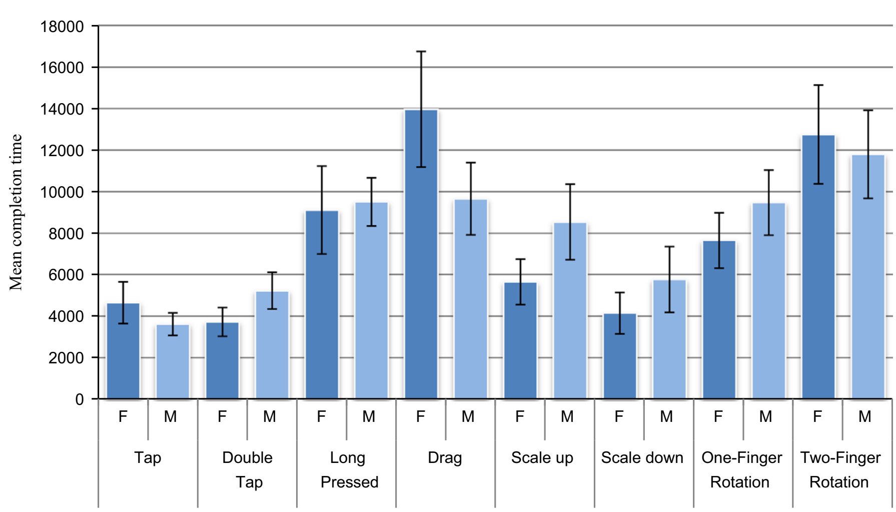

Fig. 9. Mean completion time by task and by gender (F: female, M: male).

Table 1
Main features of the experiment regarding *completion time*.

Null-hypotheses	H_1: Completion time of task *k* is not affected by gender. H_1: $\neg H_1$ H_2: Completion time of task *k* is not affected by age group. H_2: $\neg H_2$ H_{12}: Completion time of task *k* is not affected by the interaction of gender and age group. H_{12}: $\neg H_{12}$
Dependent variable	Completion time of task *k* performed by the children.
Independent variables	The *gender* and *age range* to which the children belong.
Location	Polytechnic University of Valencia (Valencia, Spain)
Date	March 2013
Subjects	32 Pre-kindergarteners (16 males and 16 females)

Table 2
F-statistics of the completion time analysis.

Task	DoF	Gender		Age group		Gender × Age group	
		F	*p*-Value	*F*	*p*-Value	*F*	*p*-Value
Tap	(1.32)	0.963	0.335	3.599	0.068	3.143	0.087
Double tap	(1.24)	2.395	0.137	7.568	0.012	1.931	0.180
Long pressed	(1.23)	0.020	0.888	1.018	0.326	2.319	0.144
Drag	(1.32)	2.179	0.151	8.246	0.008	1.778	0.193
Scale up	(1.30)	2.528	0.124	1.414	0.245	1.755	0.197
Scale down	(1.30)	2.018	0.167	14.148	0.001	1.417	0.245
One-finger rotation	(1.31)	0.715	0.405	6.250	0.019	0.185	0.671
Two-finger rotation	(1.20)	0.098	0.758	1.818	0.196	0.009	0.925

5.2. Success

The three trials carried out by each participant were also combined. If a participant performed successfully either zero or one tests in a specific task, he (she) was considered incapable of performing it, whereas if they successfully performed two or three tests in a specific task, they were considered capable of doing it as they actually show their ability to consistently reproduce the gesture several times. According to this codification, the degree of success in each task can be expressed as a percentage, as shown in Tables A3 and A4 (see Appendix A) by age group and gender and graphically in Figs. 10 and 11.

Table 3 shows the tested hypotheses. Pearson's chi-square tests were conducted on each gesture in order to determine the independence of success from two qualitative factors (gender and age group).

The tests showed that there is no empirical evidence to say that *degree of success* and *gender* are not independent (see Table 4). Hence, the Hypothesis H_3 cannot be rejected and the degree of success does not therefore have a significant relationship with gender. Furthermore, the analysis also showed that H_4, the hypothesis on the independence of *degree of success* and *age group* cannot be rejected, which means that the degree of success does not significantly differ by age group. The analysis also showed that there is no empirical evidence to say that *degree of success* is not independent of the joint gender × age group and H_{34} cannot be rejected. The success rate by task for each age group is shown in Fig. 10 and for each gender in Fig. 11, in which it can be seen to be similar for both age groups and genders.

Fig. 12 shows a histogram of the number of users able to perform a given number *k* of tasks successfully (*k* ranging between 0 and 8). On one hand, if we consider the worst performers, the data reveal that there are no users who perform six or more tasks erroneously, i.e., even the worst users are able to perform at least 3 tasks successfully. These subjects are consistently able to perform the *tap*, *scale up* and *scale down* gestures. On the other hand, if we look at the best performers we observe that 75% of the evaluated children are able to perform six or more gestures correctly. These skilled children fail consistently when performing the *two-finger rotation* and *long pressed* tasks. These observations will be discussed later with respect to cognitive and motor factors in Sections 5.4 and 6.3.

5.3. Comparing tasks

The success rate for each task is shown in Fig. 13, in which it can be seen that not all the tasks are equally feasible. A classification of the evaluated gestures was carried out: *Tap and Drag* are already implemented in commercial applications; *Scale up/down* and *one finger rotation* are not implemented in most commercial applications, despite the considerable success rate achieved by the preschool children in our tests; *Double Tap* and *Long Pressed* are classified as eligible for implementation in future apps, subject to certain guidelines (see Section 6.3); and *Two-Finger Rotation* would have to be discarded or remodeled to be included in learning applications for pre-kindergarteners.

The null hypothesis shown in Table 5 was formulated and a pair-wise task comparison was conducted to test whether *degree of success* was independent of *task*.

Pearson's chi-square test of independence was again used to analyze the degree of success of the task. Table 6 shows the results of the statistical analysis. Each cell contains the significance obtained from the analysis of each pair of tasks.

In accordance with Table 6, H5 is rejected due to the fact that there are gestures with statistically different success rates. According to the statistical tests, a first category of gestures (*tap, drag, scale up, scale down and one-finger rotation*) is identified in which there are no statistically significant differences in terms of success rate, all having a success rate close to 90%.

On the other hand, *double tap, long pressed* and *two-finger rotation* have statistically significant differences with the gestures in the first group. These are the most problematic gestures with the lowest success rate.

The variance in completion time of each task was then analyzed, as shown in Table 7. Table 8 shows the Levene's tests for the homogeneity of variances contrasting gestures. Each cell contains the significance of a combination of two tasks. In this case χ^2(DoF(Task X, Task Y)=DoF(Task X)+DoF(Task Y)-2 (see Table 2 for the DoF values of each task). Given the large number of comparisons (a family of $m=28$ hypotheses) we applied a Bonferroni correction that establishes statistical significance at $p<0.05/28=0.002$.

The results obtained show that the first group of tasks can be established which includes *tap, double tap, long pressed* and *scale down* which have the lowest level of variance, i.e. there is homogeneity in the results in terms of completion time for these gestures.

Scale up, one-finger rotation and *two-finger rotation* compose the second group, with a higher level of variance, which implies that their data is more disperse and with some differences between the subjects when performing the task.

Lastly, *drag* composes the third group, with the highest level of variance, which means a high rate of dispersion, implying wide variations in completion times caused by issues that will be discussed in the next section.

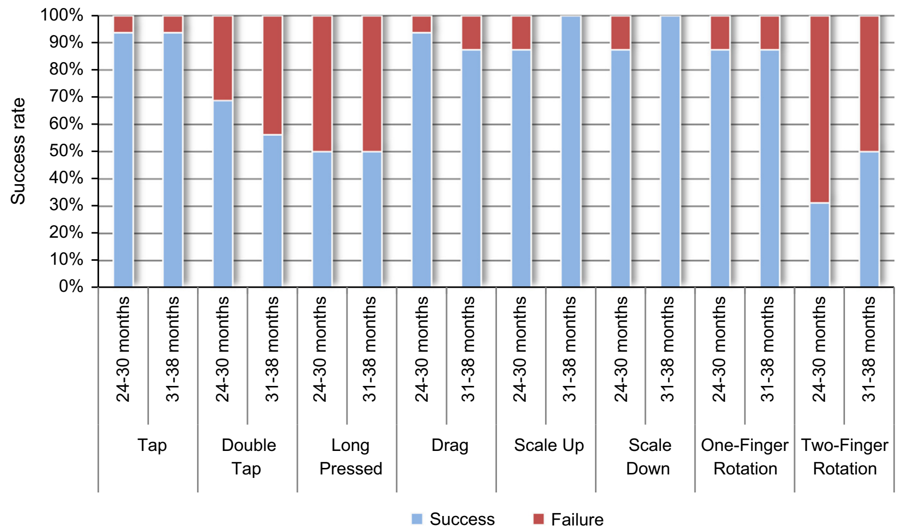

Fig. 10. Success rate by task and age group.

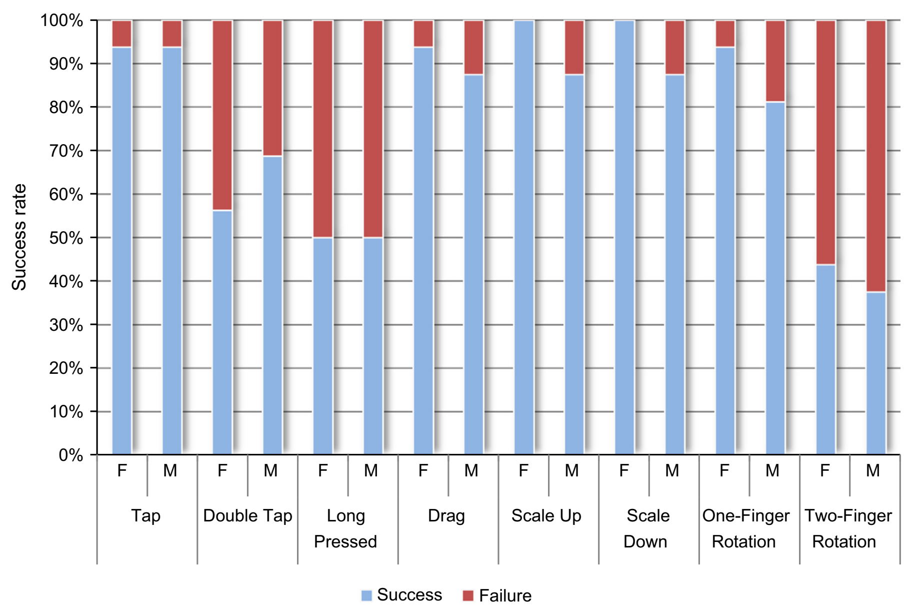

Fig. 11. Success rate by task and gender (F: female, M: male).

Table 3
Main features of the experiment regarding degree of success.

Null-hypotheses	H_3: The degree of success for task *k* is independent of gender. H_3: $\neg H_3$ H_4: The degree of success for task *k* is independent of age group. H_4: $\neg H_4$ H_{34}: The degree of success for task *k* is independent of the joint gender × age group. H_{34}: $\neg H_{34}$
Dependent variable	Success of task *k* performed by the children.
Independent variables	The *gender* and *age range* to which the children belong.
Location	Valencia, Spain
Date	March 2013
Subjects	32 Pre-kindergarteners (16 males and 16 females)

5.4. Qualitative results

In addition to the automatic data logging that was performed to measure completion times and degree of success, an external observer gathered valuable information regarding the behavior of children during the experiments. These observations revealed different problems that will now be described.

We observed several precision problems due to the subjects being in the early development phase of fine motor skills. Firstly, we observed precision problems when asking pre-kindergarteners to tap an element with one finger and hold it for a given amount of time (*long-pressed*). In this specific case, the children had an entry precision problem that prevented them from keeping their finger in a fixed position at the start of the interaction. Instead, they performed a drag around the entry point, where the finger then remained pressed. This makes the system misinterpret the initial contact, because the start of a drag gesture prevents it from identifying a long-pressed gesture, no matter how long the finger is kept pressed. Secondly, we observed problems associated with estimating the speed at which a given interaction was supposed to take place. In our particular case, this was revealed with the *double tap* gesture when some children were unable to perform the second tap as quickly as expected by the underlying gesture detection middleware.

Table 4
Statistics of Pearson's chi-square test.

Task	DoF	Gender		Age group		DoF	Gender × age group	
		χ^2	*p*-Value	χ^2	*p*-Value		χ^2	*p*-Value
Tap	1	0.000	1.000	0.000	1.000	3	2.113	0.545
Double tap	1	0.533	0.465	0.533	0.465	3	1.067	0.785
Long pressed	1	0.000	1.000	0.000	1.000	3	0.000	1.000
Drag	1	0.368	0.544	0.368	0.544	3	1.103	0.776
Scale up	1	2.133	0.144	2.133	0.144	3	6.400	0.094
Scale down	1	2.133	0.144	2.133	0.144	3	6.400	0.094
One-finger rotation	1	1.143	0.285	0.000	1.000	3	2.286	0.515
Two-finger rotation	1	0.130	0.719	1.166	0.280	3	1.425	0.700

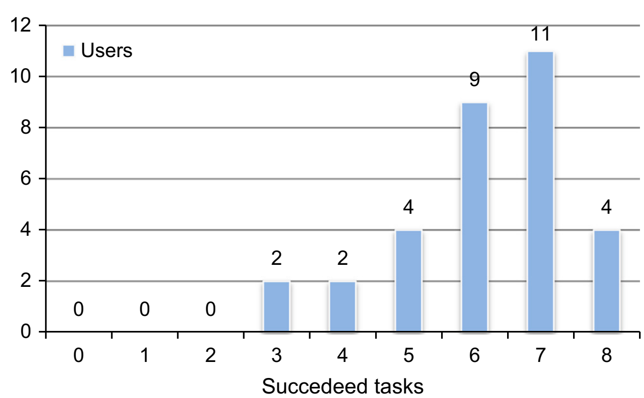

Fig. 12. Users grouped by number of successfully performed tasks.

In addition to the above precision issues, there are even more critical issues that were observed related to the cognitive complexity required by some of the interactions that have been studied in this work.

In the first place, a recurrent situation was the cognitive complexity associated with the process of counting. This was especially apparent in the double tap interaction, when several children were unable to stop the interaction after tapping twice on a given object. Instead, they would tap repeatedly on the target figure and get upset because the system was not rewarding them after performing a great number of taps. It could be argued that it is not clear whether the children were not aware of having made more than two taps or whether it was a motor inhibition problem. In this respect, a post-experimental discussion was carried out with the children's teachers and it became clear that there were several reasons. Some children, while being able to count, had motor-inhibition problems, whereas others were unable to count the number of required events.

Another cognitive-related problem was revealed when the children were asked to perform a two-finger rotation. We have to point out here that the standard two-finger rotation was not appropriate for these users, due to an ergonomic problem when they placed both hands on the surface. Consequently, we designed a two-finger rotation mechanism that required one finger to be kept on the object to be rotated (long pressed) and another to move around a stationary point displayed on the screen (one finger rotation). However, we observed that this combined interaction presented a cognitive challenge. Most of the children behaved in the opposite way by keeping a finger on the stationary rotation point and another rotating around the item that they had got used to rotating.

Finally, as has been pointed out in the statistical analysis of the quantitative data, age was a significant factor in the completion time of the scale down task but, surprisingly, this was not the case for scale up (see Table 2). The analysis of the notes on these tasks taken by an external observer revealed that when scaling up the children started from an initial situation in which their two fingers were close together, so that it was then easy for them to separate their fingers while using all the available space (see Fig. 14 left). However, when performing the scale down task, the youngest children (24–30 months) usually started the interaction with their fingers in the same position as before (close together on the surface) and so were forced to continuously repeat the following sequence: *move fingers together, take fingers off surface, put fingers on surface but close to each other*. This situation did not arise with children in the second age group (31–38 months), who were able

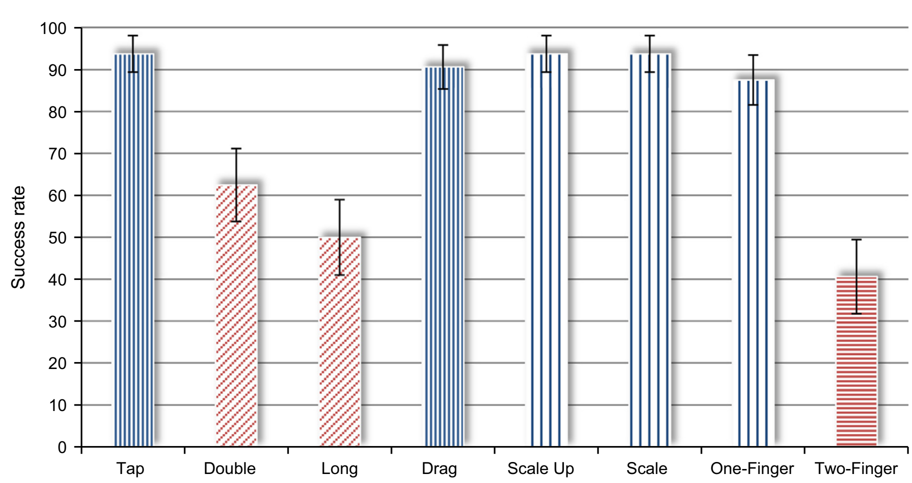

Fig. 13. Success rate by task.

Table 5
Main features *success* in the experimental tests.

Null-hypotheses	H_5: The degree of success is independent of the Task. H_5: $\neg H_5$
Dependent variable	Success of gestures performed by the children.
Independent variables	The *task* performed by the children.
Location	Valencia, Spain
Date	March 2013
Subjects	32 Pre-kindergarteners (16 males and 16 females)

Table 6
Task comparison by success with Pearson's chi-square test of independence χ^2 (DoF=1, N=32).

Success	Tap	Double tap	Long pressed	Drag	Scale up	Scale down	1-Finger rotation	2-Finger rotation
Tap		0.002*	0.000**	0.641	1.000	1.000	0.391	0.000**
Double tap			0.313	0.008*	0.002*	0.002*	0.021*	0.080
Long pressed				0.000**	0.000**	0.000**	0.001*	0.451
Drag					0.641	0.641	0.689	0.000**
Scale up						1.000	0.391	0.000**
Scale down							0.391	0.000**
1-Finger rot.								0.000**

* $p < 0.05$.
** $p < 0.001$.

Table 7
Variance of completion time (in s) by task.

Task	Variance
Tap	10.29
Double tap	7.84
Long pressed	33.83
Drag	88.69
Scale up	33.00
Scale down	24.74
One-finger rotation	33.07
Two-finger rotation	48.21

to estimate the initial distance between their fingers on the surface and could perform the task with one, or at most two, scale down operations.

6. Discussion

6.1. Debunking myths

Based on the above results, the answer to the fundamental question, “Are pre-kindergarten children ready for multi-touch technology?” is definitely affirmative, provided certain issues are dealt with. Regarding the question “What multi-touch gestures are children between two and three years of age able to use?”, we found that the general belief that pre-school children are only capable of performing tap and drag interactions is really no more than a myth. Our study found similar levels of success for interactions such as one-finger rotation and two-finger scale up and down, as for tap and drag, already mainstream in existing applications. Consequently, interaction designers have an opportunity to broaden the scope of their interfaces when creating future applications. Current applications for pre-kindergarten children might be missing the opportunity to provide richer gestures within children's abilities, and could be using a gesture that is notoriously difficult for them (e.g., double tap or two-finger rotation). Therefore, these results show there is no justification for the current situation of most commercial applications for pre-kindergarteners which only support two gestures: *tap* and *drag* (present in 99% and 56% of the analyzed applications, respectively).

The quantitative results also show that there are still challenging gestures for pre-kindergarteners (double tap, long press and two-finger rotation) with success rates ranging between 40% and 60%. These gestures will be discussed below in the context of the interaction aids or design guidelines that application designers should take into account if these touch interactions are included in future applications.

6.2. The impact of gender and age

As presented in the previous section, our results revealed no significant differences among subjects for the success variable with respect to gender or age and that completion time is not affected by gender but is affected by age. The lack of gender differences is perhaps surprising, given that previous work shows superior fine motor control in girls and that male toddlers' hands tend to be larger. In this respect, we have to point out that the average completion times for girls are in general lower than for boys for gestures that require precision, such as *scale up*, *scale down* and *one finger rotation*. However, the differences are not big enough to obtain statistical significance. It is also interesting to observe that the *Age*∗*Gender* interaction has a nearly statistical significant effect (p-value=0.094) on the *degree of success* variable (see Table 4) for the *scale up* and *scale down* tasks, but further research would be needed to verify whether hypothesis H_{34} (see Table 3) can be rejected for these tasks.

The results regarding the age factor are in accordance with the fact that children start to develop their preoperational stage at 24 months and gradually acquire fine-grained motor skills after this time. This is notably the case for double tap, drag, scale down and one-finger rotation tasks, in which the participants in the second age group (31–38 months) perform faster than those in the first (24–30 months). However, this age-related enhancement process was not observed for scale up and two-finger rotation interactions, due to the interference, precision and cognitive complexity issues described in Section 5.4 affecting both age ranges. These issues will open up a new interaction design strategy for children in which gestures with different levels of difficulty could be automatically set according to factors such as age and, eventually,

Table 8
Results of Levene's test.

Success	Tap	Double tap	Long pressed	Drag	Scale up	Scale down	1-Finger rotation	2-Finger rotation
Tap		0.386	0.026	0.000**	0.001*	0.049	0.001*	0.002*
Double tap			0.013	0.000**	0.000**	0.018	0.000**	0.001*
Long pressed				0.053	0.627	0.611	0.627	0.397
Drag					0.059	0.009	0.056	0.257
Scale up						0.239	0.998	0.571
Scale down							0.238	0.146
1-Finger rot.								0.567

* $p < 0.05$.
** $p < 0.001$.

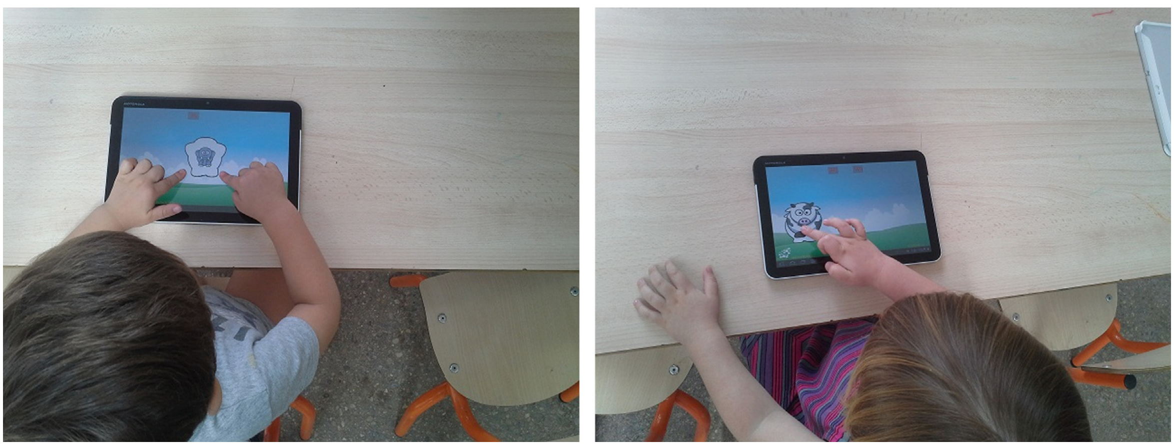

Fig. 14. Examples of actual *scale* (left) and *drag* (right) gestures.

gender. Thresholds, rotation angles and directions, etc. could be set automatically to make interfaces more or less demanding for children, according to their different characteristics and the nature of the learning activity to be carried out.

6.3. *Designing multi-touch applications for pre-kindergarteners*

The above findings, based on the quantitative results, are not the only factors that should be taken into consideration when implementing interactive applications for pre-kindergarteners. There are also lessons to be learned from the qualitative observations in this study that may have implications for the way multi-touch interactions should be designed.

In the first place, the fact that children are able to perform most of the considered gestures but experience difficulties with certain movements that need more highly honed skills, suggests that some interaction aids need to be provided. Special attention must be paid to the finalization phase of gestures with high levels of precision (see Fig. 14 right). In our opinion, this is not always feasible at this early age and the implementation of boundary detection components that detect when an object gets close to its final desired state should always be considered. In this respect, our first design guideline (DG) can thus be stated as follows:

(*DG1*) *Boundary Final/Exit Conditions*: Design boundary detection components to cope with precision problems related to the exact final state of an interactive element.

Another important issue that needs careful consideration is the initial phase of some touch interactions, as in the case of the *long press* gesture. A possible solution to avoid the initial dragging events is to consider a filtering process that would be activated when this gesture is required. In general, designers should take these issues into consideration by following our second design guideline:

(*DG2*) *Spurious Initial/Entry Events*: Design filtering processes for spurious undesired events that may occur in the acquisition/initial phase of any interaction.

There are also motor limitations that may affect the speed at which a given interaction may be performed. In general, any interaction with associated time restrictions should take into account the lowest speed at which it may effectively be performed by pre-kindergarteners:

(*DG3*) *Time-based interactions*: Design adaptive mechanisms to match the required speed for time-based interactions to the actual ability of the user.

Finally, cognitive complexity has to be adequately managed when designing touch interactions. We have observed performance issues with gestures requiring more advanced skills that require mathematical thinking, bi-manual coordination and spatial-geometric interpretation to plan a complex gesture in advance. Some previous results in the literature have shown that this is also important for adults (Nacenta et al., 2009), although not all manipulations might require this planning in advance, which makes it an even more important point for designers. These aspects should be addressed by considering our three final design guidelines:

(*DG4*) *Mathematical thinking interactions*: Avoid including interactions that involve mathematical concepts such as counting exact numbers or repeating a given number of events.
(*DG5*) *Coordinated interactions*: Avoid interactions that require complex coordination processes involving both hands.

(*DG6*) *Geometric-based interactions*: Avoid interactions that require the effective estimation of spatial relationships if performance is a mandatory requirement.

We believe the above recommendations will open up an interesting area of research on the design of adaptable interfaces for pre-kindergarteners that match their interaction requirements and challenges to their actual abilities. Additionally, it would also be of interest to design semiotic systems that include audio-visual feedback to improve the communicability of these interaction problems. These systems would motivate children to improve their interactions.

6.4. Revisiting multi-touch interactions for adults

Besides the quantitative and qualitative findings discussed above, there are specific issues related to previous studies with adults that strengthen the idea that existing multi-touch interaction models must be tailored to cope with the specific characteristics of pre-kindergarten children.

Firstly, our results obtained from the pinch gesture with pre-kindergarteners disagree with those reported for adults in Hoggan et al. (2013a). Adult users in general perform contracting pinch gestures faster because this gesture is ergonomically easier for them. As pointed out by the authors of this study, the average rotation amplitude of the index finger inter-phalangeal joint is lower for contraction than expansion. In the absence of the cognitive development problem, the main issue when considering pinch gestures by adults is ergonomic. It is interesting to note that longer distances cause significantly more ergonomic failures with adults. Consequently, as suggested in this study, it would also be worth investigating whether non-direct mappings between finger distance and zoom or scaling magnitude might improve pre-kindergartners' efficiency in this respect.

Secondly, we should not be surprised that rotations are the gestures requiring the highest level of cognitive effort in this study, as they involve some of the most complex motor skills among common multi-touch gestures. In this respect, recent studies with adult subjects (Hoggan et al., 2013b) show surprising interaction effects among the variables studied (angle, diameter, direction and position) in rotations performed with the index finger and thumb. It remains to be seen whether there are also categories of rotations (both two and one finger-based) at the earliest stages of motor development that may cause problems, as occurs with adult subjects. The study of anti-clockwise rotations and the presence of large diameters and angles should provide useful information on heuristic aids in design.

Finally, if we compare the execution times of the drag, one-finger rotation, scale up and scale down gestures against the regression model of multi-touch manipulation proposed for adults by Zhao et al. (2011), we can conclude that our observed execution times do not fit this model. Namely, children under 30 months perform these gestures on average 8.5 times slower than adults, whereas children over 30 months perform them 4.1 times slower. The differences between boys and girls are not so wide, with girls performing these gestures on average 5.6 times slower than adults and boys are 6.8 times slower. These results reveal that additional research is needed to obtain a specific application of the Mahalanobis distance metric to the index of difficulty equation from Fitts' law, in order to properly model multi-touch manipulations by children in this age range. However, taking into account the current state of the art, it is not clear whether this type of modeling is feasible for children, as the number of dimensions that affect multi-touch interactions in this early age range may be high, making it difficult to obtain a model, as Zhao et al. (2011) recognized.

6.5. Applications beyond HCI

Finally, the results obtained are not only of interest to interaction designers but also to researchers who investigate the physical and cognitive load of these gestures in general. Studying children of different ages may provide an indication of which gestures do require a certain level of cognitive development. Additionally, the increasing use of gesture-based interfaces in the very early stages of cognitive development may also be of interest to those who investigate the role of gestures in talking and thinking. In this respect, it has been observed that children exploit hand movements at the very earliest stages of language learning. However, as pointed out by Damon et al. (2006), they gradually reduce symbolic gestures as they develop. It remains to be seen whether the increased use of gesture-based interfaces by children, such as those proposed in this study, has any impact on the way they use gestures for non-verbal communication.

In addition, increasing the number of gestures in educational applications may have an effect on the design of instructional strategies for pre-kindergarteners. For example, applications that force children to perform gestures in a given sequence or according to any other pre-established requirements may contribute to the internalization of rules. This is related to behavior control, which is one the foundational skills that must be acquired at this early age. Other abilities that could be developed with the inclusion of these additional gestures are the control of attention, creativity, classification, patterning and motor planning skills.

7. Threats to validity

There are some threats in terms of the generalization of the findings of this study to other contexts and environments and several precautions must be taken.

The fact that children were able to successfully complete certain gestures after training with an adult does not mean that they will be able to perform these without guidance or by themselves. Certainly, this issue needs further research and appropriate automated guidance systems should be designed to overcome this problem.

With respect to time-based interactions, another threat is that the results are very likely dependent on the specific thresholds chosen, namely, on double taps and long pressed interactions. It is possible that relaxing these thresholds would make these gestures much more successful.

Two limitations must be considered with regard to rotation gestures. Firstly, success was achieved when the target angle was surpassed and not when the object reached a specific orientation within certain error limits. Additional experiments would be needed to verify whether this additional precision requirement would have a significant impact on performance. Secondly, the designed two-finger rotation in the end turned out to be a rather complicated way of rotating, which the children were not able to understand. This severely affected the performance of this gesture, so that a less confusing bi-manual rotation procedure should be designed and evaluated.

In relation to scaling gestures, it is also important to note that scale up and down were not separated into one-hand or multiple-hand gestures and this could have introduced noise into the measure.

Additionally, although gestures in the experimental setting were evaluated in isolation, in certain contexts they happen consecutively and therefore some of the results might not apply in these cases. In fact, although we tend to think that gestures are isolated and instantaneous, there is some evidence (Hinrichs and Carpendale, 2011) that some of them are affected by previous and subsequent events. In this respect, the results of the study are necessarily reductionist and they have not revealed the limits to combining the different gestures, i.e., we have not considered situations in which a designer might need multiple gestures to be carried out at the same time.

Another limitation of our work is related to applications that generally require touch gestures to be complete and separated from each other by "release". Although applications could be designed that work on thresholds, explicit gesture separation events (release) could be needed, and these have not really been studied in this experiment.

Finally, we still need to study the effect of space cluttering in situations in which several interactive elements need to be displayed simultaneously, leaving users with a restricted interaction area. It is not known whether a limited space would make these gestures less successful for pre-kindergarten children.

8. Conclusions and future work

In this work we analyzed a corpus of 100 commercial applications running on multi-touch devices for pre-kindergarteners and concluded that 99% of the applications used tap and 56% used drag gestures as their only supported operations. In order to analyze very young children's capacity to successfully perform additional gestures we designed an experimental evaluation in which 2–3 year old children participated as users of a multi-touch application requiring diverse types of operations, including *tap, double tap, long pressed, drag, scale up, scale down*, and *one* and *two finger rotation*.

Our findings provide evidence that additional gestures (*one-finger rotation* and *two-finger scale up* and *scale down*) may be effectively incorporated into applications targeting pre-kindergarten users and running on multi-touch devices with comparatively little implementation effort. Other gestures (*double tap* and *long pressed*) may also be considered, provided precision and cognitive limitations are taken into account. The analysis of these limitations gave us a set of design guidelines that address boundary exit conditions, spurious entry events, time, counting, distance-based and coordinated interactions.

Despite the conclusions obtained, the work presented in this paper is the first step in a study of multi-touch gestures with very young children and opens a new area of research with many pending questions and interesting issues to be addressed in future work.

There are some gestures, such as *double tap* and *long pressed,* that could be implemented differently to improve the success rate by taking into account the observed issues. For instance, the time gap for the double tap could reasonably be prolonged or dynamically adapted to children's different skill levels and the short spurious movements detected when trying to keep the finger still in the long pressed gesture could be filtered out. An improved technique for the drag gesture could also be considered, such as the one used in Rick et al. (2010) and Harris et al. (2009), which filters out temporary skipping of the finger. Although these solutions seem feasible, all these techniques will require further empirical evaluation and validation, both in isolation and when put together in a single application.

Obtaining detailed information on the accuracy with which gestures can be performed is also an interesting strand of future work. Good examples include how accurately they can rotate an object or how close they can drag an object to a target. This would certainly help in understanding the limitations and how demanding applications should be as regards the precision of a given gesture.

Another interesting issue is that of unexpected touching when holding the tablet with a finger resting on the display or when part of the palm also touches the surface if it is not carefully approached (Mansor et al., 2009). This is a difficult issue to address because children may not realize that such unintentional contacts with other parts of their body when their fingers approach the screen have a different effect to what happens when they use paper and tangible materials. It would therefore be interesting to explore potential improvements in multi-touch usability, for instance by determining and filtering out unexpected blob contacts wherever applicable. In this respect, works such as those of Schwarz et al. (2014) and Vogel and Casiez (2012), who studied the detection of different types of contacts and occlusion patterns on multi-touch surfaces, could be used as a starting point.

Further research will be needed to design effective two-finger rotations for this age range. Attentional and motivational factors are also important in moderating motor capabilities that lead to performing gestures successfully. Thus, we also plan to investigate the suitability of existing semiotic approaches, such as those proposed by Derboven et al. (2012), to advise users of the gestures they are expected to perform in multi-touch applications for pre-kindergarteners. We must also be aware of how fast many children are becoming familiar with multi-touch devices by gaining access to their parents' tablets. This exposure to multi-touch technology should have a positive effect on the way they learn and acquire abilities to perform gestures. We must therefore be on the lookout for any design guidelines and gestures that could change as soon as this situation is prolonged over time, and which ones will still apply, as motor or cognitive skills are not significantly altered despite this higher exposure and experience.

All the previous issues are worth studying in an extended age range, also involving children in the 4–5 age range. It would be particularly interesting to observe whether this extended study with an increased number of subjects exposes gender differences that were not observed in the present study.

Finally, we wonder whether users with special needs or motor restrictions could take advantage of gestures personalized to their motor skills. Although such personalization must be performed on a case-by-case basis, future work in this respect could be focused on exploring how basic gestures under typical motor restrictions can be adapted to improve usability and performance when using touch-enabled displays.

Acknowledgments

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Appendix A

See Tables A1–A4.

[2] ⟨ampa.blogs.upv.es⟩.
[3] ⟨www.ituitu.es⟩.

Table A1
Time in milliseconds to perform the tasks by age.

Task	Age Group	Average	SD
Tap	≤ 30	5140.94	3912.07
	> 30	3135.30	1957.64
	Total	4138.12	3209.01
Double tap	≤ 30	5815.72	3326.45
	> 30	3144.81	1201.32
	Total	4480.26	2800.59
Long pressed	≤ 30	10,652.62	7294.92
	> 30	8075.00	3979.02
	Total	9307.78	5817.10
Drag	≤ 30	16,017.06	11,485.80
	> 30	7620.94	3711.30
	Total	11,819.00	9417.58
Scale up	≤ 30	8072.42	6340.66
	> 30	6065.68	5191.55
	Total	7002.16	5744.57
Scale down	≤ 30	7802.85	6044.72
	> 30	2372.95	1221.70
	Total	4906.91	4974.20
One-finger rotation	≤ 30	11,108.70	6618.13
	> 30	6240.68	3611.40
	Total	8596.17	5751.21
Two-finger rotation	≤ 30	14,920.21	9253.39
	> 30	10,519.61	4509.51
	Total	12,279.85	6943.47

Table A2
Time in milliseconds to perform the tasks by gender.

Task	Gender	Average	SD
Tap	F	4656.73	4004.34
	M	3619.51	2161.85
	Total	4138.12	3209.01
Double tap	F	3728.94	2403.49
	M	5231.58	3064.52
	Total	4480.26	2800.59
Long pressed	F	9117.32	7356.77
	M	9515.55	3849.63
	Total	9307.78	5817.10
Drag	F	13,976.86	11,160.55
	M	9661.14	6985.93
	Total	11,819.00	9417.58
Scale up	F	5655.44	4380.83
	M	8541.29	6832.87
	Total	7002.16	5744.57
Scale down	F	4150.58	4017.93
	M	5771.29	5921.07
	Total	4906.91	4974.20
One-finger rotation	F	7653.27	5163.65
	M	9480.15	6288.45
	Total	8596.17	5751.21
Two-finger rotation	F	12,760.13	7508.27
	M	11,799.57	6700.27
	Total	12,279.85	6943.47

Table A3
Success rate in each task by age groups.

Task	Age Group	Average	SD
Tap	≤ 30	0.9375	0.25000
	> 30	0.9375	0.25000
	Total	0.9375	0.24593
Double tap	≤ 30	0.6875	0.47871
	> 30	0.5625	0.51235
	Total	0.6250	0.49187
Long pressed	≤ 30	0.5000	0.51640
	> 30	0.5000	0.51640
	Total	0.5000	0.50800
Drag	≤ 30	0.9375	0.25000
	> 30	0.8750	0.34157
	Total	0.9062	0.29614
Scale up	≤ 30	0.8750	0.34157
	> 30	1.0000	0.00000
	Total	0.9375	0.24593
Scale down	≤ 30	0.8750	0.34157
	> 30	1.0000	0.00000
	Total	0.9375	0.24593
One-finger rotation	≤ 30	0.8750	0.34157
	> 30	0.8750	0.34157
	Total	0.8750	0.33601
Two-finger rotation	≤ 30	0.3125	0.47871
	> 30	0.5000	0.51640
	Total	0.4063	0.49899

Table A4
Success rate in each task by gender.

Task	Gender	Average	SD
Tap	F	0.9375	0.25000
	M	0.9375	0.25000
	Total	0.9375	0.24593
Double tap	F	0.5625	0.51235
	M	0.6875	0.47871
	Total	0.6250	0.49187
Long pressed	F	0.5000	0.51640
	M	0.5000	0.51640
	Total	0.5000	0.50800
Drag	F	0.9375	0.25000
	M	0.8750	0.34157
	Total	0.9062	0.29614
Scale up	F	1.0000	0.00000
	M	0.8750	0.34157
	Total	0.9375	0.24593
Scale down	F	1.0000	0.00000
	M	0.8750	0.34157
	Total	0.9375	0.24593
One-finger rotation	F	0.9375	0.25000
	M	0.8125	0.40311
	Total	0.8750	0.33601
Two-finger rotation	F	0.4375	0.51235
	M	0.3750	0.50000
	Total	0.4063	0.49899

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