Development and Evaluation of Fingu: A Mathematics iPad Game Using Multi-touch Interaction

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ABSTRACT
We describe the design background of the mathematics game Fingu for iPad aimed at 4 to 8 year old children. We first describe how Fingu theoretically can support children's development of fundamental arithmetic skills, focusing on conceptual subitizing, the embodiment of numerosity, and finger gnosis. Then we present the results of an exploratory micro-longitudinal study of the game with 11 5- and 6-year old children playing the game for several weeks and being filmed at three occasions. We discuss how their behavior with the game develops over time and can be related to the development of arithmetic skills. Finally we discuss how we will proceed testing the effectiveness of Fingu in a larger controlled study.

Categories and Subject Descriptors
K.3.m [**Computers and Education**]: Computer Uses in Education

General Terms
Design, Human Factors.

Keywords
Fingu, embodiment, arithmetic, number sense, finger gnosis.

1. INTRODUCTION
Mastering number concepts is foundational to the development of arithmetic competence in addition and subtraction [1-3]. According to Neuman [3], mastering elementary number concepts means understanding natural numbers in the range of one to ten as part-whole relations (e.g. 6 is constituted by 5 and 1, but also by 4 and 2 and so forth). Neuman [4], in the tradition of phenomenography, proposed principles for designing learning environments that promote children's "seeing" number concepts as part-whole structure, instead of applying counting strategies. A concrete example is seeing a number of objects in a set as an organized "numeric" pattern, instead of counting the number of objects. The capacity to directly see numbers of objects – in this case parts in a part-whole relation – is known as subitizing. According to Butterworth [1], Fischer et al. [2], and Fuson [5] subitizing can be trained and contributes to the development of arithmetic skills of the same type as we are treating here.

A final important principle is the sensory-bodily dimension in the development of early number sense. An important tool for children in developing arithmetic skills is their fingers, which are used both for representing numbers as structured patterns and for counting. Thus, in a very concrete sense arithmetic skills and number concepts are embodied [6].

These principles were built into an iPad game called Fingu. Fingu is essentially developed as a research tool to study how children develop their mathematical abilities through use of an embodied game. However, its presence in the AppStore (for free) makes it available for the home- and the school-market as well.

In this paper we first describe Fingu and the backgrounds for its design related to the literature on early mathematics learning. Furthermore we discuss the results of a micro-longitudinal exploratory test of the game with 11 5- and 6-year old children.

2. FINGU DESIGN RATIONALE

2.1 The Fingu Game
In Fingu one or two small moving sets of pieces of fruit are shown and the player has to determine how many pieces of fruit there are (Figure 1 left). Before time runs out the player has to place as many fingers on the screen as there are pieces of fruit (Figure 1 right). The sets are shown for a short time, but after they have disappeared the player gets some extra time to answer. Fingers can be placed anywhere on the screen.

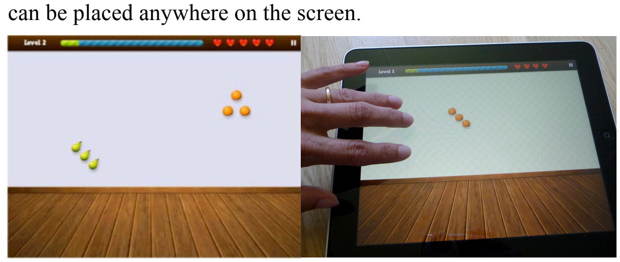

Figure 1. Typical situation with two sets of objects in Fingu (left), player placing fingers on the screen to answer (right)

Once a finger is placed on the screen a timer is started to determine when the answer will be registered. The starting of this timer is made visible as a fingerprint. The fingerprints change color in order to indicate that a final answer has been registered. Before the answer is registered the player can (by default within part of a second) remove or add fingers and each change in finger configuration restarts the timer until a stable configuration is held down long enough.

There are 7 levels, and on each level there are a number of configurations of number patterns (10, 12 or 15), which are shown twice in random order. If the player answers correctly the first time a configuration is shown the exposure time will be shorter as the configuration is shown the second time. On the first level the maximum total number of pieces of fruit is 5, on the second level 6 etc., to 10 pieces of fruit on level 6 and 7. On each level some new configurations are introduced as well.

One proceeds to the next level by answering correctly to most assignments. If the player gives an incorrect answer he/she will lose a heart. If the player runs out of time only half a heart is lost. When all the hearts are lost before the 20 assignments (24 or 30 for the higher levels) have been given, the player has to start all over at the same level.

The game saves player progress for up to 24 players. Players choose their personal character on the first screen and can continue playing on the levels that they have opened up.

We performed usability tests with children on previous versions of Fingu in order to determine the most suitable number of assignments per level, the time to hold down a stable number of fingers, and the overall appeal of the game. These tests have resulted in several adaptations of the game both before and after the exploratory study described in this paper was performed.

In the following paragraphs we will discuss how the interaction with Fingu consists of two phases and how each phase in the game could hypothetically support children's learning based on previous research on early arithmetic learning.

2.2 Phases in Fingu

There are essentially two phases in the game that both give the opportunity to develop early arithmetic skills. In the first phase the child is shown one or two patterns of pieces of fruit, for example 2 oranges and 3 pears for some time. The child has to develop strategies to determine how many objects are shown in each pattern. In the second phase the child has to place a corresponding number of fingers on the touchscreen. This means that the child has to figure out how to use his/her fingers to represent the number of objects displayed in the configuration. We will now discuss each of the phases in more detail and relate to the relevant literature on early mathematics.

2.2.1 Phase 1: Determining the number of objects in each set

In order to determine the number of objects shown on the screen children first need to determine how many objects are shown in each set. The notion of subitizing is important in this context. There are essentially two types of subitizing [7]: Perceptual subitizing and conceptual subitizing. Perceptual subitizing is the capacity to directly see the cardinality of a small set of objects without counting them. This capability is already present in infants. Conceptual subitizing however, means that people are also able to 'see' the number of objects in a larger but structured set without counting them. They may do this by structuring the larger set into smaller sets that they can subitize perceptually. This more advanced way of subitizing supports the development of number sense. Fingu may help children to develop conceptual subitizing by offering them structured object patterns during a rather short exposure time. Although perceptual subitizing is possible for the patterns at the first levels, children may develop the advanced form of subitizing in order to speedily discern the larger number of objects in the patterns used on higher levels.

Even though Fingu does not require children to determine the sum of the numbers of objects in both sets they do have to answer how many objects are shown altogether in order to produce the correct answer. We should therefore take a look at what the research says about learning of basic facts and additions. Children need to be fluent with basic number combinations, such as 7+2=9, in order to achieve mastery in more advanced mathematical operations such as multiplication and division, multi-digit mental or written calculations, as well as the use of rational numbers [8]. Children who have not mastered the basic addition combinations at the end of the first grade are at a risk of experiencing mathematics difficulties. According to the number sense perspective, fluency with these basic number combinations is not a matter of memorization. Instead, children have to discover patterns or relations, such as the number-after rule (''the sum of n + 1 is always the number after n in the counting sequence') or the commutativity of addition [8]. According to Baroody et al. learning opportunities should thus be "purposeful (personally relevant and engaging), meaningful (build on what children know), and inquiry-based (directed at promoting autonomous mathematical problem solving and reasoning)" [8, p. 76]. Fingu provides children with an environment that opens up for exploration of these number combinations, leading to the development of number sense rather than memorization of facts.

2.2.2 Phase 2: Answering with fingers

When playing Fingu children have to translate what they see into an answer using their fingers. An important assumption is that it is essential to 'experience the manyness of a set, of experiencing this manyness as a global quality which takes on an objectlike character in the sense that we can see, hear, feel it as a whole, while at the same time we can discern parts and elements within the whole' [9]. Demanding coordination between what is seen with the eyes and what is done with the hands may enhance the numerical meaning of the tasks in Fingu.

Another important concept is finger gnosis. Finger gnosis is the ability to differentiate one's own fingers when they are touched without any visual cues. Finger gnosis is typically tested by placing a child so that he/she faces the examiner, one arm extended with fingers spread out and the palm down, hidden by a box from view by the child. The examiner repeatedly touches one or two of the child's fingers and then removes the box and asks the child to point, with his/her other hand, to the finger or fingers that have been touched. Research by Noël [10] showed that finger gnosis in young children (between 5 and 7 years old) is a good predictor of their numerical abilities. Garcia-Bafalluy and Noël [11] created an intervention in which children with poor finger gnosis received specific finger gnosis training. This training consisted of four games for finger differentiation. Garcia-Baffaluy and Noël showed that their 8-week training program led to improved finger gnosis in young children as well as to better performance in three basic numerical skills: subitizing, counting raised fingers, and ordinality judgement.

We have designed Fingu so that it is hard to set down one finger after another when answering. All fingers forming the answer have to be placed on the screen at approximately the same time. Children thus have to create a configuration of their fingers that corresponds to the number of objects on the screen. Fingers cannot be placed too tightly and they have to be placed at approximately the same time, which requires a certain awareness of and control over each finger. It can therefore be hypothesized that, similarly to the games by Garcia-Baffaluy and Noël, this supports finger gnosis, and thereby also children's mathematical abilities.

3. PILOT TESTING

3.1 Procedure

We did a micro-longitudinal pilot test of Fingu with 11 children, seven girls and four boys, six 5-year olds and five 6-year olds. All children were members of a preschool group in a small city in Sweden. Children would be filmed three times during a three-week period. The first time children received instruction from a familiar teacher, giving them examples of how they were supposed to use the game. For example, she would say 'one plus three' and then press down four fingers on one hand. When the child and the teacher thought the child had understood the interaction, the game was started from the beginning and the child's playing was filmed. After that they played the game several times more during a week before they were filmed a second time. After almost three weeks, in which they were allowed to play several times, they were filmed a third time (except for two children that were away the third time).

4. RESULTS AND DISCUSSION

We analyzed all videotaped play sessions looking for the following indicators: counting all, counting from smallest, counting from largest, counting fingers to 5, counting fingers over 5, manipulating fingers with other hand, problem pressing down. We describe the results of all play sessions in Table 1 and we subsequently highlight some children's typical development to explain these numbers. Names are fictional.

Table 1. Results of each play session for all children, showing name and age, session, % correct and levels played (in order of playing, bold means completed)

Child, age	**Session**	**Correct %**	**Levels played (bold = completed)**
Erik, 5	1	60%	1
	2	68%	3
Jay, 5	1	57%	1
	2	76%	**3**, 4
	3	46%	5
Peter, 5	1	71%	**1**, 2
	2	55%	3
	3	62%	5, 3
Victoria, 5	1	82%	**1**, **2**, 3
	2	72%	6
	3	70%	6
Kay, 5	1	75%	**1**, **2**, **3**, 4
	2	79%	**7**
	3	93%	**1**, **2**, **3**, **4**, 5
Mia, 5	1	78%	**1**, **2**, **3**
	2	75%	**6**, 7
Eve, 6	1	86%	**1**, **2**, **3**
	2	67%	7
	3	90%	**1**, **6**, **2**, **3**
Naomi, 6	1	77%	**1**, **2**, 3
	2	67%	5
	3	60%	6
Evan, 6	1	65%	**1**, **2**, 3
	2	57%	7
	3	86%	7, 4, **2**, **3**
May, 6	1	81%	**1**, **2**, **3**
	2	70%	6
	3	88%	**7**, 1, 5
Bella, 6	1	74%	**1**, **2**, 3
	2	82%	**3**, 7, **5**, **6**
	3	70%	**1**, 6, 7, 5

In general we can observe that many children make more mistakes during the second session than during the first session (Peter, Victoria, Mia, Eva, Naomi, Evan, and May). This is probably related to the fact that the children play higher levels during the second session, giving an indication that the assignments on higher levels are really harder. In the third session some children start playing over the earlier levels, and we see that the percentage of correct answers is higher again (Peter, Kay, Eve, Evan, and May).

Peter is able to use perceptual subitizing for single sets up to 4, but he always counts both sets when there are two, probably meaning that he finds it hard to 'count up' from one set. He also has some troubles placing his fingers correctly. In the second session, he no longer always counts both sets but gives the answer immediately without counting. He still has problems answering, especially because he tends to press his fingers together. In the third session he starts using new strategies, such as mapping each pattern to one hand, but he still has troubles with placing his fingers correctly.

Kay initially has large troubles placing her fingers correctly. Even though she uses perceptual subitizing for small sets and is very sure of her answers, her fingers do not touch the screen correctly. During the second session she counts larger sets when they do not resemble patterns on a die, but she is very sure about how to represent an answer on her fingers. In the third session she starts at level 1 because she has completed all levels of the game. She plays through the first four levels without any problems and stops at the fifth level because she has played long enough. We see a clear difference in the percentage of correct answers between the first and the last session in which she plays the same levels.

Evan does not count during the first session but he has huge troubles forming his hand(s) to represent the answer. In the second session he starts playing at level 7. At this level he does have to count the objects and he still places his hands slightly sloppy, resulting in many incorrect answers. In the third session he still is unable to complete level 7, but when he returns to level 2 he states: "This is easy. I haven't lost a single life yet. Before, I thought this was really hard".

During the first session May only counts when there are two patterns with a sum of five and higher. In the second session she plays level 6 and almost always relies on counting (the sums on this level are up to 10). She experiences many problems in placing her fingers correctly. In session 3, she is much more precise with her fingers and is therefore able to finish level 7.

5. CONCLUSIONS AND FUTURE WORK

Children in the pilot test played Fingu during a three-week period. When children played a level in the game they hadn't played before they usually made more mistakes, resulting in a lower percentage of correct answers. However, when children replayed some levels, there usually was an increase of the percentage of correct answers.

Since the configurations on each level come in a random order it is unlikely that children just remember the answers. Looking at the children's behavior in more detail, we see that different children develop different skills when playing Fingu. Some children improve their recognition of larger patterns (conceptual subitizing), some children improve the ability to represent a number on their fingers (bodily-sensory number-sense), and some improve the precision in placing their fingers at once (possibly finger gnosis). We also see that most children still rely on counting strategies for the larger sums. However, since Fingu is fully adaptable through a settings menu, it is possible to set shorter exposure times, which can make the need for conceptual subitizing more salient. These results give us the incentive to plan a two-fold major study of Fingu in 2012.

The first part of this study will be of a controlled quantitative nature where we will involve several larger groups of children who will be able to work with Fingu for a longer period of time. In order to study the learning effect of Fingu children's mathematics ability before and after playing Fingu will be measured with variants of standardized tests, such as TEMA 3, but adapted to the Swedish school system.

The second part of this study will have a more qualitative nature. In order to understand the different learning trajectories that may lead to improvement of children's mathematical abilities we will film their use of Fingu on three occasions: at the start of the study, after several weeks of playing, and at the end of the study. We will also follow some children's mathematical development in more detail by filming them on a more regular basis and also when they are performing other mathematical activities. Finally, we are interested in how Fingu in combination with other educational materials can be used in classroom situations. In the future we therefore also envision a study including teachers making use of Fingu in their daily work.

6. ACKNOWLEDGMENTS

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