Design of the Game-Based Learning Environment "Dudeman & Sidegirl: Operation Clean World," a Numerical Magnitude Processing Training

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Abstract Numerical magnitude processing has been shown to play a crucial role in the development of mathematical ability and intervention studies have revealed that training children's numerical magnitude processing has positive effects on their numerical magnitude processing skills and mathematics achievement. However, from these intervention studies, it remains unclear whether numerical magnitude processing interventions should focus on training with a numerical magnitude comparison or a number line estimation task. It also remains to be determined whether

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there is a different impact of training symbolic versus nonsymbolic numerical magnitude processing skills. In order to answer these two questions, we developed four game-based learning environments, using the storyline of “Dudeman & Sidegirl: Operation clean world”. The first two game-based learning environments comprise either a numerical magnitude comparison or a number line estimation training and the last two game-based learning environments stimulate either the processing of symbolic or nonsymbolic numerical magnitudes.

Keywords Game-based learning environment • Numerical magnitude processing • Mathematical achievement • Educational intervention • Design principles

Mathematical skills are of great importance in everyday life. We use them, for example, when we measure ingredients for cooking, read the timetables to catch a train, or pay in the supermarket. In the last decade, there has been an increasing research interest in the cognitive processes that underlie these mathematical skills, which points to numerical magnitude processing, or people’s elementary intuitions about number and quantity, as an important factor in explaining individual differences in mathematical ability in children as well as adults (Bugden & Ansari, 2011; De Smedt, Verschaffel, & Ghesquière, 2009; Halberda, Mazzocco, & Feigenson, 2008; Sasanguie, Van den Bussche, & Reynvoet, 2012; see De Smedt, Noël, Gilmore, & Ansari, 2013, for a review). For this reason, the development of interventions to improve children’s numerical magnitude processing skills is very relevant and would provide opportunities for early intervention of children at-risk for mathematical difficulties. Furthermore, choosing a game-based learning environment might provide a motivating environment for the children, given the combination of learning and playing (Garris, Ahlers, & Driskell, 2002). We therefore developed two game-based learning environments to train children’s numerical magnitude processing skills. In this contribution, we will first discuss the concept of numerical magnitude processing and its association with mathematical skills. Afterwards, we will elaborate on previous research that investigated the effects of interventions that aim to improve numerical magnitude processing. Finally, we will explain in detail the four game-based learning environments that were developed.

Numerical Magnitude Processing

Numerical magnitude processing has been shown to play a crucial role in the development of mathematical ability (see De Smedt et al., 2013, for a review). The understanding of numbers is rooted in a very basic sense of numerosities and number symbols. This numerical magnitude processing has often been described using the metaphor of a “mental number line” (Bailey, Siegler, & Geary, 2014; Dehaene, 1992; Gallistel & Gelman, 1992; Laski & Siegler, 2007). The mental number line is characterized as a number line for which the numerical magnitudes are represented by distributions around the true location of each specific value. Because the representations of numerical magnitudes that are adjacent overlap, the closer two numerical magnitudes are, the harder it will be to distinguish them.

There are two common ways to measure numerical magnitude processing skills, namely with a numerical magnitude comparison task and a number line estimation task. In the *numerical magnitude comparison task* (Sekuler & Mierkiewicz, 1977), children are instructed to indicate the numerically larger of two presented numerical magnitudes, which can be presented in either a symbolic (digits) or a nonsymbolic (dot patterns) format (Holloway & Ansari, 2009). A second classic task is the *number line estimation task* (Booth & Siegler, 2006). In this task, children are typically shown a horizontal number line, for example, with 0 on one end and 10, 100, or 1000 on the other. In the number-to-position variant, children are instructed to position a given number on this number line, and in the position-to-number variant, children have to estimate which number is indicated on the number line (Ashcraft & Moore, 2012; Booth & Siegler, 2006, 2008). This task can also be presented in a symbolic or a nonsymbolic format (Sasanguie, De Smedt, Defever, & Reynvoet, 2012). The numerical magnitude comparison task and the number line estimation task are generally assumed to rely on the same underlying magnitude representation (Dehaene, 1997; Laski & Siegler, 2007), but this idea has recently been questioned (Barth & Paladino, 2011; Sasanguie & Reynvoet, 2013). Sasanguie and Reynvoet (2013), for example, compared the performance in the numerical magnitude comparison task and the number line estimation task directly in one study and observed no significant association between both tasks, which suggests that different processes might play a role in both numerical magnitude processing tasks.

Research on these two kinds of tasks has revealed that children who perform better on them also showed higher mathematics achievement at that time (Bugden & Ansari, 2011; Halberda et al., 2008; Holloway & Ansari, 2009; Sasanguie, Van den Bussche & Reynvoet, 2012; Siegler & Booth, 2004). More specifically, studies revealed that children who were faster or more accurate in indicating which of two numbers or quantities was the larger, showed higher achievement in mathematics (e.g., Bugden & Ansari, 2011; De Smedt et al., 2009; Halberda et al., 2008; Holloway & Ansari, 2009; Lonnemann, Linkersdörfer, Hasselhorn, & Lindberg, 2011; Mundy & Gilmore, 2009; Sasanguie, De Smedt et al., 2012; see De Smedt et al., 2013, for a review). A similar association with mathematics achievement has been observed in studies with number line estimation as a measure for numerical magnitude processing, showing that individual differences in number line estimation were strongly correlated with their mathematics achievement test scores (e.g., Sasanguie, Van den Bussche & Reynvoet, 2012; Siegler & Booth, 2004). More specifically, children with more linear estimation patterns, resulting in more precise estimations, showed higher mathematics achievement.

In the literature on numerical magnitude processing, there has been an ongoing debate on whether the representation of numerical magnitudes per se, or its access via symbolic digits, is important for mathematical achievement (De Smedt & Gilmore, 2011; Rousselle & Noël, 2007; see also De Smedt et al., 2013, for a review). This question is typically approached by comparing children's performance on symbolic and nonsymbolic tasks. If both symbolic and nonsymbolic tasks predict individual differences in mathematical achievement, this indicates that numerical magnitude processing per se is crucial for mathematical achievement. On the other hand, if only symbolic, but not nonsymbolic tasks, predict general mathematical skills, the hypothesis of the access to numerical meaning from symbolic digits is favored. Correlational evidence favoring the first hypothesis (Halberda et al., 2008; Libertus, Feigenson, & Halberda, 2011; Lonnemann et al., 2011; Mussolin, Mejias, & Noël, 2010) and the second one (De Smedt & Gilmore, 2011; Holloway & Ansari, 2009; Landerl & Kölle, 2009; Rousselle & Noël, 2007; Sasanguie, De Smedt et al., 2012; Vanbinst, Ghesquière, & De Smedt, 2012) has been reported, and it remains to be determined whether these associations are causal or not (see De Smedt et al., 2013, for a review).

Although many studies have examined the association between numerical magnitude processing and mathematical skills, the major part of these studies are cross-sectional in nature and therefore do not allow us to establish causal connections. De Smedt and colleagues (2009) provided longitudinal evidence that the speed of comparing numbers assessed at the start of formal schooling is predictively related to subsequent general mathematics achievement in second grade. Halberda and colleagues (2008) demonstrated this longitudinal evidence for nonsymbolic processing, showing that individual differences on a nonsymbolic magnitude comparison task in the present correlated with children's past scores on standardized math achievement tests, extending all the way back to kindergarten. In the same way, individual differences in number line estimation are predictive for math achievement, measured using a curriculum-based standardized test (Sasanguie, Van den Bussche & Reynvoet, 2012). These longitudinal studies suggest that symbolic and nonsymbolic processing may have a causal role in determining individual math achievement, although this possibility needs to be verified by means of experimental research designs, that is, intervention research.

Educational Interventions

There are a few studies that have examined the effect of educational interventions on the development of numerical magnitude processing (see De Smedt et al., 2013, for a review) and such intervention studies are a good way to explore causal associations. These intervention studies trained on a broad range of numerical activities, such as number recognition, playing board games, counting, and had significant effects on children's numerical magnitude processing and mathematical abilities (Griffin, 2004; Jordan, Glutting, Dyson, Hassinger-Das, & Irwin, 2012). There are also studies that have specifically focused on training numerical magnitude processing as conceived and operationalized in this contribution. For example, a set of various studies have investigated the effects of playing with linear number board games on preschoolers' symbolic number line estimation and numerical magnitude comparison skills, counting abilities, and numeral identification knowledge (Ramani & Siegler, 2008, 2011; Ramani, Siegler, & Hitti, 2012; Siegler & Ramani, 2009; Whyte & Bull, 2008). These studies comprised two conditions, that is, a numerical board game and a color board game, the latter being a control condition. Findings revealed stable improvements in performance on number line estimation and symbolic comparison after playing with the numerical board game, but not with the color board game. Another example is the study of Kucian et al. (2011), which used the game "Rescue Calcularis," which involves symbolic number line estimation tasks in combination with addition and subtraction problems. They showed that the symbolic number line estimation skills of children improved after playing this game, just like their arithmetic skills. Finally, another set of studies used the game "The Number Race," which involved symbolic and nonsymbolic numerical magnitude comparison and number board games (Obersteiner, Reiss, & Ufer, 2013; Räsänen, Salminen, Wilson, Aunio, & Dehaene, 2009; Wilson et al., 2006; Wilson, Dehaene, Dubois, & Fayol, 2009; Wilson, Revkin, Cohen, Cohen, & Dehaene, 2006) and led to positive effects on comparison skills and mathematics achievement.

From these intervention studies, it remains unclear whether numerical magnitude processing interventions should focus on training with a numerical magnitude comparison or a number line estimation task (=question 1). It also remains to be determined whether there is a different impact of training symbolic versus nonsymbolic numerical magnitude processing skills (=question 2). In order to answer these two questions, we developed four game-based learning environments[1] (see Fig. 1).

The first two game-based learning environments, which are designed and used to answer the first question, comprise either a numerical magnitude comparison or a number line estimation training (Fig. 1). Both games involve symbolic as well as nonsymbolic stimuli. With these two game-based learning environments, it is feasible to appraise the effect of both interventions on children's numerical magnitude processing skills and on their mathematical skills. These games are developed to be played by children in the last (third) year of kindergarten or the first year of elementary school, and therefore only Arabic digits up to 9 are used. We will refer to these game-based learning environments as K-games (i.e., kindergarten games).

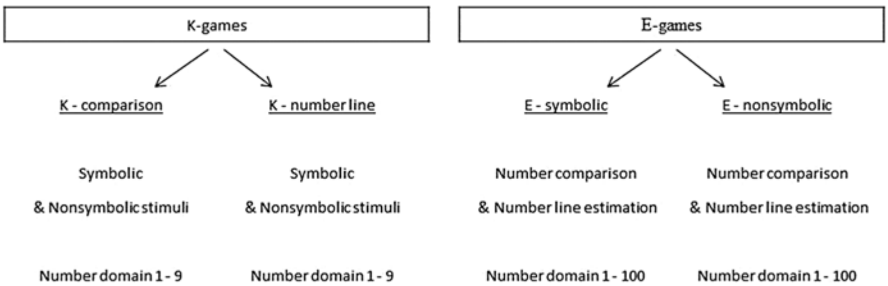

Fig. 1 Overview of the four games

[1] Learning environment is used in the broad sense of the term in this contribution. The games described in this contribution are just one type of learning environment, namely a training environment.

To address question 2, we designed two other game-based learning environments that stimulated either the processing of symbolic or nonsymbolic numerical magnitudes. By developing and contrasting two interventions that either focus on symbolic or nonsymbolic numerical magnitude processing (Fig. 1), we are able to examine whether symbolic or nonsymbolic numerical magnitude processing is causally associated with mathematical achievement. This will allow us to evaluate whether one of these interventions has a larger effect on children's numerical magnitude processing and mathematical skills, than the other. Both game-based learning environments involve a numerical magnitude comparison and number line estimation task. These games focus on children in the first years of elementary school and use numbers in the number domain 1–100. We will refer to these game-based learning environments as E-games (i.e., elementary school games).

All interventions are game-based to increase the richness and appeal of the mathematical task, hoping to provide a motivating environment to play in. Especially for young children, combining learning with playing might be an important motivational aspect (see Connolly, Boyle, MacArthur, Hainey, & Boyle, 2012, for a review). The game-based learning environments are designed to be played on tablets and computers, and taking into account the popularity of these multimedia devices, this also offers opportunities to practice the numerical magnitude processing skills at home.

All four game-based learning environments are developed in a similar environment, using the same storyline of "Dudeman & Sidegirl: Operation clean world". Although the game-based learning environments are developed for children of specific age groups, the number domains can be adapted for different age groups.

Dudeman & Sidegirl: Operation Clean World

Story Line

Children are presented with the story that the world is polluted. They have to make the world beautiful again by finding the animals that are hiding. There is a small superhero, Sidegirl, who needs to help the ill superhero, Dudeman. As a player of the game, he/she needs to look for animals in three different parts of the world, that is, under water, on land, and in the air.

Game Elements

Instructions during the game. At the start of the game, children are shown a short movie that explains the purpose of the game, that is, to collect as many animals as possible. From this point on, children have a shared control over their game progress. They can start the game and go through the levels by controlling their own pace, which can be defined as a type of learner control (Scheiter & Gerjets, 2007). Every child has a unique user-id to game-login. Thereby, it is possible to take a break and start again later at the level they ended. However, the learner control is limited because the computer program makes decisions about the amount of instruction (Lee & Lee, 1991), which is identical for all children.

At the beginning of each level, a voice-over explains the goal of the task to the player. This instruction is adapted to the specific characteristics of the level, that is, the instruction depends on the specific task (comparison or number line estimation), the format of the stimuli (symbolic or nonsymbolic), and the number domain. The number of levels and their content differ for each game and are explained in greater detail below.

Instructional design principles. Our game-based learning environments rely on the idea that one can enhance specific skills by part-task practice. This part-task practice involves repeated practice of recurrent constituent skills in the learning tasks and is one component of the 4C/ID-model (Van Merriënboer, Clark, & de Croock, 2002). Part-task practice is mainly used to promote the automatization of a specific skill. Therefore, it comprises simple tasks or skills, which are repeatedly practiced, and feedback on the quality of performance is provided during practice, immediately after performing a particular step in a procedure. Comparison and number line estimation skills are considered to be part-task practices and we assume that the practice of both skills can contribute to enhance magnitude processing skills. Other components of the 4C/ID-model are learning tasks, supportive information, and just-in-time information. However, given the focus of our intervention, that is, training on the accuracy and the speed of execution of simple tasks, these components are not included in our game-based learning environments.

Content. We use numerical magnitude comparison tasks and number line estimation tasks as a basis for the game-based learning environments. To train numerical magnitude comparison processing, children need to navigate with their vehicle through the world and they are shown two groups of animals (i.e., nonsymbolic), two animals carrying an Arabic numeral (i.e., symbolic), or a group of animals and an animal carrying an Arabic numeral (i.e., nonsymbolic and symbolic) (Fig. 2). They are instructed to collect as many animals as possible and therefore need to tap the larger group of animals or the animal with the numerically larger number.

Fig. 2 The *left* figure shows a screenshot of the nonsymbolic numerical magnitude comparison task at the beginning of a trial. The *middle* figure shows a screenshot of the symbolic numerical magnitude comparison task. The *right* figure shows a screenshot of a mixed comparison trial

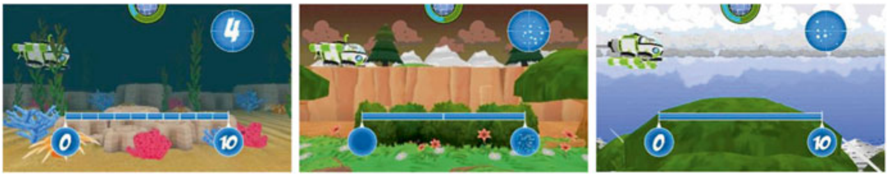

Fig. 3 The *left* figure shows a screenshot of the symbolic number line estimation task with anchor point on the units at the beginning of a trial. The *middle* figure shows a screenshot of the nonsymbolic number line estimation task with only an anchor point in the middle of the number line. The *right* figure shows a screenshot of a mixed number line estimation trial without anchor points

To train children's number line estimation skills, children need to navigate with their vehicle through the world and are shown an empty number line (Fig. 3). This number line is bounded with digit "0" (i.e., symbolic) or an empty array (i.e., nonsymbolic) on the left side and with digits "10" or "100" or an array of 10 or 100 dots on the right side. Children need to position a numerosity (i.e., nonsymbolic or symbolic), shown on the right of the screen, on the empty number line. When children tap on the correct position on the number line, that is, within the allowable range of the correct answer, the vehicle collects the animal. If the player taps on a position outside the allowable range, the animal appears on the correct position but is not collected.

Starting from this common structure four games are developed each focusing on a specific skill and age group.

K-games. The two K-games are developed to examine the differential effect of comparison versus number line training. Both game-based learning environments contain tasks in which nonsymbolic and symbolic representations are used. The two game-based learning environments consist of different levels, presented in a fixed order and characterized by increasing difficulty. For each game-based learning environment, there are specific criteria to go to the next level, which will be explained below. If the children do not reach these criteria, they have to replay the level until the target score is reached.

K-comparison game. The K-comparison game consists of 14 different levels and each level comprises 24 trials, resulting in a total of 336 trials for all levels. The levels are designed to vary in difficulty based on the *numerosities* (i.e., 1–4, 1–9, and 5–18), the *display duration* (i.e., until response and 1500 ms), and the *type of stimuli* (i.e., nonsymbolic notation, symbolic notation, and mixed notation) used in the tasks. A detailed overview of the characteristics of the levels in this game-based learning environment can be found in Table 1.

A trial is considered as correct when the player selects the larger out of two numerosities. Children need to correctly answer at least 80 % of the trials to succeed the level. This minimum score is based on several empirical studies in young children (e.g., De Smedt et al., 2009; Holloway & Ansari, 2009; Mazzocco, Feigenson, & Halberda, 2011; Sasanguie, De Smedt et al., 2012; Soltész, Szücs, & Szücs, 2010).

Table 1 Details of the K-games

K-comparison game			
Level	Numerosities	Display duration	Characteristics of the stimuli
1	1–4	UR	NS–NS
2	1–4	1500 ms	NS–NS
3	1–9	UR	NS–NS
4	1–4	1500 ms	NS–NS
5	5–18	UR	NS–NS
6	5–18	1500 ms	NS–NS
7	1–4	UR	S–S
8	1–4	1500 ms	S–S
9	1–9	UR	S–S
10	1–9	1500 ms	S–S
11	1–4	UR	NS–S
12	1–4	1500 ms	NS–S
13	1–9	UR	NS–S
14	1–9	1500 ms	NS–S
K-number line game			
Level	Benchmarks	Display duration	Characteristics of the stimuli
1	9	UR	NS–NS
2	9	1500 ms	NS–NS
3	1	UR	NS–NS
4	1	1500 ms	NS–NS
5	9	UR	S–S
6	9	1500 ms	S–S
7	1	UR	S–S
8	1	1500 ms	S–S
9	9	UR	NS–S
10	9	1500 ms	NS–S
11	1	UR	NS–S
12	1	1500 ms	NS–S
13	/	UR	NS–NS
14	/	1500 ms	NS–NS
15	/	UR	S–S
16	/	1500 ms	S–S
17	/	UR	NS–S
18	/	1500 ms	NS–S

Note. UR = until response, *NS* = nonsymbolic, *S* = symbolic

K-number line game. The K-number line game consists of 18 different levels and each level comprises 18 trials, which resulted in a total of 324 trials for all levels. Again, the levels depend on three aspects to vary in difficulty: the number of *anchor points*, the *display duration* (i.e., until response and 1500 ms), and the *type of stimuli* (i.e., nonsymbolic notation, symbolic notation, and mixed notation). A detailed overview of the levels in this game-based learning environment can be found in Table 1.

A correct answer is set to 12.5 % of the number line range on both sides of the to-be-positioned numerosity (e.g., if the child has to position the number 4 on a 0–10 number line, any answer between 2.75 and 5.25 is considered to be correct). To avoid that children get stuck up in a level because they perform too low, the cut-off score to move to the next level is set at 50 %. This criterion is based on other empirical studies (e.g., Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Booth & Siegler, 2006; Siegler & Booth, 2004; Siegler & Ramani, 2009).

E-games. The two game-based learning environments that will be explained below are developed to examine the differential effect of symbolic versus nonsymbolic numerical magnitude processing training in second grade children. Both game-based learning environments comprise a set of tasks that are variants of the numerical magnitude comparison task and the number line estimation task. One version of the game-based learning environment uses the symbolic format and the other version uses the nonsymbolic format. Each game-based learning environment comprises 32 different levels (16 levels with the numerical magnitude comparison task and 16 levels with the number line estimation task) starting with the easiest and going to the most difficult level. Each level comprises 28 trials, resulting in a total of 896 trials for all levels within a game-based learning environment. The levels are designed to vary in difficulty based on the *numerosities* in each task, the *time pressure* that is used, and the *anchor points* that are added to the number line. A detailed overview of the levels can be found in Table 2.

Each game-based learning environment starts with numbers up to 10 and becomes increasingly more difficult with numbers up to 100. In the E-games we add time pressure, as a competition element, in order to enhance automatization of children's skills and as a motivational aspect in the game. Competition is a gaming characteristic that influences motivation in the game, which might in turn influence one's performance in the game (Wilson et al., 2009). This time pressure element is an extra reward mechanism in which children received positive feedback when they are fast enough. Within each game-based learning environment children play each level first without and then with time pressure. This allows us to first train children on their accuracy and then to focus on their speed. This is done by having a shark, a rhino, or an eagle to follow them. If children are not fast enough, the animal catches them, which means that they have to start at the beginning of the level again. Children are instructed to answer each trial as fast as possible and need to avoid that the dangerous animal catches them. To indicate how close this animal is, a red bar is added to the progress bar in the middle of the screen (Fig. 2). If this red bar catches up with the blue progress bar, the child is not fast enough and is caught by the animal.

In the number line estimation task, children firstly need to succeed the levels comprising a number line with anchor points on the units (in number domain 1–10) or decades (in number domain 10–100). After this, the difficulty increases by firstly only showing an anchor point on the number 50, in the middle of the number line, followed by the most difficult levels which comprises number lines without any anchor points.

Table 2 Details of the E-games

E-symbolic game			
Level	Task	Numbers presented	Time pressure
1	NMC	Numbers up to 10	No
2	NLE	Numbers up to 10, with anchor points on units	No
3	NMC	Numbers up to 10	Strong
4	NLE	Numbers up to 10, with anchor points on units	Strong
5	NMC	One number up to 10, other up to 100	No
6	NLE	Numbers up to 10, without anchor points	No
7	NMC	One number up to 10, other up to 100	Strong
8	NLE	Numbers up to 10, without anchor points	Strong
9	NMC	Numbers from 10 to 100, same decade	No
10	NLE	Decades up to 100, anchor points on decades	No
11	NMC	Numbers from 10 to 100, same decade	Strong
12	NLE	Decades up to 100, anchor points on decades	Strong
13	NMC	Numbers from 10 to 100, different decade, compatible	No
14	NLE	Decades up to 100, anchor point on 50	No
15	NMC	Numbers from 10 to 100, different decade, compatible	Strong
16	NLE	Decades up to 100, anchor point on 50	Strong
17	NMC	Combination of levels one to eight	No
18	NLE	Decades up to 100, without anchor points	No
19	NMC	Combination of levels one to eight	Strong
20	NLE	Decades up to 100, without anchor points	Strong
21	NMC	Numbers from 10 to 100, different decade, incompatible	No
22	NLE	Numbers up to 100, anchor points on decades	No
23	NMC	Numbers from 10 to 100, different decade, incompatible	Strong
24	NLE	Numbers up to 100, anchor points on decades	Strong
25	NMC	Combination all levels	No
26	NLE	Numbers up to 100, anchor points on 50	No
27	NMC	Combination all levels	Strong
28	NLE	Numbers up to 100, anchor points on 50	Strong
29	NMC	Combination all levels	Strong
30	NLE	Numbers up to 100, without anchor points	No
31	NMC	Combination all levels	Strong
32	NLE	Numbers up to 100, without anchor points	Strong
E-nonsymbolic game			
1	NMC	Numbers up to 10	No
2	NLE	Numbers up to 10, with anchor points on units	No
3	NMC	Numbers up to 10	Average
4	NLE	Numbers up to 10, with anchor points on units	Average
5	NMC	Numbers up to 10	Strong
6	NLE	Numbers up to 10, with anchor points on units	Strong
7	NMC	One number up to 10, other up to 100	No

(continued)

Table 2 (continued)

E-symbolic game			
Level	Task	Numbers presented	Time pressure
8	NLE	Numbers up to 10, without anchor points	No
9	NMC	One number up to 10, other up to 100	Average
10	NLE	Numbers up to 10, without anchor points	Average
11	NMC	One number up to 10, other up to 100	Strong
12	NLE	Numbers up to 10, without anchor points	Strong
13	NMC	Numbers from 10 to 100, different decade, large ratio	No
14	NLE	Numbers up to 100, anchor points on decades	No
15	NMC	Numbers from 10 to 100, different decade, large ratio	Average
16	NLE	Numbers up to 100, anchor points on decades	Average
17	NMC	Numbers from 10 to 100, different decade, large ratio	Strong
18	NLE	Numbers up to 100, anchor points on decades	Strong
19	NMC	Numbers from 10 to 100, different decade, small ratio	No
20	NLE	Numbers up to 100, anchor point on 50	No
21	NMC	Numbers from 10 to 100, different decade, small ratio	Average
22	NLE	Numbers up to 100, anchor point on 50	Average
23	NMC	Numbers from 10 to 100, different decade, small ratio	Strong
24	NLE	Numbers up to 100, anchor point on 50	Strong
25	NMC	Combination of all levels	No
26	NLE	Numbers up to 100, without anchor points	No
27	NMC	Combination of all levels	Average
28	NLE	Numbers up to 100, without anchor points	Average
29	NMC	Combination of all levels	Strong
30	NLE	Numbers up to 100, without anchor points	Strong
31	NMC	Combination of all levels	Strong
32	NLE	Numbers up to 100, without anchor points	Strong

Note. *NMC* = numerical magnitude comparison, *NLE* = number line estimation

For each game, there are specific criteria to move to the next level, which will be outlined below. All these criteria were tested in a pilot study, which showed that these criteria were set appropriately for the children of this age. If the children do not reach the criterion, they have to replay the level until the criterion score is reached.

E-symbolic game. In this version of the game-based learning environment, children have to perform at an accuracy of 90 % on the numerical magnitude comparison task to succeed that level. Again, this criterion score is based on previous empirical studies (e.g., Linsen, Verschaffel, Reynvoet, & De Smedt, 2014; Vanbinst et al., 2012), which included symbolic comparison tasks in children of a similar age. In the levels that comprise a number line estimation task, children need to answer 70 % of the trials correctly to pass the level, taking into account the allowable error range of 12.5 % around the to-be-positioned magnitude. This criterion is based on a study by Linsen et al. (2014).

Children first play two levels without time pressure (one with a numerical magnitude comparison task and one with a number line estimation task), followed by two similar levels with strong time pressure. They are given 500 ms to respond and the residual time of each trial is added to the next trial cumulatively, within the level.

E-nonsymbolic game. In the numerical magnitude comparison task levels, children are required to achieve an accuracy of at least 75 %. In the number line estimation task, their accuracy needs to be above 60 %, again taking into account the error range of 12.5 %. These criteria are based on a study by Linsen et al. (2014).

Furthermore, children first play a numerical magnitude comparison task and a number line estimation task with average time pressure (1500 ms) followed by these tasks with strong time pressure (500 ms). Within each level, the residual time of each trial is again added to the next trial cumulatively.

Motivational aspects. Motivation is an important aspect in game-based learning and, therefore, several motivational aspects are added to the game-based learning environments. By situating the different levels into an attractive story, we want to keep the game interesting for the children. All game-based learning environments comprise three different polluted worlds and the player needs to clean these. The first levels (five levels for the K-comparison game, six levels for the K-number line game, and 12 for the E-games) are situated under water. Next, the player moves on to the land (five levels for the K-comparison game, six levels for the K-number line game, and ten for the E-games) and finally into the air (four levels for the K-comparison game, six levels for the K-number line game, and ten for the E-games). While progressing through each zone, the world becomes increasingly clean and the music changes accordingly, which provides an extra audiovisual reward for good performance. Additionally, each level is populated by a different kind of animal, adding a second visual incentive to continue playing.

Feedback. Motivating feedback appears visually and auditory when the player gives an answer. Nielsen (1995) formulated principles for user interface design, one of which stated that the game should always keep the player informed about what is going on through appropriate feedback. Visual feedback is provided by a blue bar in the middle of the screen indicating the progress of the child in this level (Fig. 4). By adding this bar, children can see how many trials they already completed and how many trials they still need to do. Auditory feedback is given by a voice-over, following the theory of multimedia learning that states that it is better to present words as auditory narration than as visual on-screen text (Moreno & Mayer, 2002), especially for children in kindergarten, which are not yet able to read feedback presented in words. This feedback encourages the children to perform well, independent of their performance. If the child waits too long to answer a trial, the voice-over encourages the child to hurry up.

Different kinds of feedback on accuracy are integrated in the game-based learning environment. Firstly, children are given feedback on the accuracy of each trial they play. More specifically, the vehicle in the comparison game collects the animal(s) when they correctly tap on the numerically larger item and a positive "ping" sound is played. If they do not respond correctly, the vehicle does not collect the animal(s) and a negative error sound is played. In the number line estimation

Fig. 4 The *round bar* at the top of the screen shows the progress in the level by the *blue color* that fills up the *round bar*. In the E-games, the *red bar* indicates the time pressure element, i.e., how close is the animal that can catch them. This *red bar* also fills up the *round bar*. If the *red bar* catches up with the *blue bar*, the player was not fast enough and has to replay the level again

task, the animal appears and the vehicle collects the animal when the child's answer is within the allowable range of the correct answer, but the animal is not collected by the vehicle when an answer outside the allowed range is given. In this case, the animal still appears at the position of the correct answer and hereby provides the player with feedback on the correct answer. Again, a corresponding sound is played to indicate whether the child answered correctly or not.

Secondly, children are given feedback on the overall accuracy of a level. After finishing a level, children receive general feedback on their performance in that level, that is, whether they can go to the next level or not. Specifically, if they solve the required percentage of correct trials, the world becomes more beautiful and they can start the next level. If they do not reach the required percentage of correct trials, Dudeman points out to Sidegirl that she did not collect a sufficient amount of animals and she has to restart the level until the required percentage of correct trials is reached.

Logging

The game-based learning environment is developed to register a great amount of data while children played the game. These data are stored locally during the session and are uploaded to an online central database at any chosen time. This allows the user to play in any environment, without the requirement of a wireless Internet connection, as for example is the case in many schools. First, all speed and timing measures are saved. This includes children's response time per trial, their total training time per session, and the total time that the game is played. Second, children's answer and its accuracy are saved for each trial.

Technical Specifications

The game is developed for pc as well as iOS and Android tablets. To avoid that the data collection would be influenced by the different native aspect ratios of different tablets (4:3 for iOS tablets, and 16:10 for Android tablets), all critical user interface elements are fixed to a 4:3 aspect ratio. In other words, when running on a wider screen, the extra horizontal space is occupied only by background art, and not by interactive elements.

The Unity engine was used for development of the game, due to its expansive community, affordable price, and ease of publishing code to multiple platforms. Data are stored locally on the tablets using a SQLite database, and subsequently synchronized to a server-side MySQL database.

Conclusion

The four game-based learning environments described in this contribution were specifically developed for two concrete studies, one in which we investigated whether numerical magnitude processing interventions should focus on training with numerical magnitude comparison or number line estimation, and one in which we determined whether there is a different impact of training symbolic versus non-symbolic numerical magnitude processing skills. However, despite these specific research questions, the content of our game-based learning environments can be adapted to fit other research questions. Currently, only these four versions are available, but it would, for example, be possible to use these game-based learning environments with older elementary school children simply by adapting the numerosities that are presented. One could also separate the four different basic components in the games, that is, symbolic numerical magnitude comparison, nonsymbolic numerical magnitude comparison, symbolic number line estimation, and nonsymbolic number line estimation, and only use one of these tasks, several of these tasks, or all of them. At this time, the four game-based learning environments are completely fixed, so the player itself cannot change the content of the game. For future research, it would be interesting and useful to make the game modular. In a school context, for example, this adaptation to the game would allow teachers to decide on the characteristics of the game.

Besides that, as a great amount of data is logged while children play the game, these games are also appropriated to be used for microgenetic research concerning the development of the skills trained in the games. Additionally, our game-based learning environment was developed to be played on tablets and computers, which provides the opportunities for a widespread use of the game.

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