Therapy software for enhancing numerical cognition

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Abstract: We present a novel software for the acquisition of central components of number processing and representation as well as mathematical understanding. The software is based on current neurocognitive concepts and insights. The learning process is supported through multimodal cues encoding different properties of numbers. The learning environment features 3D graphics and interaction components and thus allows immersion in a playful 3D world. To offer optimal learning conditions, a Bayes net user model completes the software and allows adaptation to a specific user. A first version of the software will be tested with normally achieving and dyscalculic children within a multi-center study in Zurich, Berlin, and Potsdam starting in 2011.

1 Introduction

Developmental dyscalculia is a specific learning disability affecting the acquisition of arithmetic skills. Genetic, neurobiological, and epidemiological evidence indicates that developmental dyscalculia, like other specific learning disabilities, is a brain-based disorder, although poor teaching and environmental deprivation have also been implicated in its aetiology [**5**]. The prevalence of developmental dyscalculia in German-speaking countries is about 6% [**7**].

1.1 Previous work

In a previous study, we developed and evaluated a computer-based training program for children with developmental dyscalculia (DD) [**4**]. In general, children with and without DD could benefit from the training. This was indicated by: (i) improved spatial representation of numbers and (ii) the number of correctly solved arithmetical problems. During the training, the control children showed the typical fronto-parietal network brain activations associated with number processing. In contrast, dyscalculic children showed main activation in medial frontal areas. Statistical group comparison corroborated that children with DD showed less activation in bilateral parietal regions. After training, less brain activation was evident in mainly the frontal lobes in both groups. Taken together, the training improves the spatial representation of numbers and arithmetical performance. Reduced brain activation in children with DD may reflect neurophysiological deficits in core regions for number processing. After the training, children rely less on frontal areas associated with reduced working memory and attentional needs. Our study shows that the training leads to an improved spatial representation of the mental number line, which facilitates processing of numerical tasks, and hence requires less neuronal capacity.

2 Concept

2.1 Design

The presented software is based on two important models of dyscalculia and the development of mathematical understanding.

The triple-code model (figure 1) postulates three modules for number processing, each of them using a different representation of number [**1**]. In the verbal module (auditory verbal word frame), numbers are represented as number words. In the Arabic module (visual Arabic number form), the Arabic notation is used for the representation of numbers. And in the analogue module (analogue magnitude representation), numbers are depicted as an analogue locus on an internal number line. There are different abilities attributed to each module. Counting, exact mental calculation, and arithmetical fact retrieval are mainly executed in the auditory verbal word frame. The visual Arabic number form is responsible for parity judgments and multi-digit operations. Approximation tasks as well as number comparisons are attributed to the analogue magnitude representation.

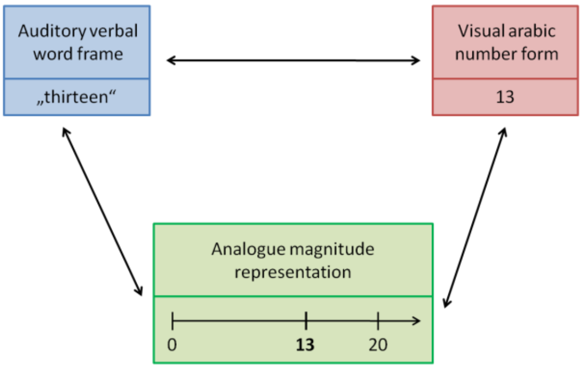
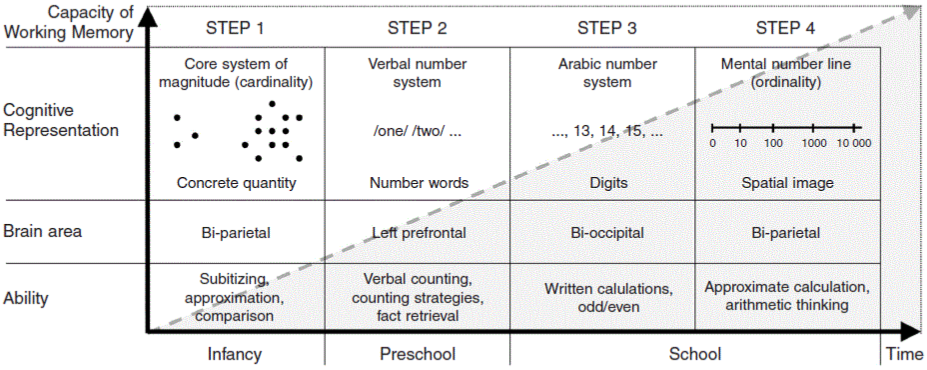


Figure 1: Triple-code model from Dehaene (1992).

According to the 4-step developmental model (figure 2), this modular system develops hierarchically over time depending on the capacity and availability of functions of general intelligence (attention, working memory, processing speed) and on experiences [**8**]. Already babies can capture and differentiate sets according to their cardinality. This core-system representation of cardinal magnitude and its functions provide the basic meaning of number (step 1). This is a necessary precondition for children to associate a perceived number of objects with spoken or written symbols. The linguistic symbolization (step 2) as well as abilities such as the principles of counting, increase/decrease schemes and simple arithmetic operations performed by counting, develop in pre-school age without systematical teaching. The Arabic symbolization (step 3) of numbers is then learnt in school. It is a precondition for the development of the analogue magnitude representation.



Capacity of Working Memory	STEP 1	STEP 2	STEP 3	STEP 4
Cognitive Representation	Core system of magnitude (cardinality) Concrete quantity	Verbal number system /one/ /two/ ... Number words	Arabic number system ..., 13, 14, 15, ... Digits	Mental number line (ordinality) 0 10 100 1000 10 000 Spatial image
Brain area	Bi-parietal	Left prefrontal	Bi-occipital	Bi-parietal
Ability	Subitizing, approximation, comparison	Verbal counting, counting strategies, fact retrieval	Written calulations, odd/even	Approximate calculation, arithmetic thinking
	Infancy	Preschool	School	

Figure 2: 4-step development model. The shaded area below the dashed line denotes the increasing capacity of the working memory.

The three different number representations and the translation between them form the basis of number processing. Therefore, we developed a special number design to enhance these representations and at the same time facilitate numerical understanding. We encode the properties of numbers with auditory and visual cues such as color, form and topology. The different positions (one, ten, hundred) of the place-value system are represented with different colors. This aspect is enhanced by showing a graph where each digit of a number is attached to a different branch (figure 3). This representation facilitates the development of the Arabic symbolization as well as the translation between the auditory verbal word frame and the visual Arabic number form.

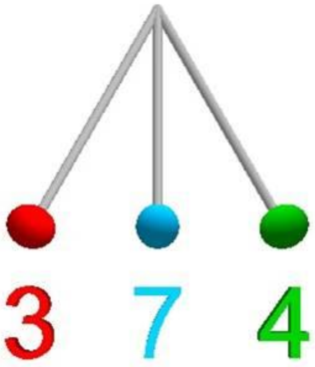


Figure 3: Visualization of number with color and topology.

Furthermore, the cardinal magnitude of number is emphasized by illustrating the number as a composition of blocks with different colors, i.e., as an assembly of one, ten and hundred blocks (figure 4, top). In this way, we highlight the fact that numbers are composed of other numbers and again refer to the Arabic symbolization. These different blocks are arranged on a line from left to right to make a connection to the analogue magnitude representation. To stress this representation even more, we also show a diverse perspective of the blocks, where they are directly integrated in the number ray (figure 4, bottom).

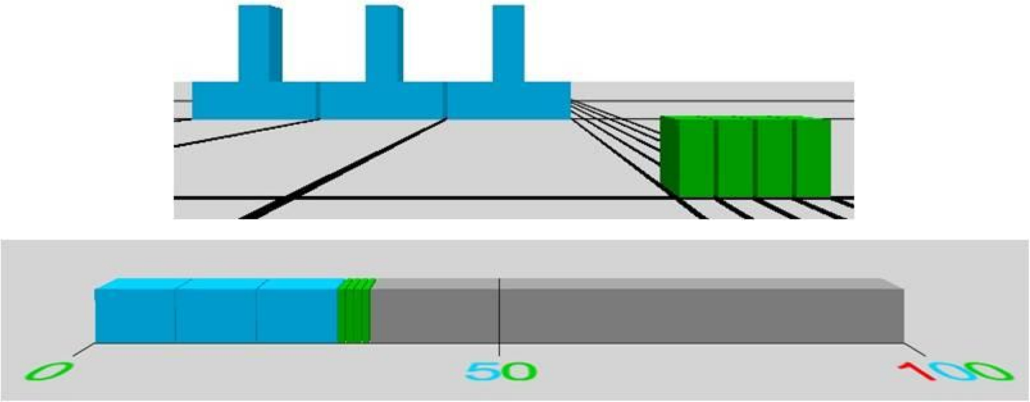


Figure 4: Visualization of number using colored blocks (top) and colored blocks integrated into the number ray (bottom).

All these special number designs are shown simultaneously in each sub-game of the software.

As a complete mathematical understanding requires the presence of all three number representations and the translation between them as well as the ability to master operations and procedures with numbers, the software is structured into two areas. Each area consists of individual therapy games constructed in a way to use the special number design:

(i) Cognitive number representation and numerical understanding

The first area focuses on cognitive number representation and numerical understanding as well as transcoding between different numerical representations. Furthermore the games concentrate on different aspects of numerical understanding that support the development of cardinal and ordinal principles of numerosity [**6**]. Basic games feature either a specific translation between two different number representations or highlight an aspect of numerosity. The more difficult games require a combination of translations and knowledge about principles of numerosity. One important game in this area is for example the landing game (figure 5). In this game, the child needs to find the analogue position of an Arabic digit on a number ray.

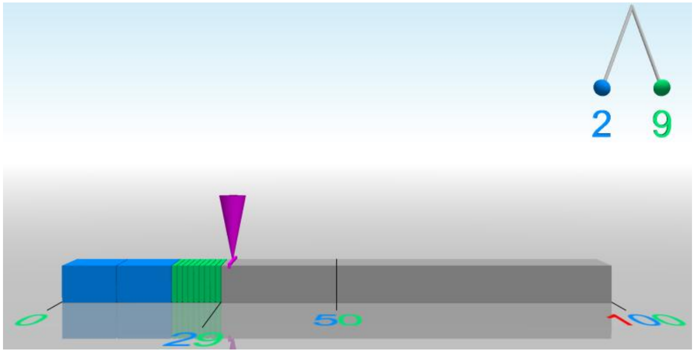


Figure 5: Illustration of landing game in the number range from 0-100.

(ii) Cognitive operations and procedures

The second area focuses on cognitive operations and procedures. Each of the games in this area trains a mathematical operation at a specific difficulty level. To consolidate the skills acquired in the first area, the representation of the task and its solution makes use of different number representations. The games in this area are hierarchically ordered according to their difficulty. We differentiate between two types of difficulty. The so-called vertical difficulty denotes the inherent difficulty of the task, e.g., an addition in the number range from 0-10 is easier than an addition in the range from 0-100. The horizontal difficulty depends on the presentation of the task and on the allowed means to solve the task, e.g., solving an addition with material is easier than doing a mental calculation.

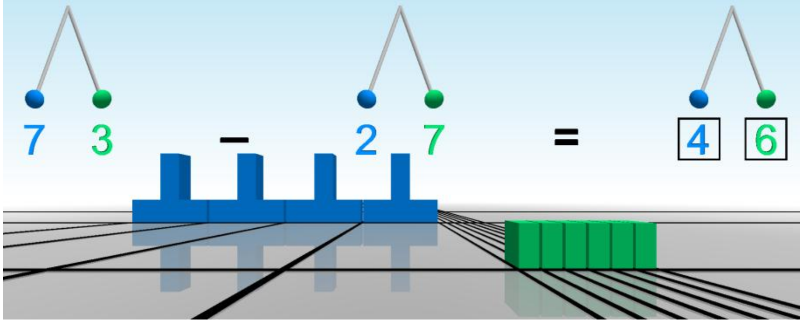


Figure 6: Illustration of addition game in the number range from 0-100.

2.2 Game control

In order to offer optimal learning conditions, the software adapts to the needs of a specific user. At the beginning of the training, all users start with the same game. After each input, the software estimates the actual knowledge state of the user and displays a new task adjusted to this state. In this way, the velocity of advancement can be adapted to each user and specific problems of a user can be recognized and addressed.

In order to do so, the software holds an internal representation of the user's knowledge. In our case, the knowledge is modeled using a dynamic Bayes net. This net consists of a directed acyclic graph representing different mathematical skills and the dependencies between them. These skills can again be associated with the two areas of the software:

(i) Cognitive number representation and numerical understanding

The first area contains skills regarding number representations and general number understanding. The skills are ordered hierarchically according to two criteria. The coarse criterion is the separation between the different number ranges. Within each number range, the hierarchical ordering is based on the 4-step development model.

(ii) Cognitive operations and procedures

Skills regarding procedures and operations with numbers are attributed to the second area. Again, a hierarchical ordering of the skills is performed. Here the first criterion is the split into the different operations, i.e., addition and subtraction. Within a specific operation, we order the skills according to their vertical and horizontal difficulty described above.

As we cannot observe the skills of the user directly, the software has to infer them by posing specific tasks and evaluating the user actions. Such observations indicate the presence or absence of a particular skill with some probability. Therefore, we assign all types of tasks and their outcome to the different skills (figure 7).

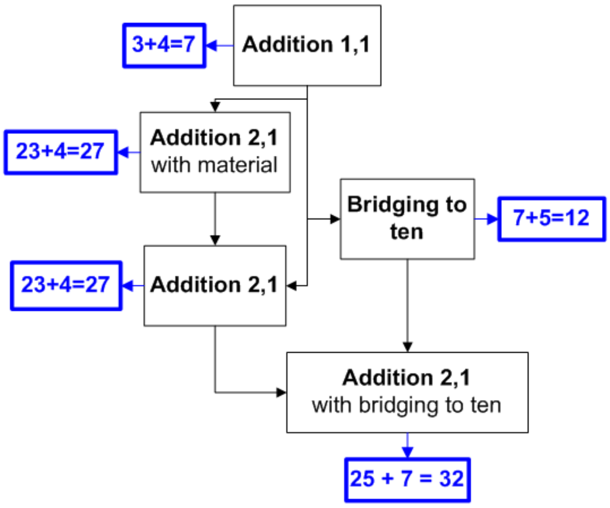


Figure 7: Extract of skills, dependencies among them, and associated tasks in second area.

Each input of the child is now evaluated and fed into the Bayes net accordingly. In this way, the net can be updated with each input of the student and compute an estimate of the student's actual knowledge state. Based on this estimate, the next game to play is then selected and adapted to the specific student.

3 Study

A first version of the software will be tested with normally achieving and dyscalculic children within a multi-center study in Zurich, Berlin, and Potsdam starting in 2011. The study will be conducted using a cross-over design, both groups of children will be divided into a training group, a control training group and a waiting group. They will play with the software for 20 minutes per day on five days per week during 6 weeks. As a control training, the computer-based dyslexia therapy software Dybuster will be used [**3**]. To prove the effect of the training and its temporal stability, psychometric data will be collected at four specific points in time. Tests include measurements regarding intelligence, attention and working memory as well as different methods to measure number processing and calculation, math anxiety and the so called "spontaneous focusing on numerosity" (SFON) [**2**]. We expect that the training with our software will have positive effects on the development of mathematical understanding which will be reflected in the different measurements on number processing and calculation as well as in the SFON test.

4 Conclusion

We presented a new software for the acquisition of central components of number processing and mathematical understanding. The structure of our software is based on neurocognitive models. The number design developed for the software enhances important aspects of number understanding and facilitates learning of important concepts of number. The adaptivity of the software allows to adjust learning speed and to focus on specific problems of each particular user. Pilot tests with a first prototype have shown that the playful environment and the interaction components increase motivation of children positively, one of the most important qualities of a successful training. In the multi-center study starting in 2011, we will be able to assess our software in terms of progress in mathematical understanding as well as other effects such as increased motivation. With the data gathered during the study, we will also analyze and in a next step further improve the control mechanism of the software in order to make the software even more adaptive to the user.

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