Hands-On Math: A Training System for Children with Dyscalculia

Georg Erfurt
Eva Hornecker
Jan Ehlers
Bauhaus-Universität Weimar
99423 Weimar, Germany
georgerfurt@gmail.com
eva.hornecker@uni-weimar.de
jan.ehlers@uni-weimar.de

Silke Plaschkies
IPF Institut für pädagogische Förderung
99867 Gotha, Germany
IPF-Gotha@live.de

Figure 1: Test participant using the system.

ABSTRACT

Dyscalculia affects comprehension of numerical mathematical problems, working with numbers and arithmetics. We describe our work on a training system for an exercise that trains connections between verbal and numerical representations of numbers and finger counting. Fingers support embodied cognition and constitute a natural numerical representation. We describe the design rationale and iterative development process, and first evaluation results for our system that enables children to train without guidance and feedback by a trainer.

KEYWORDS

Embodiment; Learning; Counting; Neurodiversity; Gesture Input; Marker-based tracking.

CHI'19 Extended Abstracts, May 4–9, 2019, Glasgow, Scotland Uk

ACM ISBN 978-1-4503-5971-9/19/05
https://doi.org/10.1145/3290607.3313012

INTRODUCTION

While dyslexia is a well-known learning disability, dyscalculia (see sidebar) is less well understood [2]. Several embodied and tangible interaction projects have sought to address dyslexia [5, 6, 14]. In contrast, to our knowledge, no intervention systems for arithmetic skills that rely on embodied and tangible interaction have been developed, apart from simple touchscreen interactions. Given various playful methods associated with Montessori /Fröbel approaches, such as Cuisenaire rods, and known advantages of physical manipulatives for children's numerical strategies [13], this is surprising.

With the IPF Gotha experts, we identified an existing exercise, established to improve mathematical skills, that has children show fingers to represent numbers. However, the exercise is time consuming and needs supervision by a trainer - and most children only have a weekly 1-hour session at IPF. This along with its simple nature makes the exercise a target for digital support. This would enable children to train at home, and could also be used as as waiting-time filler and preparation before a tutoring session, thus increasing practice. Moreover, it could enable speed and progress tracking. We describe the background for the exercise chosen for augmentation, the design of our system, and its iterative design and testing process. We discuss the design and technical challenges involved in creating a digital version of an existing activity which provides real-time automated feedback. Current evaluation results indicate that children consider the system to be motivating, fun, and challenging.

Dyscalculia [10] is thought to be a neurobiological disorder and learning disability that does not affect general intelligence. It refers to permanent difficulties with comprehension of mathematical problems, working with numbers, and arithmetics [2].
Dyscalulics have problems understanding the meaning of numbers; they struggle learning the number word sequence, with counting, arithmetic facts, the Arabic number system, its rules and operators, and transcoding from one system to another (e.g. numbers to words). An estimated 3-7 % of children are affected [2]. Problems with basic numerical skills can make it difficult to focus, affect working memory and ability to remember numbers. Often children also have ADHD (attention deficit hyperactivity disorder), further limiting their ability to concentrate.

One of the authors of this paper leads the IPF Gotha, a tutoring center for children with learning difficulties (dyscalculia, dyslexia, ADHS), that provides training in math, German and English as well as learning strategies. She has a diploma in dyscalculia and dyslexia training. Besides her, there are three freelance teachers.

BACKGROUND AND MOTIVATION

Basic skills for mastering fundamental number concepts are particularly important in treating dyscalculia [2]. Dyscalculics need far more practice and repetition than neurotypical children to understand and memorize basic numerical concepts. Drill exercises can help to internalize and automate procedural knowledge, which then enables higher-level activities. The drill exercise chosen trains the connection between number words, signs, and number concepts in an embodied way. Neurocognitive science and math education agree that finger counting has an important role for basic mathematical skill and concept acquisition [1, 2, 9], as fingers constitute a natural numerical representation. It provides multi-sensory input, externalizes, helps reciting the numerical chain and keeping track of mental calculations. Finally, it embodies our 10-base numerical system. The ability to mentally represent and differentiate fingers is strongly associated with children's numerical abilities [9, 11].

Counting ability is solidified in several steps [7] where the integration of different abilities is important. Three independent neural networks are involved in number processing: the auditory verbal frame (number words), an analogue magnitude representation (an imagined number line) and Arabic numbers [4]. Motoric deficits also influence development of counting and calculation, as finger counting and cognitive representation of fingers is important in this process [2].

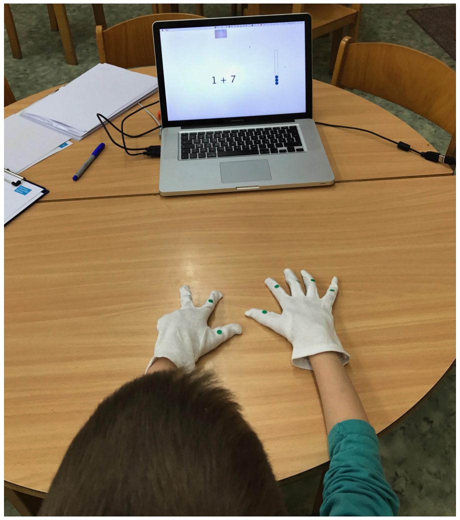

Figure 2: Green markers on white gloves provided the best contrast for detection. The system was tested with a MacBook Pro (in pilot testing and the final larger study) with a FullHD webcam mounted on a tripod.

Note that we are agnostic regarding whether a dyscalculia diagnosis adheres to a disability model that may not acknowledge neurodiversity and its associated strengths [3]. Our main motivation is that children benefit from early intervention, which can increase success at school, reduce experienced stress (math anxiety) and increase self-esteem.

THE FINGER COUNTING EXERCISE AND OUR SYSTEM

Our software implements the same overall structure as a tutored exercise used at IPF Gotha, that was identified as a candidate for digital support. The child sits at a table with the hands placed on it. A trainer calls numbers from 1 to 10, and the student shows the number with their fingers. This is done 20 times, semi-randomized. In a second phase, simple addition tasks are given where the results range from 0 to 10. This exercise helps to automatize the link between numbers and quantities, using fingers as external representation. Another learning goal is to internalize finger patterns in counting, and how larger numbers can be split up into 5+x, which then helps in learning the multiplication tables. In dyscalculia, these patterns tend to be inconsistent, 7 being represented as 5+2, and next time, with 4+3 fingers on each hand, thus training is important.

Our digital system also has simple numbers and then additions, twenty subtasks each, in randomized order. Instructions are provided via voice output and numbers displayed on-screen. Intentionally, there is no negative feedback, as this could be demotivating or might disrupt learners who are slow in deciding on the correct answer. Learners receive visual and auditory feedback ('Correct') once they display the correct number of fingers. The graphical interface is as minimalistic as possible to reduce distraction (see figure 3). The system relies on camera-based marker detection, which was the most reliable solution for unknown light conditions and an inexpensive setup. Markers are attached to gloves worn for the exercise. Each session starts with calibration, ensuring the user's hands are in the correct position to detect markers, which also reminds users of where the detection area is.

DEVELOPMENT PROCESS AND INSIGHTS

The system was developed in an iterative process. We began by observing a tutoring session at IPF, that gave insight into system requirements. Repeated user tests determined an acceptable compromise between technical tracking accuracy and speed of detection. For all studies, informed consent was given by parents, who received an information letter upfront with the consent form.

We first observed a supervised 45 minute training session of finger counting with a newly diagnosed 10-year old boy, Mike. Important observations were: 1) inconsistent patterns of fingers shown (software thus needs to count fingers, rather than look for patterns), 2) an indecisive, tentative way of showing fingers: Mike only shifted his fingertips, with no detectable gap between fingers (see figure 4). Therefore, it was clear that we cannot rely on detecting finger silhouettes - initial ideas based on kinect-style gesture detection were devoid and other solutions required.

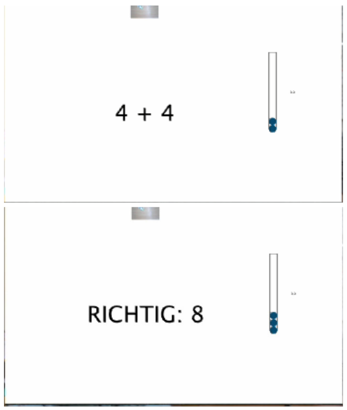

Figure 3: Screen for addition task (top) and feedback on giving correct answer (bottom). The little grey box in the top middle shows the camera view, supporting the child in placing their hands in camera view.
The screen design is intentionally minimalistic. To indicate task progression, a stack of first five blue and then five red circles builds up; in the bottom image a third circle has appeared.

Figure 4: A vague, but valid finger representation for "4", observed in the prestudy.

Most software for maths training relies heavily on gamification (e.g. MeisterCody, Rescue Calcularis [8, 12]). However, the IPF experts advised to simplify the design. Children with dyscalculia often have problems concentrating, are taxed by the exercise, and game elements or elaborate graphics could distract and divert attention. Also, children should focus on their hands, not the screen.

Approach for Tracking and Finger Detection

Requirements included that the system be cheap, robust and reliable, and to ensure reliable detection under unstable light conditions. Most algorithms for finger detection rely on visible gaps between fingers. Our observation had indicated this would not be practicable (see figure 4). 3D motion sensing devices, such as the leap motion, were also ruled out, as hovering above them is straining and they are too expensive.

We decided to use marker-based tracking as the most reliable and fast for detecting number of fingers and to use little sticky dots as markers. Depending on a child's preferences for how to show numbers, markers can be placed on top of fingers or at the fingertips. Sticking markers on user's fingers is time-consuming, as these easily fall off and need to be carefully placed - all of which would be too tedious for our user group. Thus, we use white gloves with fixed markers, which significantly reduces preparation effort for the exercise.

User tests of the first prototype revealed issues linked to false-positive detections during response preparation. While children think about how to show a result and begin to move their fingers (embodied thinking), they may accidentally briefly present the correct number of fingers. Therefore, it seemed appropriate to delay responses based on averaging techniques and to reduce feed-back latency, waiting until the hands rest. On the other hand, we found that if the system is slow in detection and response is delayed, children became impatient or confused. This indicates immediacy of feedback as a key factor for efficient use. Since the trade-off between too-fast (false-positive detection) and too-slow detection (feedback delay) could not be resolved on a purely technical level, we adjusted the procedure for the exercise. Premature detection was avoided by telling children to position their hands outside the capture area while preparing their fingers and only to move their hands in, once they want to show the result. This is not an optimal solution, but ensures reliable and user-friendly training.

Iterative Testing and Development

A first version was pilot tested with 19 1st-graders at a local school (8 girls, 11 boys, ∅ age 7), and three dyscalculic children at IPF (2 girls, 1 boy, in grade 3, 4 and 8), who use the exercise to train. This confirmed that children understood the interaction concept and could use the system autonomously after an introduction. 18 of 22 children stated in an interview that they liked the system and 72% said they would use it again. Those that did not like it, found it too easy as they were already advanced in maths. Most importantly, the test revealed issues with tracking quality and detection. Children got

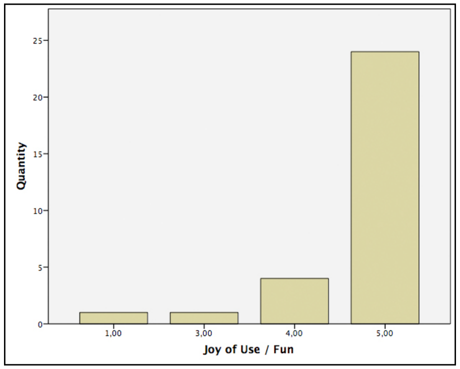

Figure 5: A clear majority stated they had fun interacting with the system. 93,33% (n=28) rated this 4 or 5 (mean of 4,667), only two had no fun.

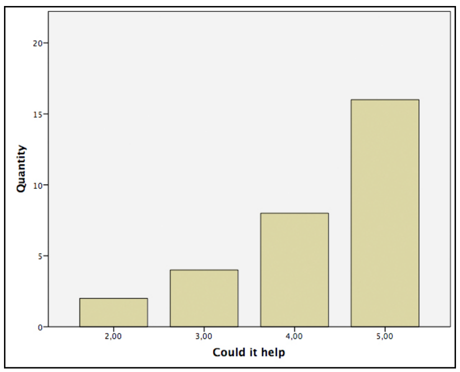

Figure 6: 80% (n=24) think the software could help in learning math and calculation (mean of 4,2667).

confused and began to re-check their fingers when the system was slow in responding. Sometimes temporary finger states were identified as a correct solution.

The next version, with improved tracking, was installed at the IPF on one of their laptops for a longer trial. Mike, whom we had observed in the pre-study and still needed to practice basic math skills, used our prototype in five training sessions distributed over four weeks. Three further children, who were more advanced, each tried the system once over this period. IPF trainers reported that Mike enjoyed working with the system, tracking worked well and there were no problems interacting, apart from detection sometimes being too slow for the children at more advanced levels. Still, all four children were reported to feel challenged by the system to train their skills.

Following further tweaking of the system, we ran a study focusing on user experience. Unfortunately, at any point, there are only has a few diagnosed children at IPF. The children involved so-far had all progressed beyond the exercise. Therefore, we recruited children, who still learn to count and relate the various numerical representations with each other: primary school pupils in 1st grade. In collaboration with teachers from two local schools, the system was tested with 30 children (6-8 years old, 18 boys, 12 girls). All children used the system alone. They were recorded with a camera and microphone to capture hands, facial and verbal expressions. Following a brief introduction, children put on gloves and went through the exercise with 20 number tasks and 20 additions. A follow-on questionnaire used the smileyometer [15], a 1-5 Likert scale to ask whether they had fun, would like to use the system again, think it is helpful for learning, and if it was OK to wear gloves.

On average, each interactive session took 7:07 minutes including calibration, task 1 and task 2. Almost all children had fun using the system (figure 5). Just over half (18) said they would use it again. probably because many were already proficient counting. Nevertheless, 80% thought the software could help learning maths (figure 6). 90% (27) were OK with or even liked the gloves. Logfiles revealed huge differences in how long children took, with the average time for a successful task between 774 and 4217 ms. Premature detection still was somewhat of an issue, but only occurred in 7,5% of trials. Videos revealed that most children quickly learned where to place their hands, and to only place them into the detection area when finished thinking. During interaction, the children looked concentrated and did not laugh or smile (even those that stating having a lot of fun with the system). But when receiving the positive feedback 'Correct', their facial expression quickly changed to a smile.

CONCLUSION

We provide the (we believe) first dyscalculia training system based on principles of embodied cognition, which uses direct gestural interaction. Iterative testing provided valuable insights for the design of a minimalistic, practice-oriented intervention system. Despite our decision to forego any game mechanics, children were eager to complete all arithmetical tasks, said they had fun, and smiled when their answers were correct. The minimalistic design may be particularly suited for children with diagnosed dyscalculia, assuming these to be easily distracted. Further investigations that involve clinical samples and long-term training sessions are necessary for a more thorough evaluation.

ACKNOWLEDGMENTS

We thank IPF staff, teachers and children at Lindenschule and Einstein Schule Sömmerda, and all study participants.

REFERENCES

[1] Jo Boaler, Lang Chen, Cathy Williams, and Montserrat Cordero. 2016. Seeing as Understanding: The Importance of Visual Mathematics for our Brain and Learning. *Journal of Applied & Computational Mathematics* 5, 5 (2016), 1–6. https://doi.org/10.4172/2168-9679.1000325

[2] Brian Butterworth, Sashank Varma, and Diana Laurillard. 2011. Dyscalculia: From brain to education. *Science* 332, 6033 (2011), 1049–1053. https://doi.org/10.1126/science.1201536

[3] Nick S. Dalton. 2013. Neurodiversity HCI. *ACM interactions* 20, 2 (2013), 72–75. https://doi.org/10.1145/2427076.2427091

[4] S. Dehaene, E. Spelke, P. Pinel, R. Stanescu, and S. Tsivkin. 1999. Sources of Mathematical Thinking: Behavioral and Brain-Imaging Evidence. *Science* 284, 5416 (1999), 970–974. https://doi.org/10.1126/science.284.5416.970

[5] Min Fan, Alissa Antle, and Emily S. Cramer. 2016. Design Rationale: Opportunities and Recommendations for Tangible Reading Systems for Children. In *Proceedings of the 2016 Conference on Interaction Design and Children (IDC '16)*. ACM, NY, USA, 101–112. https://doi.org/10.1145/2930674.2930690

[6] Min Fan, Alissa Antle, Maureen Hoskyn, Carman Neustaedter, and Emily S. Cramer. 2017. Why Tangibility Matters: A Design Case Study of At-Risk Children Learning to Read and Spell. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, NY, USA, 1805–1816. https://doi.org/10.1145/3025453.3026048

[7] Karen C. Fuson, John Richards, and Diane J. Briars. 1982. The Acquisition and Elaboration of the Number Word Sequence. In *Brainerd (ed.) Children's Logical and Mathematical Cognition*. Springer, NY, USA, 33–92.

[8] Kaasa Health GmbH. [n. d.]. Meister Cody. Retrieved 29.8.2018 from https://www.meistercody.com/?lang=en.

[9] Maria Gracia-Bafalluy and Marie-Pascale Noël. 2008. Does finger training increase young children's numerical performance? *Cortex* 44, 4 (2008), 368 – 375. https://doi.org/10.1016/j.cortex.2007.08.020

[10] ICD10data.com. 2018. 2018/2019 ICD-10-CM Diagnosis Code F81.2. Retrieved 25.11.2018 from https://www.icd10data.com/ICD10CM/Codes/F01-F99/F80-F89/F81-/F81.2.

[11] Tim Jay and Julie Betenson. 2017. Mathematics at Your Fingertips: Testing a Finger Training Intervention to Improve Quantitative Skills. *Frontiers in Education* 2 (2017), 22. https://doi.org/10.3389/feduc.2017.00022

[12] Tanja Käser, Gian-Marco Baschera, Juliane Kohn, Karin Kucian, Verena Richtmann, Ursina Grond, Markus Gross, and Michael von Aster. 2013. Design and evaluation of the computer-based training program calcularis for enhancing numerical cognition. *Frontiers in Psychology* 4:489 (2013). https://doi.org/10.3389/fpsyg.2013.00489

[13] Andrew Manches and Claire O'Malley. 2016. The Effects of Physical Manipulatives on Children's Numerical Strategies. *Cognition and Instruction* 34, 1 (2016), 27–50. https://doi.org/10.1080/07370008.2015.1124882

[14] Sumit Pandey and Swati Srivastava. 2011. Tiblo: A Tangible Learning Aid for Children with Dyslexia. In *Procedings of Creativity and Innovation in Design (DESIRE '11)*. ACM, NY, USA, 211–220. https://doi.org/10.1145/2079216.2079247

[15] Janet C. Read and Stuart MacFarlane. 2006. Using the Fun Toolkit and Other Survey Methods to Gather Opinions in Child Computer Interaction. In *Proceedings of the 2006 Conference on Interaction Design and Children (IDC '06)*. ACM, NY, USA, 81–88. https://doi.org/10.1145/1139073.1139096