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Differential Effectiveness of Flash Training to Strengthen Basic Arithmetic Factual Knowledge in Children—An Experimental Study

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Abstract

In this study, we applied a pre–post-follow-up design to an online based intervention for improving basic arithmetic facts (facts-intervention) in a cohort of primary school children. The participating children of the intervention group independently trained for five weeks, four times a week for 15 minutes. This condition was compared to a control group that received a phonologic training with the same frequency. At post-test, children who received the facts-intervention solved significantly more addition and substraction tasks and subtraction tasks correctly, compared to the children who received a control training. Moreover, children who received the facts-intervention solved more addition tasks and subtraction tasks correctly, compared to the children of the control condition at the follow-up, four months after the end of the intervention. Further analyses revealed that training effects cannot be attributed to children who performed below a certain level in a standardized mathematics test for second graders. Possible reasons for the differential effects of the facts-intervention are discussed.

Keywords

Basic Arithmetic Facts, Online Intervention, Primary School Children, Randomized Control Group Design

1. Introduction

The development of a stable knowledge of solutions to simple arithmetic problems in the small number range, the *basic arithmetic* factual *knowledge* (Ashcraft & Fierman, 1982; Gawin, 2024; Liu, Tan, Yan, & Li, 2024) is an important task in the acquisition of initial arithmetic and an essential foundation for later arithmetic skills. The educational standards of the Standing Conference of the Ministers of Education and Cultural Affairs in the Federal Republic of Germany (KMK) for primary school mathematics stipulate, among other things, that children in Year 4 should "master the basic tasks of mental arithmetic (multiplication tables, number decompositions) in their memory" (KMK—Kultusministerkonferenz, 2004; P. 9). Achieving this standard is also desirable against the background of cognitive information processing, as the cognitive demands of solving a task by memory are lower than when using counting solution strategies. The demands associated with initial arithmetic can be analyzed using the working memory model according to Baddeley (1986, 2025) to illustrate this. For example, when a child works on task "2 + 7", the visual-spatial sketchpad temporarily stores the visual information of the symbols (digits and operator) on an "inner board" (Heathcote, 1994). Similarly, the visuospatial sketchpad is involved in counting with fingers (Rasmussen & Bisanz, 2005). The other subsystem of working memory, the phonological loop, holds the linguistic-sound information in the short term ("two plus seven"). The central executive, which is superordinate to both subsystems, compares information via the episodic buffer with the content of long-term memory. If a child has already memorized the arithmetic task, there is a strong association between the task and the solution in memory; in other words, a so-called confidence criterion is exceeded (Campbell, 1995; Siegler & Shipley, 1995) and the solution to the task can be recalled directly from memory. The requirements are much higher if a child does not yet have the solution sufficiently strong in long-term memory. If there are similarly strong memory associations with different solutions to a task (e.g. the numbers 8 and 9 could be similarly strongly associated with task 2 + 7), the confidence criterion is not exceeded and the child resorts to counting strategies as so-called backup strategies when solving the task (Siegler, 1988). The central executive has a further function, which consists in the coordination of solution strategies, such as the selection of suitable counting strategies (Fuson, 2012). In addition, the central executive also monitors the counting process by controlling attention so that no step is omitted and no number is counted twice (principle of one-to-one mapping; Gelman & Gallistel, 1986), while the phonological loop provides the individual counting steps (Fürst & Hitch, 2000). If the child repeatedly arrives at the same result when processing the same task by counting, the strength of the association between the task and the result increases (Siegler & Shipley, 1995) and the solution is permanently stored in long-term memory and thus memorized. The result can then be retrieved directly from memory when this task is performed again.

The (non-)availability of basic arithmetic factual knowledge when solving arithmetic problems has an influence on the cognitive load. A memory-based retrieval of the result proves to be more favourable compared to counting arithmetic, as the central executive only has to take over the function of retrieval from long-term memory, so that the previously described working memory processes necessary for counting are omitted (Imbo & Vandierendonck, 2007). This avoids errors that often result from overloading the limited capacity of working memory (Geary, 1990; Woodward, 2006). Practicing factual knowledge is therefore essential in order to free up working memory resources for further arithmetic operations (Heine, Engl, Thaler, Fussenegger, & Jacobs, 2012). Consequently, working memory resources that were previously tied to counting arithmetic are then available for solving more complex tasks. Basic arithmetic factual knowledge therefore plays an important role in arithmetic.

Insufficiently present basic arithmetic factual knowledge is an essential cognitive characteristic of children with below average numeracy skills or dyscalculia (Busch, Schmidt, & Grube, 2015; Jordan, Hanich, & Kaplan, 2003). It is assumed here that factual knowledge is insufficiently consolidated because those children use counting strategies more frequently (Dowker, 2009; Geary, 2004; Jordan & Montani, 1997) than children with average numeracy skills, who increasingly move away from counting arithmetic from the end of second grade and recall basic arithmetic facts directly (Ashcraft & Fierman, 1982; Bailey, Littlefield, & Geary, 2012; Torbeyns, Verschaffel, & Ghesquière, 2004). On the one hand, children with lower numeracy skills make more errors in simple arithmetic tasks (Geary, 1990; Ostad, 1997). On the other hand, they often need more time than average calculators (Geary, Hoard, Byrd-Craven, & DeSoto, 2004; Hanich, Jordan, Kaplan, & Dick, 2001; Torbeyns et al., 2004). These findings indicate the use of the more cognitively demanding, time-consuming and error-prone strategies (e.g., counting or decomposition; Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Hanich et al, 2001; Joy Cumming & Elkins, 1999; Schuchardt & Maehler, 2010) and serve as evidence that children with lower numerical skills do not build a stable network for arithmetic facts in memory and do not have the typical developmental trajectory that children with average numeracy skills go through (De Smedt, Holloway, & Ansari, 2011).

But how can basic arithmetic fact knowledge be trained in children? According to Hoelscher (2016), two approaches are particularly suitable: 1) memorization—possibly taught using drill and practice principles, and 2) strategy training (e.g. Isaacs & Carroll, 1999). Born and Oehler (2013) note that although memorization and recall of arithmetic facts are among the most frequently reported deficits in children with dyscalculia, there are few empirical studies that examine the effectiveness of training programs to build and strengthen arithmetic facts. Intervention approaches for children should take into account the specific deficits and build up basic arithmetic factual knowledge accordingly (Dowker, 2004; Wißmann, Heine, Handl, & Jacobs, 2013). This raises the question of how children can succeed in acquiring stable basal arithmetic factual knowledge and which training measures and principles are suitable for promoting the development of basal arithmetic facts.

1.1. Training Principles and Training Programs for Building and Strengthening Basic Arithmetic Factual Knowledge

Training programs to build or strengthen basic factual knowledge have a long tradition in the Anglo-American language area and are considered to be very effective (Kroesbergen & Van Luit, 2003, for example, report a mean effect size of Cohen's d = 1.50 for fact training in their meta-analysis). There are already various evaluation studies that have examined the effectiveness of interventions to build and strengthen basic arithmetic fact knowledge (e.g. Burns, Kanive, & DeGrande, 2012; Koscinski & Gast, 1993; Pixner, Moeller, & Kraut, 2023). Burns and colleagues (2012) evaluated the fact training program *Math Facts in a Flash* (Burns, Kanive, & DeGrande, 2012). Third and fourth graders with and without dyscalculia trained three times a week for eight to 15 weeks with the computer-based training program MFF. The children who trained with MFF showed a clear improvement in a maths test after training compared to the control group without training. MFF is based on a combination of two established training principles. On the one hand, the use of *computer-based* training programs is considered suitable for effectively supporting children (Räsänen, Salminen, Wilson, Aunio, Dehaene, 2009; Ysseldyke, Thill, Pohl, & Bolt, 2005) on the other hand, the use of the so-called *drill and practice principle* has proven to be effective (Ashcraft, 1987; Fuchs et al., 2008; Powell, Fuchs, Fuchs, Cirino, & Fletcher, 2009). Drill and practice involve the systematic repetition (drill) of exercises (practice) with the aim of automating what has been learnt (Lim, Tang, & Kor, 2012). Powell et al. (2009) showed that 9-year-old children with dyscalculia who completed computer-based drill and practice fact training were able to improve significantly. In addition, Fuchs et al. (2006) demonstrated that the so-called *flash principle* (used in MFF) is particularly suitable for building up basic arithmetic facts. In flash training, complete arithmetic facts (i.e. task and result) are presented for a brief moment (1.3 seconds in MFF). The children are asked to memorise the complete arithmetic fact, reproduce it in memory and type it in on the computer. The authors argue that repeated presentation of complete maths facts can strengthen the associations of the maths facts in memory (Fuchs et al., 2008; Fuchs et al., 2010). For example, the third-graders with dyscalculia studied by Fuchs et al. (2008) showed significantly better performance in fact recall (addition and subtraction) after training. Furthermore, Pixner et al. (2023) showed long-term effectiveness of a holistic approach to multiplication fact training for primary school children who show difficulties in solving simple multiplication problems. Participants of the experimental groups show a significant increase in correct answers and faster reaction times, with the effects being stable over time. The program helped children develop a structured network of multiplication facts, enabling them to solve even untrained problems more quickly and accurately after the intervention.

While current intervention studies on fact trainings tend to focus primarily on rote memorization in drill and practice interventions (Burns et al., 2019; Sleeman et al., 2021), conceptual understanding is often left unaddressed. In some studies, however, *strategy training* has also been discussed and evaluated to build up stable factual knowledge (Fuchs et al., 2008; Kroesbergen & Van Luit, 2003; Tournaki, 2003). Tournaki (2003) investigated the effectiveness of drill and practice training compared to strategy training in children with and without dyscalculia. The results of Tournaki (2003) show that children with dyscalculia were able to benefit from strategy training—but not from drill and practice training—whereas both training programs led to an improvement in children without dyscalculia. However, it should be critically noted that the implementation of both principles differed in terms of feedback: While the children with strategy training received immediate feedback on the result after completing a task, the feedback with drill and practice training was delayed. It is therefore unclear to what extent the differential effectiveness of the two training programs can also be attributed to different feedback strategies.

According to Lenhard and Lenhard (2016), there are numerous advantages to learning on a PC in particular. Hence, the combination of a support program with an *amplification system* (token system) proves to be useful.

1.2. Research Questions and Hypothesis

The aim of this study is to evaluate the effectiveness of a computer-based fact training program based on the drill and practice and flash training principles. The MFF training program by Fuchs et al. (2004) was adapted and tested with children with average and below average numeracy skills. The central question was whether the computer-based flash training program can improve performance in the recall of basic arithmetic facts in children. It was hypothesized that children from the fact training group would show higher arithmetical performances than children that completed an alternative but comparably attractive control training to improve written language performance (fact training vs. control training; hypothesis 1).

Furthermore, it was examined whether there were specific training effects in children with lower numeracy skills who completed the fact training compared to the children with lower numeracy skills who completed the control training (research question 2). No directed hypotheses were generated in this regard.

2. Method

2.1. Participants

N = 50 children from Lower Saxony took part in the training study. The children were recruited as part of an initiative funded by the Federal Ministry of Education and Research (BMBF) to develop a computer-based numeracy support program for children. The children were between 8 - 10 years of age at the time of the first survey. The children who took part in the research project were randomly assigned to either the fact training or the "Lautarium" control training. Of the 50 children, 24 received the fact training and 26 the control training. On average, the children trained 20 times with the fact training (SD = 3). One child who had only participated in fact training 6 times during the entire intervention period was removed from further analyses.

For further analyses concerning research question 2, children from both groups were divided into two subgroups: children who obtained average and children who received below average performances in a standardized mathematic skill test (Demat 2+; Krajewski, Liehm, & Schneider, 2004). Children's performances were classified as below average if they achieved a *T-score* of less than or equal to 39 in the Demat 2+ (n = 21), whereas children with at least average performances achieved a *T-score* greater than 43 (n = 29). Children with scores between 40 and 43 were not included in the study.

2.2. Procedure

The children were analyzed in terms of arithmetic, reading and spelling performance as well as non-verbal intelligence. In the form of class tests, the German Mathematics Test for Second Grade (DEMAT 2+; Krajewski, Liehm, & Schneider, 2004), the reading comprehension test for first to sixth graders (ELFE 1-6, Lenhard & Schneider, 2006; assessment of reading performance at word, sentence and text level), the Weingartner spelling test (WRT 2+, Birkel, 2007; cloze dictation) and a figural and non-verbal intelligence test (CFT 1-R; Weiß & Osterland, 2013) were used at baseline.

For the pre, post, and follow-up measurements of the arithmetical performances, the basic module of the Diagnostic Inventory for Arithmetic Skills in Primary School Children (DIRG; Grube, Weberschock, Blum, & Hasselhorn, 2010) was admitted as the outcome measures (AT20 and ST20). The children were given a time limit to solve addition and subtraction tasks in the number range up to 20 with and without tens transition.

Furthermore, the addition and subtraction tasks within the number range up to 1000 (AT1000 and ST1000) were administered as additional outcome measures to examine potential transfer effects of the fact training. The post-test was conducted immediately after the intervention. The tests administered during the pretest to assess calculation skills (AT20, ST20, AT1000 and ST1000) were also conducted immediately after the intervention phase in the post-test and again four months later at follow-up. The research project was authorized by the ethics committee of the Carl von Ossietzky University of Oldenburg, the Lower Saxony state education authority. Written informed consent was obtained from each child's parent, and the children's participation was entirely voluntary. We confirm that all experiments were performed in accordance with relevant guidelines and regulations of the Ethics board.

2.3. Design

The study entailed a 2 (groups) × 3 (time points) within-between-subjects ANOVA design with repeated measures to test the research hypotheses (H1). Various standardized paper-pencil test procedures were used for the pre-, post- and follow-up tests in order to assess the children's arithmetic skills and to check the possible effectiveness of the fact training.

2.4. Fact Training & Control Training

The training effects were tested using a 2 × 3 pre-post follow-up design with two different conditions (fact training and control training) to which the children were randomly assigned. The children were examined before and after completion of the respective training programs. A further examination of possible long-term effects took place after four months (follow-up testing). The children in the two training groups each trained four times a week for around 15 minutes for five weeks. The introduction to the training programs took place immediately after the pre-testing by trained student employees. The training was then completed independently at home. At the time of the training, the children were in fourth grade. All children received maths lessons at least once a day in accordance with the Lower Saxony curriculum, whereby the teaching of basic arithmetic facts is no longer the focus of the fourth grade. The expected competence in the area of numbers and operations at the end of the fourth grade is that the children "[...] transfer the automated tasks to analogue tasks in the extended number range" (KMK—Kultusministerkonferenz, 2004, p. 29); in other words, it is assumed that the basic arithmetic facts can be recalled automatically.

Fact training

The fact training used was based on Fuchs et al. (2004). The support program was developed as an online-based program. The user interface was designed to be neutral in order to direct the children's attention to the individual tasks. After logging in, the children were greeted personally by name before the training program began.

The repeated presentation of correct arithmetic facts (e.g. 4 + 3 = 7) was intended to consolidate these in the child's memory. To ensure that the children arrived at the correct result, incorrect reproductions were immediately reported back and corrected by the child. Based on the program by Fuchs et al. (2004), quantities were illustrated using visual representations of the quantities in order to facilitate (correct) counting where necessary. Only addition and subtraction tasks in the number range up to 20 were used for the training. Tasks with 0 and with equal summands or subtractives were not included in the program. For each training session, 15 tasks were presented from one of the four different task sets (in this order: addition without transition of tens, addition with transition of tens, subtraction without transition of tens and subtraction with transition of tens). Accordingly, all children began with the addition set without a transition between tens and ended with the subtraction set with a transition between tens. The tasks presented were randomized in the presentation according to their order in a set; for the addition tasks, randomization was also carried out according to the place value of the larger summand. Before the first training session, the children were given an introduction to the program by a student assistant. They were guided through the program using explicit instructions before they were able to solve tasks themselves. During the next training sessions, the children were informed that they would have to complete tasks in a specific area again today. If required, the children were able to watch the tutorial again. The training principles mentioned in the introduction were realized as follows:

Drill and practice: For five weeks, the children were asked to repeatedly work on tasks in the number range up to 20 four times a week for approx. 15 to 20 minutes, so that the same tasks (in different sequences) were practiced again and again.

Flash principle: A complete arithmetic fact including the result appeared on the screen for 1.3 seconds (like a flash). After the arithmetic fact had faded, the children were asked to type it in. To prevent the facts from remaining as an "image" on the retina, the screen was masked between the fact presentation and the fact reproduction. If a task was reproduced correctly, the child immediately moved on to the next task. If the task was reproduced incorrectly, the complete arithmetic fact was presented permanently so that the child could type it out. The next task was only presented if the reproduction was correct. In the addition tasks, inverse entries (i.e. the production of the exchange task) were also considered correct. The flash training principle is shown in Figure 1.

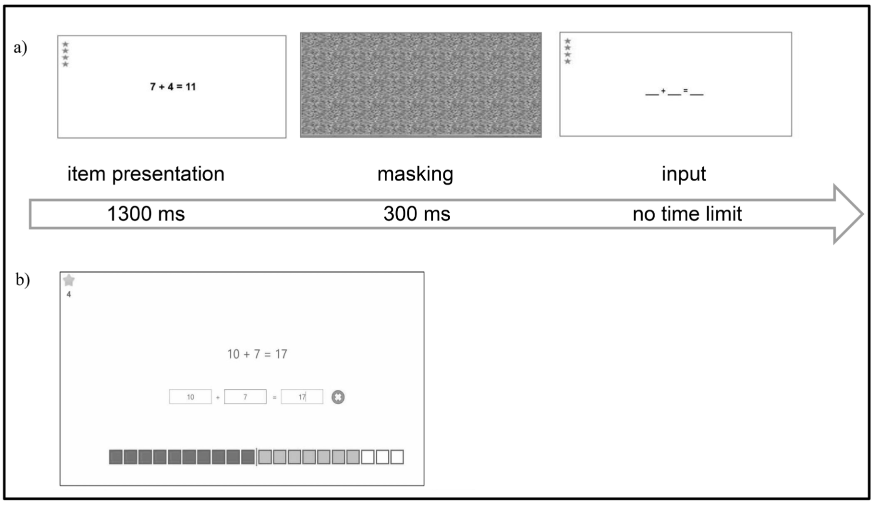

Figure 1. The flash training principle: a) A mathematical fact is presented for 1300 ms. It is requested to memorize and type in the fact after a masking interval of 300 ms. There is no time limit for typing the fact. b) If a fact is incorrectly reproduced, it will stay on screen and the child is asked to copy the presented term. This guarantees that children will get the right answer and allows to overwrite wrong memory associations.

Reinforcement system: For each task solved (regardless of whether the task was solved correctly at the first attempt or after the continuous performance), the children received stars that they could exchange for virtual animal figures for their jungle in the so-called jungle shop after the training. The children also received a paper-based training plan that could be customized with stickers and helped them to keep track of the number of training sessions they still had to complete.

Control training **(*****Lautarium*****)**

In order to exclude diffuse training effects (e.g. due to attractiveness or novelty), the control training was Lautarium (Klatte, Steinbrink, Bergström, & Lachmann, 2017) which is equally attractive. Lautarium comprises exercises that build on each other in the areas of phoneme perception, phonological awareness and phonetic reading and writing. Just like the fact training, Lautarium also has a reinforcement system to keep the children motivated. The children assigned to the control training group trained with Lautarium four times a week for 15 minutes over a total of five weeks. The duration and frequency of the two interventions (fact training and Lautarium) were therefore the same for the entire duration of the intervention.

2.5. Treatment Fidelity Measures

Following recommendations by Wiens and Gordon (2018), we sought confirmation of treatment fidelity in several ways. For example, the assistants who were trained in administering the interventions received a detailed teaching script of the different lessons for each group (Fact training and Lautarium training). Execution of the training could be tracked online. Later inspection of the notes showed that the teaching script was overall closely followed. Mean of trained sessions was 19.75 (SD 3.08) for fact training and 17.04 (SD 5.14) for Lautarium (n = 23).

2.6. Data Analyses

Descriptive and inferential statistical methods were applied. The latter included repeated measures analysis of variance (ANOVA) models for hypothesis testing. Preconditions for the ANOVAs with repeated measurement (normality, Box's M test of equality of covariance matrices and Levene's test of equality of variance) were tested for all dependent variables separately and were met in all cases. In addition, multiple one-tailed t-tests for subsequent comparisons of means were conducted.

A power analysis using G*Power (Erdfelder, Faul, & Buchner, 1996) suggested that a sample size of N = 44 was needed to ascertain small to medium effects (f = .25) in a mixed within-between-subject design with repeated measures (α: .05, power (1 − β): .95, correlations between repeated measures: r = .50).

In addition, correlation coefficients were calculated on the basis of Pearson correlations. Probability level was set to $p < .05$. All analyses were conducted with SPSS version 30.

3. Results

The two training groups did not differ in terms of gender distribution ($\chi^2 = 1.34$; df = 2; $p = .25$). Furthermore, there were no differences between the two training groups in terms of age, $F(1, 49) = 1.35$, $p = .251$, $\eta^2 = .027$, verbal intelligence, $F(1, 49) = .13$, $p = .73$, $\eta^2 = .003$, reading, $F(1, 49) = 2.43$, $p = .13$, $\eta^2 = .047$, spelling, $F(1, 49) = 3.13$, $p = .083$, $\eta^2 = .062$ and arithmetic performances, $F(1, 49) = .01$, $p = .92$, $\eta^2 = .001$ at T1. Table 1 summarized the children's performance in reading, spelling, numeracy and non-verbal intelligence. Table 2 reports the mean values and standard deviations for the dependent variables of both the experimental and control group.

Table 1. Means (and SD) of the control variables age, reading and writing, numeracy, as well as verbal intelligence for the fact training (FT), and control training (CG) groups at baseline (T1).

	FT	CG			
Measures	M (SD)	M (SD)	df	f-value	*p*
Age	8.92 (.47)	9.08 (.65)	48	0.91	.35
Reading	49.73 (8.06)	46.18 (8.14)	48	2.34	.13
Spelling	44.13 (6.47)	40.85 (6.50)	48	3.13	.08
Numeracy	43.48 (7.76)	43.73 (7.84)	48	0.13	.91
Verbal IQ	99.48 (8.43)	99.83 (10.18)	48	.02	.90

Next, the ANOVAs for repeated measures were performed on the dependent measures. In order to ensure that the prerequisites were met, a series of statistical tests were performed. These included the Box-M test for equality of covariates, the Levene test for equality of variance, and the Mauchly test for sphericity. Subsequent comparison of means for within subject effects were conducted after the ANOVAs.

Correlational analyses for dependent and independent measures for all groups and time points are reported in Table 3.

3.1. Arithmetic Skills: Fact Training versus Control Training

For the pre, post, and follow-up measurements of the arithmetical performances, repeated measures analysis of variance were conducted with group as the between and time as the within factor. The reports of analyses start with the two addition tasks in the number range up to 20 or 1000 followed by the subtraction tasks in corresponding number ranges.

Table 2. Means and standard deviations (SD) for the dependent variables from children in the fact and the control training groups.

	Fact training group (FT)			Control training group (CG)		
Parameter	Pretest (T1)	Posttest (T2)	Follow-Up (T3)	Pretest (T1)	Posttest (T2)	Follow-Up (T3)
AT 20	74.52 (22.66)	88.87 (27.96)	84.52 (26.02)	76.08(29.22)	82.50 (28.93)	78.65 (32.60)
ST 20	44.48 (19.44)	58.35 (26.75)	54.46 (25.50)	52.72 (27.82)	52.50 (25.36)	51.16 (28.22)
AT 1000	16.30 (7.34)	21.83 (9.64)	20.05 (8.39)	16.96 (8.67)	19.39 (9.10)	17.24 (9.39)
ST 1000	6.26 (6.52)	9.91 (9.39)	9.50 (6.44)	6.46 (8.14)	8.73 (8.88)	8.88 (7.70)

Note: AT20 = Addition task in the numerical range extending to 20; AT1000 = Addition task in the numerical range extending to 1000; ST20 = Subtraction task in the numerical range extending to 20; ST1000 = Subtraction task in the numerical range extending to 1000.

Table 3. Correlations (r) between variables at all time points (T1, T2, and T3).

Measures	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
1. Age_T1	−.293*	.026	−.030	−.108	−.047	−.081	−.208	−.249	−.229	−.149	−.176	−.179	−.341*	−.234	−.248
2. Reading_T1		−.113	.223	.361*	.357*	.327*	.322*	.390**	.435**	.286*	.420**	.307*	.332*	.352*	.465**
3. Verbal IQ_T1			.255	−.039	−.070	−.149	−.045	−.072	−.087	.007	.029	−.045	.078	.011	−.127
4. Numeracy_T1				.302*	.239	.275	.104	.030	.195	.310*	.415**	.358*	.191	.290*	.430**
5. AD20_T1					.897**	.913**	.869**	.746**	.830**	.869**	.869**	.890**	.625**	.659**	.759**
6. AD20_T2						.919**	.734**	.821**	.827**	.778**	.893**	.888**	.552**	.695**	.728**
7. AD20_T3							.786**	.768**	.879**	.815**	.855**	.941**	.637**	.668**	.788**
8. AD1000_T1								.719**	.824**	.793**	.739**	.796**	.724**	.595**	.704**
9. AD1000_T2									.846**	.702**	.807**	.778**	.610**	.675**	.716**
10. AD1000_T3										.776**	.818**	.887**	.714**	.698**	.780**
11. ST20_T1											.837**	.888**	.589**	.540**	.740**
12. ST20_T2												.923**	.587**	.734**	.822**
13. ST20_T3													.667**	.683**	.804**
14. ST1000_T1														.605**	.708**
15. ST1000_T2															.766**

Note: AD20 = Addition task in the numerical range extending to 20; AD1000 = Addition task in the numerical range extending to 1000; ST20 = Subtraction task in the numerical range extending to 20; ST1000 = Subtraction task in the numerical range extending to 1000. * = $p <. 05$; ** = $p < .01$; *** = $p < .001$.

The addition task in the number range up to 20 (AT20) revealed a main effect of time [$F(2, 94) = 19.14$, $p < .001$, $\eta_p^2 = .29$] and an interaction effect of time*group [$F(2, 94) = 3.43$, $p < .036$, $\eta_p^2 = .07$]. No main effect of group could be reported [$F(1, 47) = .21$, $p = .65$, $\eta_p^2 = .004$]. Subsequent comparisons of means indicated that children in the facts training group showed a significant increase in the AT20-score from T1 to T2 [t(22) = 5.67, $p < .01$, $d = 1.18$], T1 to T3 [t(22) = 3.73, $p = .001$, $d = .79$], whereas children in the control group only significantly improved their performances from T1 to T2 [t(24) = 2.74, $p = .01$, $d = .54$].

Results for the addition task in the number range up to 1000 (AT1000) obtained a main effect of time [$F(2, 90) = 16.03$, $p < .001$, $\eta_p^2 = .26$] and an interaction effect of time*group [$F(2, 90) = 3.55$, $p < .033$, $\eta_p^2 = .07$]. No main effect of group was found [$F(1, 45) = 1.18$, $p = .28$, $\eta_p^2 = .03$]. Furthermore, subsequent comparisons of means indicated that children from the fact training group significantly improved their performances from T1 to T2 [t(22) = 5.27, $p < .001$, $d = 1.01$], T2 to T3 [t(21) = 2.28, $p = .01$, $d = .47$], and T1 to T3 [t(21) = 3.23, $p = .002$, $d = .69$]. Children in the control group only significantly improved their performances from T1 to T2 [t(24) = 2.09, $p = .05$, $d = .41$] and from T2 to T3 [t(24) = 2.71, $p = .01$, $d = .54$]. Figure 2 shows the results of the arithmetic skills for both groups.

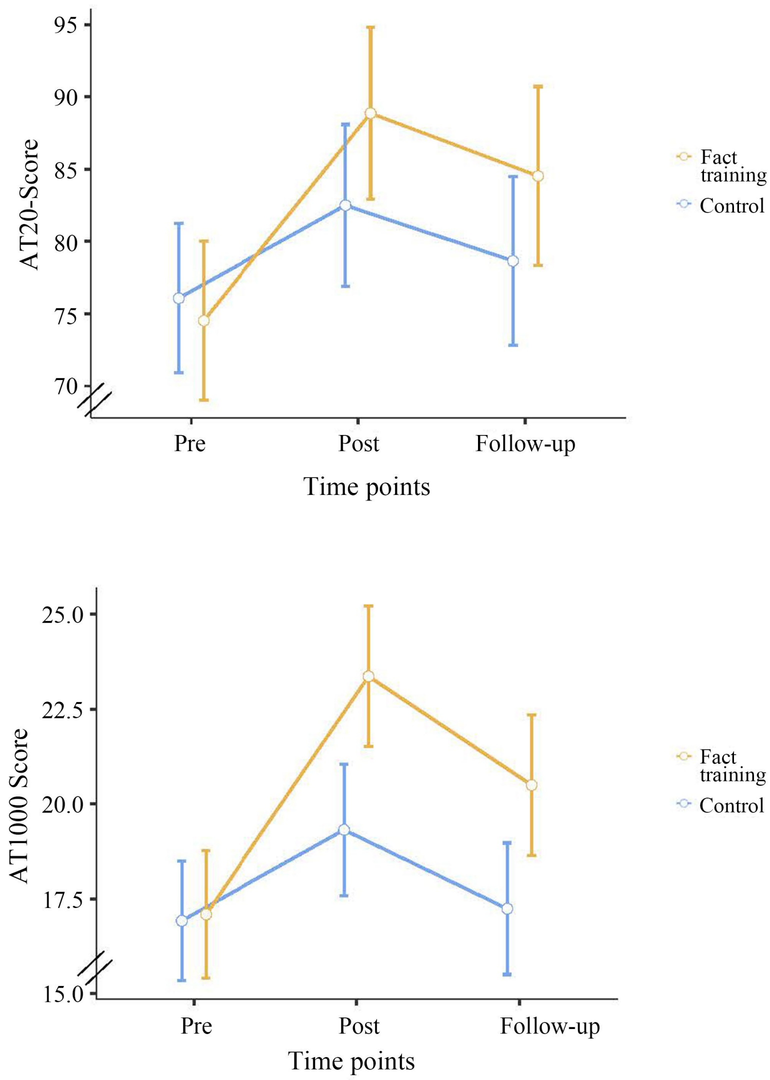

Figure 2. Mean Scores of the addition task in the number range up to 20 or 1000 for the fact and the control training groups at three time points. Error flags indicated standard error of means (SEM).

Analyses of the subtraction tasks in the number range up to 20 (ST20) obtained a main effect of time [$F(2, 88) = 9.21$, $p < .001$, $\eta_p^2 = .17$] and an interaction effect of time*group [$F(2, 88) = 8.73$, $p < .001$, $\eta_p^2 = .17$]. No main effect of group was found [$F(1, 44) = .02$, $p = .90$, $\eta_p^2 = .001$]. Subsequent comparisons of means showed that children from the fact training group significantly improved their performances from T1 to T2 [t(22) = 4.22, $p < .001$, $d = .88$], T2 to T3 [t(21) = 2.30, $p = .02$, $d = .49$], and T1 to T3 [t(21) = 3.01, $p = .003$, $d = .65$]. Children in the control group did not show any improvements over time [all *t*'s < .72, *p-values* > .48].

The final set of analyses was conducted for the subtraction tasks in the number range up to 1000 (ST1000). Results only revealed a main effect of time [$F(2, 90) = 5.96$, $p < .004$, $\eta_p^2 = .12$]. No main effect of group [$F(1, 45) = .05$, $p = .83$, η_p^2

= .001] or interaction effects were found [$F(2, 90) = .22$, $p = .80$, $\eta_p^2 = .01$].

Subsequent comparisons of means showed that children from the fact training group significantly improved their performances from T1 to T2 [t(22) =2.01, $p = .03$, $d = .42$], and from T1 to T3 [t(21) = 2.62, $p = .008$, $d = .56$], whereas children in the control group did not significantly improved their performances over time [all *t*'s < 2.04, *p-values* > .05]. **Figure 3** shows the results of the subtraction tasks for both groups.

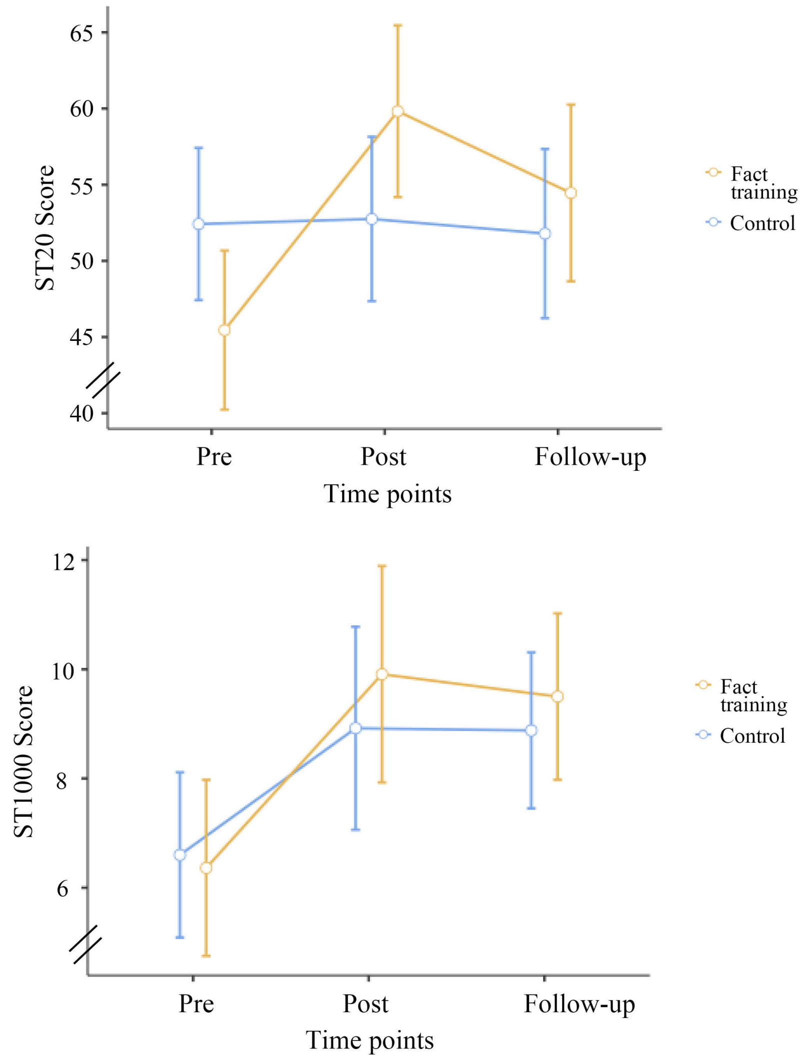

Figure 3. Mean Scores of the subtraction task in the number rage up to 20 or 1000 for the fact and the control training groups at three time points. Error flags indicated standard error of means (SEM).

3.2. Analyses of Children with below-Average Mathematical Performance

It was further of interest whether children of both groups who achieved a *T-score of* less than or equal to 39 in a standardized mathematics test for second graders (DEMAT 2+), differ in their arithmetical skills. This was true for $n = 10$ children in the facts training group and $n = 11$ children in the control group.

A final set of ANOVAS with repeated measurements was conducted for the four arithmetical tasks (AT 20, AT 1000, ST 20, and ST 1000). Results for the four tasks did not show any main effects of group (all *F*s > .52, *p-values* > .48) or interaction effects (all *F*s > 1.60, *p-values* > .22). Analyses for the addition tasks AT 20 and AT 1000, however, showed a significant main effect of time [AT 20: $F(2, 38) = 9.55$, $p < .001$, $\eta_p^2 = .34$; AT 1000: $F(2, 36) = 10.92$, $p < .001$, $\eta_p^2 = .38$]. For an overview of the four arithmetical tasks for the children with below-average mathematical performances see **Figure 4**.

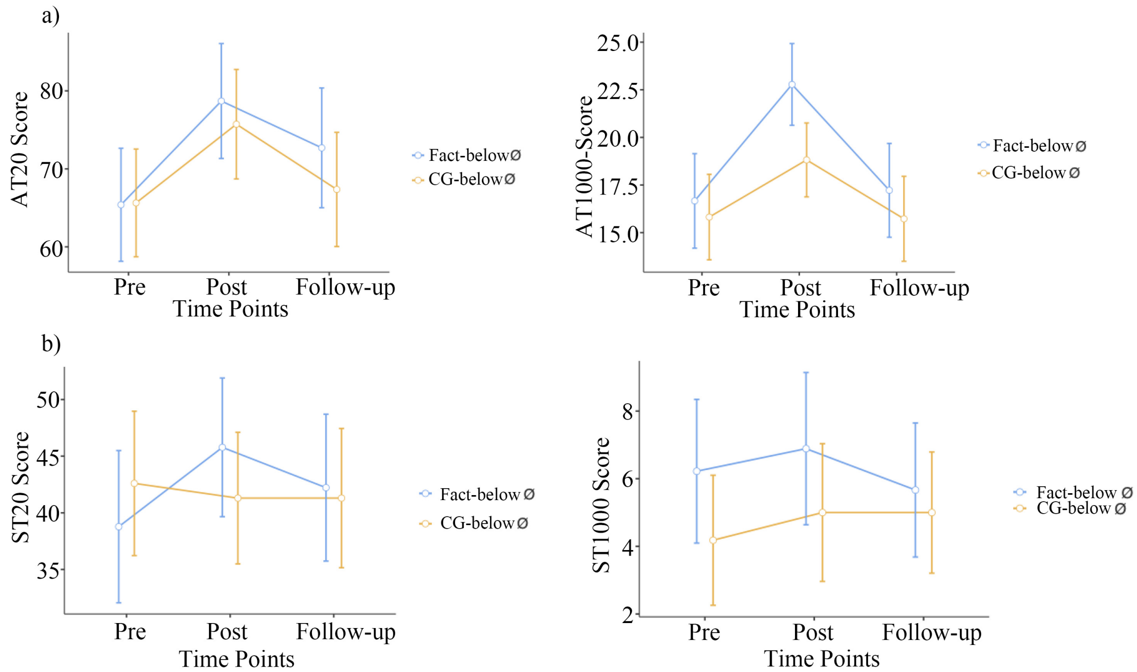

Figure 4. Mean scores of the two addition tasks (a) in the number range up to 20 or 1000 followed by the substation tasks (b) in corresponding number rages for the children with below average mathematical skills of the fact and the control training groups at three time points. Error flags indicated standard error of means (SEM).

Subsequent comparison of means for the AT 20 showed that children from both groups significantly improved their performances from T1 to T2 [Fact training: [$t(9) = 3.26$, $p = .01$, $d = 1.03$]; control group: [$t(10) = 2.25$, $p = .05$, $d = .68$]]. However, the effect size for the children in the fact training group was higher than the effect size for the children in the control group. Moreover, children in the control group showed a significant decrease in their performances from T2 to T3 (follow-up) [$t(10) = 2.34$, $p = .04$, $d = .70$], whereas children in the fact training group did not [$t(09) = 2.15$, $p = .06$, $d = .67$].

Finally, the subsequent comparison of means for the AT 1000 revealed that children in the fact training group significantly improved their performances from T1 to T2 [$t(9) = 3.91$, $p = .004$, $d = 1.24$], whereas children in the control group did not [$t(10) = 1.55$, $p = .15$, $d = .47$]. However, the performances of children in the fact training group decreased significantly from T2 to T3 (follow-up), indicating an absence of long-term effects of the fact training.

4. Discussion

The aim of the present study was to test the effectiveness of a fact training program based on various established training principles (drill and practice, flash, computer-based).

We expected that the children who completed the fact training would improve more in tasks for recalling basic arithmetic facts than the children who used the "Lautarium" control training (hypothesis 1). The results confirm this expectation. There was both a short-term and a long-term advantage of the fact training over the control training. Children who worked with the fact training showed higher gains from the pre-test to the post-test in the tasks for addition and subtraction in the number range up to 20. Moreover, the fact training showed long-term positive effects on tasks involving addition and subtraction up to 20. Encouragingly, a long-term transfer effect was also observed for the addition within the number range up to 1000 task (AT1000). Since the fact training focused exclusively on addition and subtraction within the number range up to 20, this finding indicates a transfer effect beyond the trained number range. However, no long-term effects were found for the subtraction task within the number range up to 1000. Encouragingly, the fact training showed long-term positive effects for the tasks for addition and subtraction up to 20 and for written addition in the number range up to 1000.

The subsequent analyses of research question 2 served a differentiated investigation of the training effects. It was analyzed whether children with below-average mathematical performance—who have been shown to have a deficit in the recall of basic arithmetic facts (e.g. Dowker, 2020; Geary, Hoard & Hamson, 1999; Jordan & Montani, 1997; Jordan, Hanich & Kaplan, 2003) can benefit from the fact training. To this end, those group of children who received the fact training were compared with those group of children who received the control training. No clear differential effect was detected as there were no significant interactions or main differences between the two groups studied. Only higher increase from pre-to post-test in the AT20 and AT1000 task performances for the children in the fact training group was observed. Although the results of the small sub-sample should be interpreted with caution, these findings confirm and extend previous studies reporting a positive effect of fact training on arithmetic skills in primary and secondary school children (Re et al., 2020; Morano et al., 2020). For example, in the study by Tournaki (2003) younger children with and without dyscalculia (on average 7.5 years old) underwent drill-and-practice training or strategy training. Their results showed that the children with dyscalculia who received the drill-and-practice training showed no improvement in the recall of basic arithmetic facts—comparable to our results—whereas the children without dyscalculia benefited from the training.

Based on the results from other studies that report a positive effect of fact training, particularly for children with dyscalculia (Pixner, Moeller, & Kraut, 2023), the question arises as to why the fact training used in the present study only appears to be effective for children with average mathematical performances. Potential reasons for the ineffectiveness in children with below-average mathematical performances could be the comparatively short duration and frequency of the fact training: In the present study, the children in the experimental group trained with the fact training an average of 19.75 times, whereas a significantly higher workload was achieved in other studies (e.g. Powell et al. (2009) 45 times; Burns et al. (2012), 24 - 45 times). The assumption that the duration of the training (the children trained for around 300 minutes) had an influence on its ineffectiveness is supported, for example, by the meta-analysis by Ise et al. (2012). The authors show that the effectiveness of numeracy training for children with dyscalculia increases with the duration of the training (the mean effect size was highest when the training lasted more than 600 minutes). Similarly, Fuchs et al. (2006) were able to achieve a significant improvement in children with (a risk of developing) dyscalculia with their computer-based flash training program with an average of 45 training sessions. It can therefore be assumed that more sessions would have been necessary to achieve a specific effect of the training on the children with weaker mathematical skills in our study. Another reason could be the relatively old age of the children studied, which averaged 9; 9 years at the start of the training. It could be assumed that the training supports younger children with weaker mathematical skills—who are still learning arithmetic facts—in their acquisition to a greater extent than is the case with older children. For example, Hasselbring, Goin, and Bransford (1988) after attempting to support fourth-graders with dyscalculia in the acquisition of arithmetic facts, concluded that it can be a challenge for older primary school children with dyscalculia to overcome the existing fact deficit. The results of Garnett & Fleischner (1983) came to a similar conclusion. On the other hand, Burns et al. (2012) reviewed a computer-based math fluency intervention with 216 third- and fourth-grade students who were at risk for math difficulties. Results showed that significantly fewer students remained at risk for math failure in the intervention group after participating in the intervention, suggesting that the intervention was a useful supplemental math intervention. Although further studies are needed on the age of successful use of fact training in children with below-average mathematical performance or dyscalculia, the findings of the present study support the use of fact training before the age of 9 years.

The result that children with below-average mathematical skills do not show any specific advantage of fact training over the control training is apparently in contradiction to various studies from the Anglo-American area (Burns et al., 2012; Fuchs et al., 2008; Fuchs et al., 2004; Powell et al., 2009). Nevertheless, there are (in some cases older) studies in which drill and practice training did not prove effective for children with dyscalculia (e.g. Garnett & Fleischner, 1983; Hasselbring et al., 1988; Tournaki, 2003). Various authors argue that drill and practice training can only be effective if the skill being trained is already securely mastered

(Haring & Eaton, 1978; Hasselbring et al., 1988) that is, when arithmetic facts are securely represented in memory. Hasselbring et al. (1988) conclude from their results "[...] if a child has not established an association between a problem and its answer before engaging in a drill and practice activity, time spent in drill and practice is essentially wasted" (p. 4). Since the flash principle of the fact training used (i.e. the presentation of complete arithmetic facts with task and result) does not teach any solution strategies, but merely attempts to strengthen the association between arithmetic problem and solution in the memory, this could explain why there were no differences between the fact and control training of the children with below-average mathematical performance in the present study.

In addition, it can be argued that the context-free presentation of maths facts (i.e. mathematical problems), as it was done in the fact training used, results in lower learning success than linking mathematical problems to everyday activities, as these are perceived as more meaningful by the children (Kaufmann, Delazer, Pohl, Semenza, & Dowker, 2005). Thus, the teaching of mathematical content—perhaps especially for children with below-average mathematical performance—should be geared towards relating mathematical concepts and procedures to situations from the children's real lives in order to gain an understanding of mathematical relationships and operations.

Overall, the approach that a skill must first be mastered before drill and practice training is effective (Haring & Eaton, 1978; Hasselbring et al., 1988) seems to be the most obvious explanation for the finding that the fact training used showed no effectiveness in children with below-average mathematical performance. This is supported by the fact that fact training in children with average mathematical performance (for whom it can be assumed that the basic arithmetic facts are securely represented in long-term memory) led to an improvement in the sense of faster recall of arithmetic facts (within the given time, children with average mathematical performance were able to solve more tasks correctly).

Based on this, it would perhaps be more helpful for children with below-average mathematical performance if they received strategy training - and only after it has been ensured that the basic arithmetic facts are securely represented in memory—subsequent or accompanying drill and practice training. The results of Tournaki (2003) also support this hypothesis. Tournaki was able to show that the strategy-based intervention for children with dyscalculia is more effective than the drill and practice training used. The children without dyscalculia, on the other hand, benefited from both training programs. In contrast to Tournaki's drill and practice training, however, an immediate feedback system was integrated into the training in the present study, meaning that the children received immediate feedback on the quality of their answers. However, as the fact training did not show any specific effectiveness with children with below-average mathematical performance, it can be assumed that Haring and Eaton's (1978) assumption that arithmetic facts must be consolidated before training is correct. To counteract this problem, future studies should consider supporting children with mathematical problems through targeted teaching of solution strategies, as this may lead to automatization in the recall of basic arithmetic facts (i.e. a switch from procedural knowledge using strategies to declarative knowledge using the recall of basic arithmetic facts; Isaacs & Carroll, 1999; Thornton, 1978).

Ultimately, it cannot be ruled out that the use of a computer-based support program—and therefore a lack of interaction between the child and support worker—could be detrimental to children with below-average mathematical performance. The meta-analysis by Ise et al. (2012) showed that individual support from learning therapists is more effective than computer-based programs. However, the pilot study by Fuchs et al. (2006) showed that computer-based promotion of basic arithmetic factual knowledge can also be effective for children with (a risk of developing) dyscalculia. The implementation of the flash training program by Fuchs et al. (2006) was carried out under supervision (by research assistants), while we only had a student assistant accompany the first intervention session. To a certain extent, this is accompanied by the fact that the fact training we presented was standardized for all children (i.e. without an adaptive principle). However, various authors recommend that the support should be structured according to the children's skills and deficits, i.e. to offer the child an individualized support program (e.g. Dowker, 2004).

The children's motivational assessment of the training should also be noted. Although the fact training did not achieve any specific effects, at least for children with weaker mathematical performances, 71% of the children who trained with the fact training responded to the question "How well did you like the training overall?" with "good" or "very good". The implemented reward system (jungle) was also very well received by the children; 80% of the children stated that they liked the jungle well or very well. Half of the children (54%) would also have liked to continue training after completing the program (60% of the children with weaker mathematical performances stated that they would have liked to continue training). In addition to the above-mentioned positive assessments by the children, the economy of the program and the possibility of immediate corrective feedback (in contrast to traditional paper-based exercises) can be mentioned as further advantages of the computer-based fact training used.

In conclusion, it can be stated that the fact training program developed can at least be made available in schools as an alternative to paper-based practice of basic arithmetic operations in the number range up to 20. In terms of differentiation, higher-achieving pupils could make good use of the program to achieve further automation of the recall of basic arithmetic facts. However, the program is only suitable to a limited extent for older children with weaker mathematical performance. Permanent supervision by a teacher or parents and a combination of strategy-based and meaningful approaches for those children may be useful. Nevertheless, the fact training program is an easy-to-implement, cost-effective and motivating alternative to the usual paper-based drill-and-practice exercises.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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