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Research paper

Training numerical skills with the adaptive videogame "The Number Race": A randomized controlled trial on preschoolers

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ABSTRACT

Adaptive computer games offer an attractive method for numeracy training in young children. However, the evidence for transfer of learning to standard measures of numerical and arithmetic skills is scarce. We carried out a randomized controlled trial on a sample of preschool children of middle socio-economic status to evaluate the effectiveness of the freeware videogame "The Number Race" (Wilson et al., 2006). Children were randomly assigned to the training group or to the control group performing an alternative computer-based activity matched for duration and setting. The groups were matched for age, gender, and IQ. Training yielded large improvements in mental calculation and spatial mapping of numbers, as well as smaller improvements in the semantic representation of numbers. Our findings complement previous studies that showed beneficial effects for disadvantaged children, thereby suggesting that "The Number Race" is a valuable tool for fostering mathematical learning in the general population of young children.

1. Introduction

Proficient mathematical learning represents a key aspect of academic achievement and it is also an important skill for the 21st century competitive workforce [1]. Mathematical achievement can be considered a socio-economic goal from both a national and individual perspective. It has been estimated that an increase in half a standard deviation in mathematics and science performance can significantly enhance annual growth rates of GDP (i.e., gross domestic product) per capita of 0.87% [2,3]. Moreover, individuals with poor mathematical achievement are more likely to be unemployed, incur depression, or have trouble with law [4]. In light of this, early intervention in strengthening basic numerical skills may promote learning in later stages of development [5] and prevent failure in school mathematics. Recently, several low-technology math training programs (i.e., based on instruction and/or paper-pencil activities) have demonstrated efficacy in fostering number sense, numerical knowledge and math skills in young children [6–16].

There is also growing interest in the use of computer-based training to improve numerical skills and math learning [17]. Computer-based training offers several practical advantages compared to more traditional training programs: (i) presentation of information can readily exploit multiple sensory channels (e.g., visual and auditory); (ii) training is individually and progressively delivered (e.g., presenting small core concepts at the beginning and more complex problems later); (iii) reinforcement of acquired information is guaranteed by rapid positive feedback; (iv) learners can usually control their navigation through tasks and deploy an active style of learning; (v) training can be more entertaining, and the use of an adaptive algorithm based on individual performance substantially decreases the need for supervision [18]. Moreover, computer-based training may come in the form of interactive games, which provide an alternative way for learning and teaching, and may additionally decrease math anxiety, enhance time on task, combine learning and fun, place math content in an exploratory and challenging context [2,19]. It is also worth noting that videogame playing does not only improve game-related skills but it furthermore enhances a variety of cognitive abilities, in particular attention and executive control [20,21]. In the last decade, several computer games have been released with the aim to promote numerical and mathematical learning in both typically and atypically developing children [22–34].

In the present study we assessed the effectiveness of the Italian version of the freeware adaptive videogame "The Number Race"

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[35] (hereafter NR; the software can be downloaded from http://www.thenumberrace.com). The game is based of four principles: enhancing number sense, cementing the links between representations of number, conceptualizing and automatizing arithmetic, and maximizing motivation. The player competes against the software in a numerical comparison task by choosing the larger between two numerical quantities that range from 1 to 9. The numerical quantities can be represented either as object sets (i.e., non-symbolic), digits, or as the result of small additions or subtractions (which can also involve zero). Visual presentation is also supplemented (depending on game level) by the corresponding spoken number-words. The child is given the opportunity to select one of the numerical quantities, and the other quantity is then assigned to the opposing player controlled by the software. The difficulty of the task is modulated by varying the numerical distance between sets, the time limit for responding, and the format of the displayed quantities (from simple non-symbolic comparison to more complex symbolic calculation). An adaptive algorithm modulates these three dimensions in order to keep task difficulty optimally challenging (approximately 75% of accuracy) for each child, thereby working in the individual "zone of proximal learning" [36]. After each numerical comparison, the child is presented with a new screen in which she has to advance the game characters on a linear board for the number of spaces (i.e., cells) that correspond to the numerosities previously shown in the comparison trial. Though the numerical board is composed of forty cells (arranged in four rows of 10 cells each), all the numerical quantities presented in the game are smaller than ten (note that a version of the game with number up to 40 has been recently made available). The race ends when one of the players (i.e., the child or the computer) has reached the 40th position on the board. The game then proposes to start a new race and winning six races allows the player to unlock a new game character that can be used by the child. Verbal and sound feedbacks are continuously provided throughout the play to foster motivation.

At the easier levels, the child is instructed to select the larger between two non-symbolic numbers (i.e., sets of objects), which are progressively substituted by Arabic digits and arithmetic operations. The ability to compare the numerosity of two sets is at the heart of the number sense [37,38] and it is thought to be linked to math achievement [39–41]. Indeed, numerosity comparison has been found to be impaired in children with mathematical learning difficulties [42–44]. In addition, recent studies have demonstrated that training numerosity comparison or non-symbolic arithmetic has a positive transfer to symbolic numbers and math [45,46]. In a broader perspective, the ability to compare numerical quantities (non-symbolic and symbolic) and understand magnitude relationships between numbers and sets constitutes a foundational skill for young children [40,47–55].

The mixing of numerical formats in the game strengthens the connections between different numerical representations (i.e., non-symbolic, symbolic, verbal) [56]. In particular, the repeated association between digits and the corresponding non-symbolic quantities can consolidate access to numerical meaning via symbolic notation, which has been highlighted as a crucial deficit in developmental dyscalculia [57,58]. The game also fosters the spatial representation of numbers [59,60] by asking the player to move the game characters on a linear board, thereby associating the numerosity of the sets with an equal linear space. The ability to correctly place numbers on a visual line [61] (e.g., in the "number-to-position" task) supports the understanding of the magnitude relation between numbers in preschool children [62,63] and correlates with math achievement in primary school pupils [55,64]. Accordingly, children with math difficulties show a reduced accuracy in mapping numbers onto a spatial position [65–67]. Moreover, training spatial mapping of numbers is a useful tool for improving numerical skills in preschool children [10–12,68].

To the best of our knowledge, there are only four studies that formally assessed the effect of training with NR on numerical and mathematical competence [31,33,34,69]. The first study was an open trial (with no control group) carried out by Wilson et al. [33] shortly after the release of the game and it targeted primary school children with mathematical learning disability (i.e., dyscalculia). At pre-test, children completed a series of tasks assessing counting, transcoding between different number formats, enumeration, syntactic comprehension, arithmetic (e.g., addition and subtraction), and both symbolic and non-symbolic numerical comparisons. Children individually played the game in half-hour sessions over a period of five weeks, for a total average play time of 8 hours. Results demonstrated significant improvements in number sense measures (e.g., subitizing, numerical comparison) and subtractions. In a subsequent study, Wilson and colleagues [34] tested the NR in a sample of low socio-economic status preschool children. The study had a cross-over design and used commercial software targeting reading skills as control condition. The NR mainly improved the accuracy in comparing digits whereas the ability to compare non-symbolic numerosities did not improve. These results led the authors to conclude that the game fosters access to numerical meaning from symbols rather than improve number sense per se. Similar results were found by Rasanen and colleagues [31] in a randomized controlled trial on a sample of children with low-numeracy skills; NR specifically enhanced number comparison ability, but there was no evidence for an effect on other numerical skills. Finally, Obersteiner, Reiss, and Ufer [69] modified the NR in order to increase reliance on numerical approximation (approximate version of the game) as opposed to the use of exact numbers (exact version of the game). In a randomized controlled trial on first graders, the approximate version of the NR improved performance in tasks tailored to assess numerical estimation skills, whereas the exact version improved performance in tasks requiring exact representation of numbers, without any cross-over effect. Both versions significantly improved arithmetic performance.

The previous studies adopting the original version of the NR involved low-income preschool children or children with math difficulties in order to compensate for their poor basic numerical skills [31,33,34]. In the present study, we implemented a Randomized Controlled Trial (RCT) to assess the effectiveness of the Italian version of the NR [70] for enhancing basic numerical skills in a general sample of preschoolers (mostly belonging to families of middle socio-economic status). Thus, one important aim was to establish whether the NR might be a valid tool for training number skills in the general population of preschoolers. Moreover, we designed the study so that the training sessions mimicked a realistic school scenario (e.g., short sessions in large groups with minimal supervision), thereby respecting practical constraints that teacher or educators would face when using the NR as part of their curricular activities. Finally, we mainly based our analyses on measures of effect size to better highlight the practical significance (as opposed to just statistical significance [71]) of the results. We expected to replicate the findings of previous studies, with the training group demonstrating improvements in number comparison and arithmetic, relative to the control group.

2. Material and methods

2.1. Participants

Forty-five preschool children from a preschool located in north-eastern Italy took part in the present study after obtaining informed consent from parents or legal guardians. The study was approved by the ethics committee of the Department of General Psychology at the University of Padova and it was submitted to the Registry of Randomized Controlled Trials of "What Works Clearinghouse".

Children were randomly assigned to the training or control group. Twenty-three children (14 boys; $M_{\text{age-in-months}}=62$, SD=8, range=49–72) were in the Training group whereas the other 22 children (9 boys; $M_{\text{age-in-months}}=60$, SD=7, range=51–72) were in the Control group. The two groups did not differ in terms of age ($t(43)=0.93$, $p=.359$) or gender ($\chi^2(1)=1.08$, $p=.298$). Moreover, the Training group and the Control group displayed a similar IQ (Training: $M=117$, SD=17; Control: 116, SD=10, $t(33)=0.22$, $p=.828$)[2] as estimated from the combination of the Vocabulary and the Block Design subtests of the Wechsler Preschool and Primary Scale of Intelligence (WPPSI-III; [72,73]).

2.2. Pre-training and post-training measures

We administered a standardized paper-and-pencil battery to assess several aspects of numerical competence [74] (*The Numerical Intelligence Battery-BIN: Batteria Intelligenza Numerica*), as well as a mental calculation test [75] (AC-MT). The latter is devised and standardized for primary school children, which implies that most calculation problems are too challenging for the younger preschool children. Accordingly, it was administered only to a smaller group ($N=21$) of older preschool children. Children also completed two number line tasks (i.e., number-to-position task) with 1–10 and 1–20 intervals to assess their ability to correctly map numbers onto a visual horizontal line [61,62]. Finally, we measured children's letter recognition ability as a control measure, which is not expected to be influenced by training or control activity.

2.2.1. The Numerical Intelligence Battery-BIN

The BIN assesses different aspects of numerical competence in preschool children and has four subscales: Semantic subscale, Lexical subscale, Pre-syntactic subscale, and Counting subscale. Each subscale demonstrated good psychometric characteristics with high test-retest reliability (Semantic subscale: $r=.69$; Lexical subscale: $r=.89$; Pre-syntactic subscale: $r=.79$; Counting subscale: $r=.74$). For each subscale, we calculated the percentage of correct responses.

The *Semantic subscale* is composed of two subtests: dots comparison and digits comparison tasks. In the dots comparison task, children indicated the larger between two sets of dots and received one point for each correct response. There were ten trials with numerosities ranging from 1 to 9 (comparisons: 4 vs 2, 1 vs 2, 5 vs 8, 8 vs 3, 7 vs 6, 2 vs 5, 4 vs 9, 8 vs 5, 9 vs 6, 9 vs 8). Similarly, in the digits comparison task, children chose the larger between two Arabic digits and obtained one point for each correct response. There were eleven trials with digits ranging from 1 to 9 (comparisons: 2 vs 4, 7 vs 2, 8 vs 3, 1 vs 2, 7 vs 8, 4 vs 5, 6 vs 3, 6 vs 7, 5 vs 1, 3 vs 9, 4 vs 1).

The *Counting subscale* is composed of three subtests: forward sequence, backward sequence, and sequence completion. In the forward sequence task, children recited aloud the numerical sequence from 1 to 20 and obtained one point for each correct response. Skipped numbers (e.g., "11, 13, 14") were scored with 0 points. In the backward sequence task, children recited the numerical sequence backwards from 10 to 1 and obtained one point for each correct response. In the sequence completion task, children were required to identify which number/s was/were missing in a visually presented sequence of numbers from 1 to 5: there were four sequences with one missing number, and one sequence with two missing numbers. Children received one point for accurate completion of each sequence.

The *Lexical subscale* is composed of three subtests: number-name correspondence, number naming, and number writing. In the number-name correspondence task, children had to indicate the number read aloud by the experimenter among three Arabic digits. There were nine trials and the child obtained one point for each correct response. In the number naming task, the child had to read aloud digits from 1 to 9 and received one point for each correct response. In the number writing task, the child wrote the Arabic numbers from 1 to 5 upon dictation by the experimenter and received one point for each correct response.

The *Pre-syntactic subscale* is composed of three subtests: digit-dots correspondence, magnitude ordering, and one-many. In the digit-dots correspondence task, children had to match a presented digit with the corresponding set of dots among three visually presented sets. There were nine trials and children received one point for each correct response. In the magnitude ordering task, the child had to order five cartoon baskets (height × width: 6×4, 5×3.5, 4.5×3, 4×2.5, 3.5×2 cm^2) from the biggest to the smallest and received one point for each correctly ordered object. Then, four cartoon balls were ordered from the smallest to the largest in front of the child and a mid-size cartoon ball was given to the child, and they were instructed to insert it in the correct position within the ordered magnitude series (diameters of the balls: 5, 4, 3.5, 3, 2.5 cm). Subsequently, a similar trial with a different mid-size ball was presented. The child received one point for each correct insertion on these two trials. Finally, in the one-many task, the child was asked to complete sentences which conveyed numerosity relationships such as: "A hand is composed of many…?". There were six sentences and a child received one point for each correct response.

2.2.2. Number line tasks

We administered two computerized version of the number line task [61,62] (NL task) with intervals 1–10 and 1–20. In both versions, a horizontal black line (approximately 25.4 cm) was presented in the middle of a laptop screen (resolution 1280 × 1024 pixel), the digit one was placed just below the left-end of the line, whereas the digit ten or twenty was placed just below the right-end. Children moved the cursor of the mouse and clicked one of the buttons to correctly place a number along the line. The number to be positioned was presented in the upper left corner of the monitor. At each trial, the experimenter said: '*This line goes from one to ten/twenty* [pointing to the digits]. *Where is the correct place of this number* [pointing to the digit in the upper left corner]*? Show me the correct place moving the cursor and clicking the mouse button!*'. There were three training trials for the end points (i.e., 1 and 10, 1 and 20 for each interval respectively) and the middle points (i.e., 5 and 10). In training trials with end points, the experimenter corrected the child by showing the correct position in the case of wrong estimation. For instances where responses were misplaced due to double clicking with the mouse, the experimenter allowed the child to repeat the same trial. For each interval, there were eight randomly presented numbers to be placed (i.e., 2, 3, 4, 5, 6, 7, 8, 9 for the 1–10 interval; 2, 4, 6, 7, 13, 15, 16, 18 for the 1–20 interval). We obtained an index of accuracy on this task by computing the percentage of error (i.e., |Estimate-Target Number|/Numerical Interval)*100. For each child we computed the mean percentage of error in both intervals.

2.2.3. Mental calculation

This subtest was taken from the AC-MT battery for assessing math achievement in primary school children [75]. Children had to

[2] Wechsler scale subtests were administered at the end of the post-test phase to those children who completed both the pre-test and post-test assessments. IQ was measured in 16 children from the control group and in 19 children from the training group (a few children were not available at the time of post-testing).

Table 1
Mean of percentage scores and 95% CI of outcome measures for Training and Control group in the pre-test and post-test session.

Measures	Pre-test			Post-test		
	N	Mean	95% CI	N	Mean	95% CI
Counting subscale (% correct)						
Control	20	64.9	[50.6–79.2]	20	74.4	[59.9–88.9]
Training	20	76.2	[63.3–89.2]	20	87.1	[78.4–95.9]
Pre-syntactic subscale (% correct)						
Control	20	55.9	[41.9–69.9]	20	66.8	[54.5–79.1]
Training	20	68	[58.6–77.3]	20	83.2	[75.6–90.8]
Semantic subscale (% correct)						
Control	20	80.7	[72.8–88.7]	20	87.9	[81.9–93.8]
Training	20	87.6	[82–93.3]	20	96	[92.9–99]
Lexical subscale (% correct)						
Control	20	58.9	[45.8–72]	20	69.8	[56.7–82.8]
Training	20	72.4	[62.2–82.5]	20	81.5	[73.9–89.2]
NL 1–10 interval (% error)						
Control	19	20.5	[15–25.9]	19	24.3	[16.1–32.5]
Training	20	20.9	[15.3–26.5]	20	14.1	[8.6–19.6]
NL 1–20 interval (% error)						
Control	18	22.6	[17.2–28.2]	18	25.9	[17.8–34]
Training	20	21.2	[15.1–27.3]	20	15.5	[11.6–19.4]
Mental calculation (% error)						
Control	9	68.5	[39.6–97.5]	9	70.4	[44.1–96.6]
Training	9	64.8	[48.6–81.1]	9	18.5	[−1.2–38.2]
Letter recognition (% error)						
Control	20	34	[20.1–48]	20	27.4	[15.3–39.5]
Training	19	26.3	[17.2–35.4]	19	17	[8.1–26]

solve six verbally presented arithmetic problems (3 additions and 3 subtractions), which involved numbers below 10 (i.e., $1+2$, $3+4$, $2+6$, $3-1$, $8-5$, $7-3$). Children earned one point for each correct response. Only older preschool children ($N=21$) in our sample completed the mental calculation task.

2.2.4. *Letter recognition*

Children had to indicate the letter read by the experimenter among a triple of letters. There were 21 triplets and children earned one point for each correct recognition. We calculated the percentage of errors as the outcome measure.

2.3. *The "Number Race" and the control activity*

Children completed the training and control activity divided into small groups (max 13 children) in the school computer-room under the supervision of the experimenter and/or research assistant who acted as a guide [18]. Children in the training group played with the Italian version of NR, whereas children in the control group completed an alternative activity to foster their drawing skills using the free software TuxPaint (www.tuxpaint.org). Supervisors encouraged children to keep playing or drawing and reinforced them with verbal feedback related to their efforts (e.g., "You are doing a good job!"). Nevertheless, children could interrupt the session at any time without receiving penalization. The training and the control activity lasted for 10 weeks, there were usually 2 sessions per week, and each session lasted approximately 20 min. The NR training and control groups completed a similar number of sessions (Training: $M=16.9$, $SD=2.7$, range: 11–20; Control: $M=16$, $SD=2.7$, range: 9–19, $t(43)=1.07$, $p=.289$). Outside the experimental sessions, children attended their regular scholastic program, which entailed numerical activities for half-hour to one hour once a week. Specifically, children played numerical games that mainly required the comparison of non-symbolic numerical quantities (e.g., choosing the larger or the smaller between two sets of objects, creating two sets with equal number of elements) and the implementation of counting routine (i.e., determining the exact number of elements in a set).

3. Results

In the pre-test phase, one child did not complete both NL tasks, one child did not complete the NL task with 1–20 interval, and another child did not complete the letter recognition task. However, these children completed the remaining tasks and their scores were retained for subsequent analyses. Five children were absent at the post-test session for different reasons (e.g., health condition, vacation with parents) and their data was excluded from subsequent analyses. Nevertheless, training and control groups did not differ in any pre-test measure, neither for number of training sessions nor for gender proportion and IQ (all $ps > .05$). The performance scores are reported in Table 1 as a function of group and testing session.

We analyzed scores at the Post-test in a series of ANCOVAs[3] with Group [Training, Control] as between-subjects factor and Pre-test as covariate. We also followed the guidelines of the "What Works Clearinghouse" [76] which recommends the adoption of specific effect size measures to evaluate training effectiveness in education. We calculated the Hedges' g between training and control groups for each dependent measure in the pre-test phase. If the absolute value of g exceeded 0.05 at the pre-test, it meant that the two groups substantially differed before training. Therefore, we calculated the post-test Hedges' g on groups' means that were adjusted using pre-test means as a covariate. Because our pre-test Hedges' g_s usually exceeded the cut-off (i.e., $|0.05|$), we implemented the covariate correction as a rule of thumb for all comparisons in the post-test. The corrected value of Hedges' g was converted to the proportion of the area under the standard normal curve using z-score values (e.g., for a corrected Hedges' $g=0.25$ we calculated the area under the normal curve of z-score$=0.25$, that is 60%). From the obtained proportion under the curve we subtracted 50%, which represents the difference in percentile rank

[3] In all the ANCOVAs conducted, Pre-test scores did not differ between training and control groups (all $ps > .05$; i.e., assumption of independence of the covariate and the training effect) and all interactions between Pre-test scores and Group were not significant (all $ps > .05$; assumption of homogeneity of regression slopes).

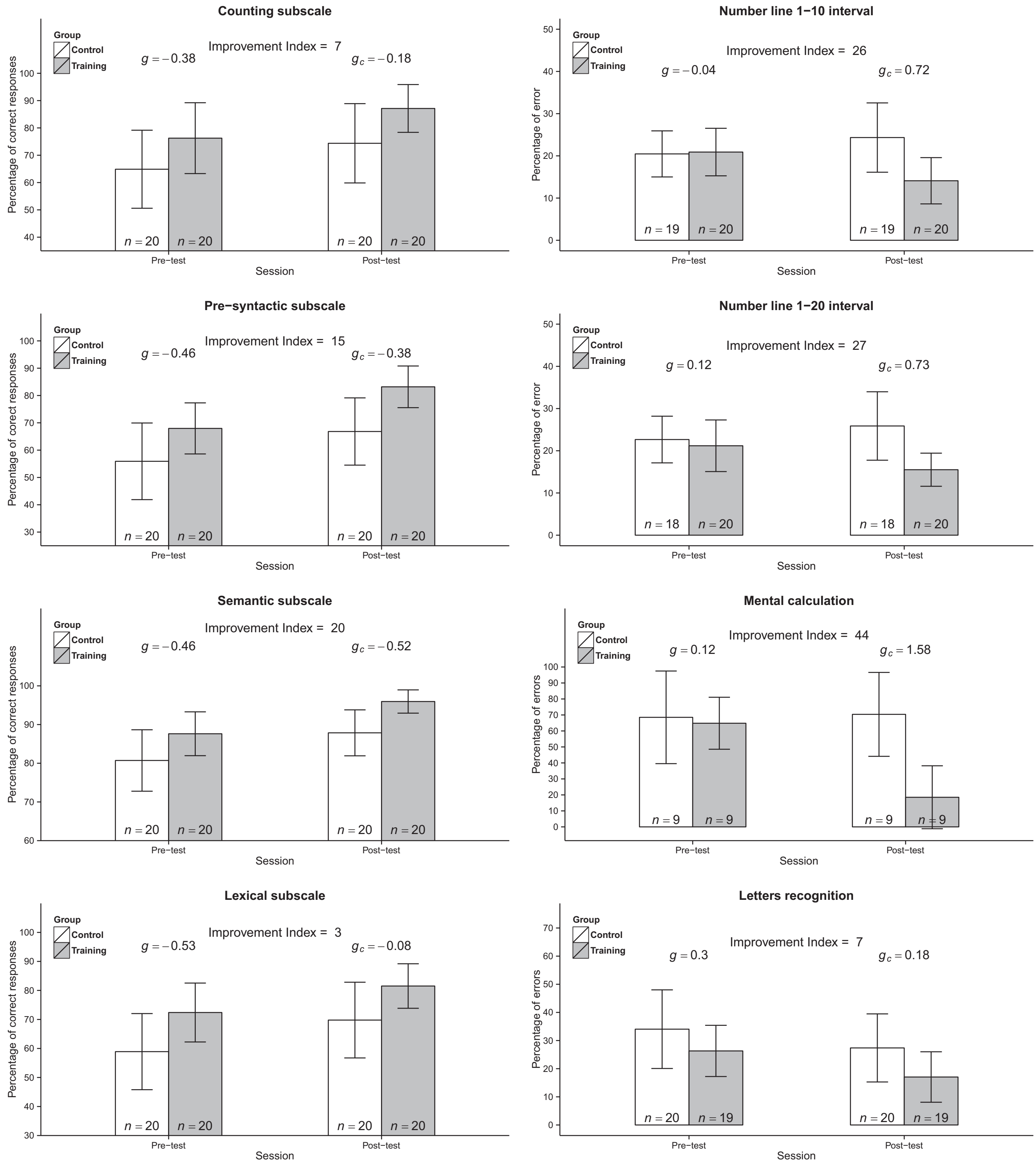

Fig. 1. Percentage scores for each assessed measure as a function of group (Training vs. Control) and testing session (pre-test vs. post-test. Error bars represent 95% CI. Hedge's g for the pre-test, corrected Hedge's g, and improvement index are shown as measures of effect size.

between an average training group member and an average control group member. Therefore, the improvement index represents the expected change in percentile rank for an average-skilled child if he/she had completed the training (see Fig. 1).

To further investigate the effect of training on the assessed measures, we adopted a bootstrap technique to obtain a precise description of the improvement indexes distribution. We randomly resampled with replacement (1000 times) participants from the Training and the Control groups, and then we calculated the corrected Hedges' g and the corresponding improvement index. We report the distributions of the estimated improvement indexes for each measure in Fig. 2.

3.1. BIN battery-Counting subscale

We analyzed the percentage of correct responses in the Counting subscale at post-test in an ANCOVA with Group [Training, Control] as between-subjects factor and Pre-test as covariate. The covariate, Pre-test scores, was significantly related to the Post-test scores, $F(1, 37)=65.3$, $p < .001$, whereas the effect of Group on

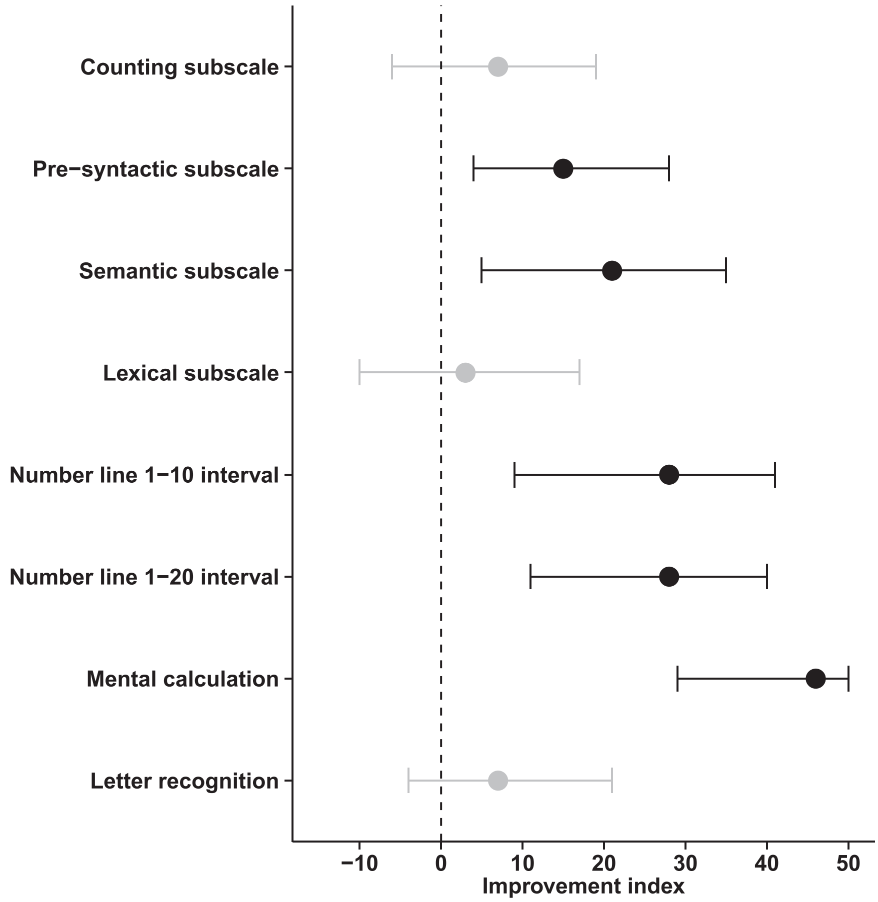

Fig. 2. For each measure we calculated the distribution of the improvement indexes using a bootstrap technique (1000 resamplings with replacement). Dots and errors bars represent the median and the 95% limits of the distribution, respectively. Distributions for improvement indexes overlap the zero value (dashed line) for Counting subscale, Lexical subscale and Letter recognition (grey dots and error bars). Conversely, distributions of improvement indexes for Pre-syntactic subscale, Semantic subscale, Number line tasks with 1–10 and 1–20 intervals, and Mental calculation have positive values without overlapping zero (black dots and error bars).

Post-test scores after removing the effect of Pre-test scores was not significant, $F < 1$.

Indeed, looking at the effect size measures comparing the training and the control groups, we note that both the corrected Hedge's *g* and the improvement index values are negligible. Accordingly, the distribution of bootstrapped improvement indexes for the Counting subscale includes values around zero.

3.2. BIN battery-Pre-syntactic subscale

We analyzed the percentage of correct responses in the Pre-syntactic subscale at post-test in an ANCOVA with Group [Training, Control] as between-subjects factor and Pre-test as covariate. The covariate, Pre-test scores, was significantly related to the Post-test scores, $F(1, 37) = 53.19$, $p < .001$. The effect of Group on Post-test scores after removing the effect of Pre-test scores approached significance, $F(1, 37) = 3.32$, $p = .077$. Accordingly, the small corrected Hedge's *g* and improvement index values highlight that the training group slightly improved syntactic knowledge compared to the control group. Indeed, the distribution of bootstrapped improvement indexes is positive and does not overlap with zero.

3.3. BIN battery-Semantic subscale

We analyzed the percentage of correct responses in the Semantic subscale at post-test in an ANCOVA with Group [Training, Control] as between-subjects factor and Pre-test as covariate. The covariate, Pre-test scores, was significantly related to the Post-test scores, $F(1, 37) = 19.25$, $p < .001$. There was also a significant effect of Group on Post-test scores after removing the effect of Pre-test scores, $F(1, 37) = 3.94$, $p = .05$. Accordingly, the corrected Hedge's *g* and the improvement index show relevant values, suggesting that NR training slightly improved semantic knowledge compared to the control activity. The distribution of estimated improvements indexes confirms the effectiveness of the training. In the NR, children had to continuously compare symbolic and non-symbolic numbers. Therefore, it is not surprising to observe an improvement in the Semantic subscale that includes the comparison of Arabic digits and set of dots.

3.4. BIN battery-Lexical subscale

We analyzed the percentage of correct responses in the Lexical subscale at post-test in an ANCOVA with Group [Training, Control] as between-subjects factor and Pre-test as covariate. The covariate, Pre-test scores, was significantly related to the Post-test scores, $F(1, 37) = 68.5$, $p < .001$, whereas the effect of Group on Post-test scores after removing the effect of Pre-test scores was not significant, $F < 1$. Both the corrected Hedge's *g* and the improvement index values are negligible, suggesting that NR training did not improve lexical knowledge more than normal development as highlighted by the main effect of Session. Accordingly, the distribution of estimated improvement indexes includes values around zero, thereby showing no effect of training on lexical knowledge.

3.5. Number line with 1–10 interval

We analyzed the percentage of absolute errors in the Number line task with interval 1–20 at post-test in an ANCOVA with Group [Training, Control] as between-subjects factor and Pre-test as covariate. The covariate, Pre-test scores, was significantly related to the Post-test scores, $F(1, 36)=15.72$, $p<.001$. The effect of Group on Post-test scores after removing the effect of Pre-test scores was also significant, $F(1, 36)=7.14$, $p=.011$. Both the corrected Hedge's g and the improvement index have relevant values, suggesting that NR training improved spatial knowledge of numbers more than the control activity. This result is confirmed by the distribution of bootstrapped improvement indexes, which consists of large positive values.

3.6. Number line with 1–20 interval

We analyzed the percentage of absolute errors in the Number line task with interval 1–20 at post-test in an ANCOVA with Group [Training, Control] as between-subjects factor and Pre-test as covariate. The covariate, Pre-test scores, was significantly related to the Post-test scores, $F(1, 35)=12.54$, $p=.001$. The effect of Group on Post-test scores after removing the effect of Pre-test scores was also significant, $F(1, 35)=7.02$, $p=.012$. Also for the 1–20 interval, the corrected Hedge's g and the improvement index have relevant values, suggesting that NR training improved spatial knowledge of numbers compared to the control activity.

It is worth noting that the Training group showed a significant improvement in the mapping of numbers that were larger (i.e., >9) than those presented in the NR. To further investigate this issue, we verified whether the Training group showed a different improvement for target numbers below and above 10. We analyzed the percentage of absolute error of the children in to the Training group using a repeated measures ANOVA with Session [Pre-test, Post-test] and Interval [Below 10, Above 10] as within-subjects factors. In line with the ANCOVA result, only the main effect of Session was significant, $F(1, 19)=9.7$, $p=.006$. The lack of a significant interaction Session x Interval ($F<1$) suggests that the observed improvement in mapping accuracy was similar for target numbers below and above ten, even if the latter numbers were not presented in the NR. It is conceivable that children improved their accuracy in placing numbers below ten and then used these as anchor points to rescale the estimates for larger (above ten) target numbers. Consistent with this, a recent study found that young children's number line estimate at a given trial is actually influenced by previous estimates [77].

3.7. Mental calculation

We analyzed the percentage of errors in the Mental calculation subscale at post-test in an ANCOVA with Group [Training, Control] as between-subjects factor and Pre-test as covariate. The relation between the covariate, Pre-test scores, and the Post-test scores approached significance, $F(1, 15)=4.22$, $p=.058$. The effect of Group on Post-test scores after removing the effect of Pre-test scores was significant, $F(1, 15)=14.86$, $p=.002$. Indeed, both the corrected Hedge's g and the improvement index have large values, suggesting that NR training strongly improved calculation abilities compared to the control activity. The skewed distribution of bootstrapped improvement indices confirms that training had large benefits on basic arithmetic skills.

3.8. Letter recognition

We analyzed the percentage of errors in the Letter recognition test at post-test in an ANCOVA with Group [Training, Control] as between-subjects factor and Pre-test as covariate. The covariate, Pre-test scores, was significantly related to the Post-test scores, $F(1, 36)=140.71$, $p<.001$. The effect of Group on Post-test scores after removing the effect of Pre-test scores was not significant, $F(1, 36)=1.51$, $p=.23$. As expected, both the corrected Hedge's g and the improvement index values were negligible, suggesting the training activity did not influence letter recognition.

4. Discussion

The present study evaluated the effectiveness of the Italian version of NR [35,70] in enhancing numerical skills in a sample of preschool children from families of middle socio-economic status. We randomly assigned children to the training and control groups in order to control for a variety of confounding factors. The two groups were matched for gender, age, general intelligence (estimated IQ) and numerical competence in the pre-test phase. The training group played with the NR, whereas the control group performed activities to foster their familiarization with a personal computer (i.e., drawing). Children carried out the control and training sessions in the school PC-room for a similar amount of time (approximately 16 half-hour sessions). Both activities were conducted under the supervision of the same experimenter/s who guided children through the proposed activities. We highlight that both activities were conducted in small groups during school hours. Therefore, we simulated realistic conditions that teachers may adopt in future implementations of training using the NR.

The training group demonstrated large improvements in the ability to spatially map numbers in the number line tasks (both intervals 1–10 and 1–20) compared to the control group. Older children in the training group also demonstrated a large enhancement in basic mental calculation, as indexed by their accuracy in solving verbally presented arithmetic operations. The training group also showed small improvements regarding syntactic and semantic knowledge (i.e., dots and digits comparison) compared to the control group. Conversely, there were no differences between groups for counting and lexical knowledge. As expected, the accuracy in the letter recognition task similarly increased for both groups, suggesting that the improvements in the numerical tasks is a specific result of NR training and cannot be attributed to higher motivation in the NR training compared to the control activity. It is worth noting that children in the control group improved their performance between the pre-test and the post-test session in several of the assessed measures[4]. Therefore, the teaching-as-usual within the preschool context generally improved children's numerical knowledge. Crucially, the effect of NR training reliably exceeded the expected improvement associated with teaching-as-usual.

The improvement in spatial representation of numbers could be the direct consequence of the NR requirement to perform repeated mappings between numbers and space. For instance, in the second screen of the game, children moved their own and the computer's character on the board by mapping numerosities onto a linear space. Interestingly, although the NR entails play with numbers only up to ten, children transferred their spatial knowledge to the 1–20 numerical interval in the number-to-position task. It is conceivable that children improved their accuracy in mapping target numbers below ten and used these as anchor

[4] We ran a series of paired t-tests to compare the pre-test and post-test scores of the assessed measures in the Control group. We found a significant increase in performance for the Counting subscale ($t(19)=2.39$, $p=.027$), the Lexical subscale ($t(19)=2.91$, $p=.009$), the Semantic subscale ($t(19)=2.41$, $p=.026$), the Pre-syntactic subscale ($t(19)=2.66$, $p=.015$), and the Letter recognition task ($t(19)=2.77$, $p=.012$).

points to rescale the estimates for larger (above ten) target numbers. In line with previous studies [10–12], linear board games can improve the spatial representation of numbers, which has been found to promote the understanding of numerical magnitude and to foster future mathematical achievement [64,78]. The ability to place numbers on the visual line is compromised in children with math disability [65–67], thereby suggesting that accurate spatial mapping of numbers is important for mathematical learning.

In the advanced levels of the game, children had to solve summation and subtraction problems in order to choose the larger numerical quantity. The proposed arithmetic operations were often presented in terms of concrete sets, which might facilitate understanding of addition and subtraction. Indeed, the NR greatly improved basic arithmetic knowledge in older preschool children, which is known to be important for later math achievement [49].

The training group also showed improvements, albeit small, in semantic and pre-syntactic subscales of the numerical assessment battery, whose tasks required judgment of magnitude relationships between numerical sets and digits, as well as mapping digits to the corresponding non-symbolic numerosity. This improvement is not surprising given that the basic structure of the game is rooted in the comparison of numerical quantities. Strengthening these basic skills is crucial given that they are predictive of math achievement and have been found to be compromised in children with math disability [39,40,42,47–50,52–54,57,78–80] (for a different account see [81]). In contrast, both counting skills and lexical knowledge did not improve after the NR training.

Previous training studies based on the NR have assessed its effectiveness for compensating poor numerical knowledge in preschool children belonging to low socio-economic status [31,34]. These studies have reported that the NR was effective in facilitating access to the meaning of the symbolic representation of numbers, thereby reinforcing the connection between the analog magnitudes and the visual-Arabic code [56]. Other studies reported on the potential of the NR for ameliorating arithmetic skills in older children with and without math disability [33,69]. The present study confirmed and extended these previous results. Children in our sample demonstrated large improvements in more advanced numerical skills such as spatial representation of numbers and mental calculation, whereas more basic skills (e.g., non-symbolic and symbolic comparison and magnitude relation understanding) showed smaller enhancements. This difference could be partly related to the fact that basic numerical skills improved also in the control group, whereas advanced skills did not show significant changes across testing sessions in the control group.

Despite the random assignment to the groups and the ecological setting of the training, the present study suffers from some limitations. We ran our RCT in only one school, which implies that generalization to different contexts is not guaranteed. In particular, we encountered highly collaborative principal, teachers, and school staff, who provided a very positive environment for the realization of the present study. Broader studies should be conducted to verify the effectiveness of the training when implemented in different school contexts (e.g., disadvantaged schools or classes with high proportion of immigrant children). Moreover, though the control activity was performed in the same room, with the same supervisors, for the same amount of time and, more importantly, involving the use of computers, we cannot completely exclude that the improvements in the training group could be related to the structure of the NR compared to the control activity. Indeed, the NR was a more meaningful activity with subtasks, aims, and feedback compared to the control activity. Children in the NR training group could have experienced a more stimulating training which enhanced their motivation and auto-efficacy. Nevertheless, this possible confound of generalized motivation is ruled out by the fact that there was no influence on the control measure (i.e., letter recognition). Expectation is another possible difference between training and control group. Children who played with the NR probably had a great expectation to improve their numerical skills compared to the control group who possibly lacked a specific expectation regarding the control activity [82]. Finally, the post-test measures were gathered immediately after the training and there was no follow-up session. Future studies might therefore investigate whether the benefit of NR training is long-lasting, thereby assessing whether training gains hedge or dissipate over the course of subsequent mathematical learning.

5. Conclusion

The present RCT demonstrated the efficacy of the NR for enhancing numerical skills in preschool children from families of middle socio-economic status. Large improvements were observed for more advanced skills such as spatial representation of numbers and mental calculation, whereas basic numerical skills (e.g., dots and digit comparisons) were characterized by small improvements. Previous studies showed the NR efficacy in improving the connection between symbolic and non-symbolic representation of numbers in preschool children from low-income families. Therefore, the NR appears to be an effective and versatile tool for enhancing both basic and advanced numerical skills in a wide range of children from different social and economic backgrounds, and with different numerical pre-training competences.

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