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# Math anxiety interferes with learning novel mathematics contents in early elementary school

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Abstract

Whereas some evidence exists that math anxiety may interfere with math performance from the very beginning of primary school, no study to date has attempted to investigate whether math anxiety may also interfere with early math learning (i.e., the encoding of new math knowledge), and not only with recalling already mastered contents in test situations. Across two experiments carried out in two different countries (Study 1: *N* = 115, conducted in Italy; Study 2: *N* = 120, conducted in the UK), we addressed this question by presenting 6-year-old children with two math contents that had not been covered by their school curriculum before the study. Children were tested immediately before and immediately after the learning phase, and after a one-week delay. Results of longitudinal structural models revealed that math anxiety was negatively related to initial level of knowledge in the case of 3 out of 4 math contents. More importantly, math anxiety was also negatively related to rate of learning in two out of four tasks (one task in Study 1 and one in Study 2). These studies provide the first evidence that math anxiety may reduce the encoding of novel math contents in memory in very young children, potentially leading to cumulative gaps in math proficiency for children with math anxiety from the very beginning of their formal education.

*Keywords*: early elementary school children; math anxiety, math learning, training effects.

## Educational impact and implications statement

In this study we investigated whether math anxiety may interfere with learning novel math concepts - and not only with the recall of already mastered contents in testing situations - among primary school children. Across two experiments carried out in two different countries and school systems (Italy and the UK), we presented each participant with two math contents that had not been covered by their school curriculum before the study, and we found that math anxiety reduced the rate of learning in 2 out of the 4 tasks. Thus, math anxiety may reduce the acquisition of novel math knowledge in very young children, potentially leading to cumulative gaps in math proficiency over time.

# Math anxiety interferes with learning novel mathematics contents in early elementary school

Math anxiety is a negative emotional response to mathematics, or to the mere prospect of working with numbers (Ashcraft, 2002; Hembree, 1990). As a consequence of their feelings of discomfort, apprehension, or, in some cases, overt fear, individuals with high math anxiety tend to avoid situations involving mathematics, both in academic contexts and in private and social life (Richardson & Suinn, 1972). For example, they tend to avoid courses and careers that require intensive mathematical skills (i.e., global avoidance; e.g., Hembree, 1990), or minimize their involvement (e.g., Ashcraft & Faust, 1994) and make less use of basic mathematical knowledge (e.g., Jansen, Schmitz, & van der Maas, 2016) in daily life situations that require the manipulation of numbers (i.e., local avoidance). High levels of math anxiety are linked to lower math proficiency (see Hembree, 1990, and Ma, 1999, for meta-analyses), as well as to failure in performing daily life tasks, such as drug calculations (McMullan, Jones, & Lea, 2012), understanding medical risks (Rolison, Morsanyi, & O'Connor, 2016; Rolison, Morsanyi & Peters, 2020; Silk & Parrott, 2014), or financial decision making (McKenna & Nichols, 1998). Math anxious individuals have also been found to engage in less cognitive reflection (Morsanyi, Busdraghi, & Primi, 2014; Primi, Donati, Chiesi, & Morsanyi, 2018), which is an important contributor to making good decisions. This is most likely because cognitive reflection is demanding of working memory resources, and intrusive thoughts associated with math anxiety occupy working memory (cf., Morsanyi et al., 2014).

Against this backdrop, it is unsurprising that research into math anxiety has shown an exponential growth over time (Morsanyi et al., 2016). Yet, relatively few studies have focused on math anxiety and its relation to math proficiency among young children (although see e.g., Cargnelutti, Tomasetto, & Passolunghi, 2017a; Ramirez, Gunderson, Levine, & Beilock, 2013). Moreover, studies conducted thus far have focused on the relations between math anxiety and the recall and use of already mastered math skills in evaluative contexts, whereas no study to date has attempted to investigate whether math anxiety may also interfere with the process of math *learning* (i.e., with the encoding of new math knowledge) in young schoolchildren. In two experiments, we addressed this issue by investigating 6-year-old children's learning of novel math contents that had not been part of their school curriculum up to the time of the study.

**Math anxiety and math performance in young children.**

Several age-specific scales have been recently developed to improve the assessment of math anxiety among primary school children (e.g., Carey, Hill, Devine, & Szűcs, 2017; Caviola, Primi, Chiesi, & Mammarella, 2017; Primi, Donati, Izzo, Guardabassi, O'Connor, Tomasetto & Morsanyi, 2020), and reliable individual differences in math anxiety have been detected as early as 6-to-7 years of age, when children enter primary school in numerous educational contexts worldwide (e.g., Ramirez et al., 2013; Gunderson, Park, Maloney, Beilock, & Levine, 2018). Even among young schoolchildren, math anxiety has been found to be dissociable from – even though moderately related with - general anxiety (Cargnelutti et al., 2017a; Hembree, 1990; Wang et al., 2014). In an fRMI study with children aged 7-to-9 years, Young, Wu, and Menon (2012) showed increased activation of cortical regions associated with emotional processing, and decreased activation of networks implied in numerical elaboration, among highly math-anxious children during a math problem solving activity, independent of children's level of general anxiety.

The negative relation between math anxiety and math proficiency is well-established in adolescents and adults (e.g., Foley et al., 2017; Hembree, 1990; Ma, 1999; OECD-PISA, 2012), and recent evidence suggests that both concurrent and predictive associations between math anxiety and math performance can be detected from the earliest elementary grades (Gunderson et al., 2018; Harari, Vukovic, & Bailey, 2013; Jameson, 2014; Ramirez et al., 2013; Ramirez, Chang, Maloney, Levine, & Beilock, 2016; Sorvo et al., 2017), even when controlling for general anxiety (Cargnelutti, Tomasetto, & Passolunghi, 2017b; Wu, Amin, Barth, Malcarne, & Menon, 2012; Wu, Willcutt, Escovar, & Menon, 2014). Meta-analytic findings, however, suggest that the strength of the anxiety-performance association is stronger among older than among younger primary school pupils (e.g., Zhang, Zhao & Kong, 2019). Although most studies conducted with children have assumed a prevalent causal direction whereby high math anxiety leads to lower achievement, evidence has also been found for bi-directional and reciprocal influences in primary school children (e.g., Cargnelutti et al., 2017b; Gunderson et al., 2018), with math anxiety and math performance influencing each other over time in potentially virtuous or vicious cycles (see Carey Hill, Devine, & Szücs, 2016).

**Anxiety, encoding of new information, and math learning**

Most of the studies conducted thus far on the relation between math anxiety and math proficiency have assessed adults' and children's performance on standardized math tests and arithmetic tasks (see Dowker, 2019, for a review). These types of tests require individuals to retrieve information, procedures and abilities that have been constructed and consolidated in the past, and to apply such knowledge to current tasks. Much less attention has been devoted to the role of math anxiety in the *learning* process, i.e., in the phases of knowledge acquisition and consolidation. In part, this lack of interest may relate to the fact that research on the interplay between emotions and memory has traditionally assumed that information retrieval from consolidated memory systems might be impaired, whereas information encoding (i.e., new learning) may even be enhanced in stressful situations – such as those experienced by highly math-anxious individuals faced with math tasks (e.g., Cahill, Gorski, & Le, 2003; Roozendaal, 2000). Recent advances, however, have nuanced these statements, by demonstrating that neurotransmitters (such as norepinephrine and dopamine) and hormones (such as cortisol) associated with stress responses trigger complex remodulations of neurocognitive networks, that reverberate in both enhancing and derailing effects on memory formation and consolidation (for recent reviews, see Quaedflieg & Schwabe, 2018; Vogel & Schwabe, 2016).

On the one hand, a "salience network" (Seeley et al., 2007) is activated when a situation is appraised as threatening, which includes subcortical structures (e.g., basolateral amygdala and hippocampus) and cortical areas (e.g., temporal and dorsal-anterior cingulate cortex) involved in rapid processing of threat-related information (Menon, 2011; Quaedflieg & Schwabe, 2018).

Activation of the salience network actually facilitates the encoding of emotionally arousing – as compared to neutral – episodes (for a review, see Shields, Sazma, McCullough, & Yonelinas, 2017), as well as simple stimulus-response associations (Wingard & Packard, 2008; Schwabe & Wolf, 2010). On the other hand, a parallel down-regulation of the "executive control network" (Seeley et al., 2007) occurs, which includes prefrontal and dorsolateral cortical areas that are involved in controlled, time-consuming and effortful cognitive processes. Reduced activation of the executive control network prevents the possibility to encode complex, detailed concepts, and relations among pieces of information (see Ralph, Jefferies, Patterson, & Rogers., 2017). Importantly, down-regulation of controlled and effortful processing also impairs the efficient use of prior knowledge to elaborate ongoing stimuli, and the integration of new information into past knowledge structures (Schwabe, Nader, & Pruessner, 2014; Vogel, Kluen, Fernández, & Schwabe, 2018).

Because learning mathematics not only involves remembering simple numerical facts, but often requires effortful elaboration to integrate new information into an existing basis of knowledge to solve complex problems, it is arguable that anxiety experienced during math classes (i.e., when teachers explain new math contents), is likely to activate stress-induced changes in memory systems that prevent effective learning of math. Indeed, prior research suggests that high math-anxious individuals, during numerical information's processing, display attentional biases toward threatening stimuli and reduced attentional control (e.g., Rubinsten, Eidlin, Wohl, & Akibli, 2015; Suarez-Pellicioni, Nunez-Pena, & Colomé, 2013, 2015), which are both associated with the down-regulation of the executive control network (Seeley et al., 2007).

Although not specific to math anxiety, related research also suggests that anxiety experienced during the encoding process may thwart the ability to acquire new knowledge, and that anxiety may interfere with learning through processes that are relatively different from – albeit related to – those implied in performance assessment. Research on stereotype threat, for example, demonstrates that individuals who feel at risk of failing in evaluative tasks in which their groups are negatively stereotyped display less efficient learning of strategies to solve new math problems, and were less able to transfer the knowledge they had acquired to other math tasks (Rydell, Rydell, and Boucher, 2010a). Similar findings also emerged from studies on perceptual (Rydell, Shiffrin, Boucher, Van Loo, & Rydell, 2010b) and motor learning (Heidrich & Chiviacowsky, 2015). A study on memory among older adults (Krendl, Ambady, & Kensinger, 2015) specifically compared the effects of stress administered either in the learning (i.e., encoding) or in the evaluation (i.e., retrieval) phase of a standard memory test. The results revealed that although performance impairments were most pronounced when the threat was experienced prior to retrieval as compared to the encoding phase, in both conditions memory performance was impaired relative to a control (i.e., non-stressful) condition. Overall, these findings suggest that negative emotions and fear of failure experienced during the learning phase have a negative impact on memory formation that is dissociable from the impact exerted on the evaluation phase (i.e., retrieval), and probably cumulate to produce observable performance deficits (Appel & Kronberger, 2012). Although self-threatening stimuli are not necessarily present in the case of math anxiety, the underlying mechanisms might be similar to stereotype threat (Maloney, Schaeffer, & Beilock, 2013).

More comprehensive theoretical models on the relations between emotions, motivation, and academic achievement, such as the control-value theory (Pekrun, 2006; Pekrun, Goetz & Tizt, 2002), also provide important insights into the underlying mechanisms that may differentially implicate anxiety with knowledge construction and retrieval. According to the control-value theory, both negatively and positively valenced emotions may affect content learning though task-contingent regulation (e.g., allocation of attentional resources, use of rigid vs. flexible learning strategies), whereas the long-term influence of emotions on academic performance and achievement may be related to more complex and over-determined motivational and cognitive processes (e.g., effort withdrawal over time, strategies to cope with failure, effort to integrate and deepen knowledge over time, etc.; Pekrun et al., 2002). Empirical evidence supports the impact of achievement-related emotions on learning of novel contents, and not only on long-term achievement. In a study with undergraduate students, for example, both positive and negative emotions affected the extent to which participants overcame their prior misconceptions on debated scientific topics (i.e., gained new knowledge) through autonomous text study (Muis et al., 2015; see also Chevrier, Muis, Trevors, Pekrun & Sinatra, 2019).

Nevertheless, no study to date has sought to disentangle whether math anxiety - by inducing a domain-specific state of discomfort when doing mathematics – not only prevents children from displaying their math ability at their optimal level, but also impedes on their ability to acquire novel math knowledge at the earliest school grades. This question is critical for understanding the causal mechanisms that link math anxiety to math performance, as well as the long-term consequences of math anxiety.

**The present studies**

The central hypothesis of our studies was that math-anxious young children would benefit less from learning opportunities. Nevertheless, math-anxious children might also start out with lower levels of relevant knowledge, which could have a knock-on effect on their ability to understand new content and integrate it with their existing knowledge. For this reason, it was important to separate anxiety-related performance deficits that stem from differences in initial knowledge between math-anxious and non-math-anxious children before they are presented with novel content, and the differences that might arise during the learning process. To address these issues, we presented young children aged 6 years with novel math contents that were not formally taught to them up to that point. Nevertheless, as children might acquire new concepts outside the school setting, we also assessed their initial familiarity with these concepts. We expected that math-anxious children might start out with lower levels of understanding of some concepts. More importantly, we predicted that they might learn less from a training that is aimed at developing their understanding of those concepts. In order to evaluate the robustness of the hypothesized effects, the studies were conducted in two different countries and school systems (in Italy and the UK), which differ in school starting age, as well as in the content of the school curriculum. Additionally, to further test the generalizability of the findings, the acquisition of four different novel math contents was investigated.

## Study 1

The first study investigated the effect of math anxiety on the acquisition of two unfamiliar concepts (the order invariance of addends and addition with tens) in first grade children in Italy.

### Method

**Participants.** After approval from the Ethical Committee of the University of XXXX (blinded), children attending the first grade of primary school were recruited from six different schools in the district of XXXXXX (blinded), in the Center-North of Italy. All schools were located in sub-urban and rural areas. The district of XXXXXXX is characterized by a generally favourable socio-economic situation, with an average per-capita income that is higher than the national average, and a markedly lower unemployment rate (https://www.istat.it/storage/urbes2015/cesena.pdf). The national student assessment results reported by the schools involved in the study (https://www.invalsi.it/snv/) were similar to or slightly higher than the national and the regional average.

Parents provided informed consent for 130 children (67 boys; $M_{age}$= 79.32 months; *SD* = 3.58). Seventy-seven mothers and 4 fathers provided information as regards their educational background (65% of participants). Parents with university degrees were 24.75%, whereas 52.40% had a high-school diploma, and 22.85% had a lower qualification. Because 15 children were absent from school at the time of one or both of the two data collection sessions, and it was not possible to reschedule the sessions, the final sample included 115 children (59 boys).

**Materials.** In the baseline, the immediate post-test, and the delayed post-test phases, children completed numerical problems based on two different mathematical concepts: addition with tens and order invariance of addends. These concepts were not included in the first grade primary school curriculum, and teachers of all classes involved in the study confirmed that the two concepts had not yet been taught to the children at this stage, and would also not be covered during the subsequent month.

***Addition with tens.*** The test for adding tens included 10 addition problems. Participants were required to answer as quickly as possible, but were not explicitly given a time limit, and they were not made aware of being timed. However, to make sure that children could not rely on unit by unit counting procedures, answers provided beyond 5 seconds were coded as incorrect. If children failed to provide any answer within ten seconds, the experimenter invited the children to skip the task and move on to the subsequent item. An accuracy score was calculated as the proportion of correct answers over the number of presented items (range: from 0 to 1). Cronbach's alpha for the measure was .92 at baseline, and .95 and .92 at immediate and delayed post-test, respectively.

***Order invariance of addends.*** To assess the principle of order invariance of addends, children were shown 10 equations, with one addition on the left side and one on the right, and were asked to indicate if both additions gave the same answer. Six equations included the same addends in reverse order (e.g., 5 + 3 = 3 + 5), whereas 4 included different addends on the two sides of the equation (e.g., 4 + 4 = 2 + 3). An accuracy score was calculated as the proportion of correctly answered trials over the number of items within 5 seconds (range: from 0 to 1). Cronbach's alpha for the measure was .77 at baseline, .90 at immediate post-test and .79 at delayed post-test.

***Math Anxiety.*** Children's mathematical anxiety was measured using the Early Elementary School Abbreviated Math Anxiety Scale (EES-AMAS; Primi et al., 2020), a version of the Abbreviated Mathematical Anxiety Scale (AMAS; Hopko, Mahadevan, Bare, & Hunt, 2003) adapted for children in the first elementary grades. The EES-AMAS includes 9 items concerning mathematical situations in a school setting (e.g., "When your math teacher gives you homework that is long and difficult."; "When you watch your teacher solving a math sum on the whiteboard."). Children were first explained the meaning of feeling anxious, before they were shown a five-point scale with squares that increased in the amount of space that was filled inside them, which represented increasing anxiety. The leftmost box (which was empty) represented being not anxious at all, whilst the rightmost box (which was completely filled up) represented being very anxious. The math anxiety score was calculated by averaging children's raw answers on the 9 EES-AMAS items. Cronbach's alpha was .62.

**Design and procedure.** Data collection took place in a quiet room made available by the schools' principals during regular school time. Data collection was organized into two sessions scheduled 7 days apart. In session 1, children participated in pairs. After being welcomed by a male or a female experimenter, the children engaged in two different mathematical exercises tapping into the addition of tens and order invariance of addends contents, in order to provide a baseline measure of children's existing knowledge of the tasks. The order of presentation of the tasks was counterbalanced. Because preliminary analyses revealed that the order of presentation did not influence any of the measured outcomes, this variable will not be further considered in subsequent analyses.

After the baseline phase, children engaged in the training exercise for the first of the two mathematical contents. To train children on adding with tens, a bracelet game was used, which consisted of two bands with numbers (from 0 to 9) representing the tens and the units, respectively, that could be wrapped around the child's wrist. This way, children were shown that it was possible to add 10 very quickly by turning the tenth band, without having to count each unit until reaching the result. To train children on the principle of order invariance of addends, a comics story was used, where a character (Daniel) ate either 2 cookies for breakfast and 3 cookies at break time, or the other way round, so that the number of cookies eaten on the day remained the same.

After participating in the training for each concept, the children completed an immediate post-training assessment by answering a set of problems tapping into the just-presented mathematical content. There was a short break between the two trainings.

Session 2 was scheduled 7 days after the first session. Children completed a delayed post-test consisting of number problems based on the two contents they had been trained on a week earlier. The structure of the questions was the same as in the baseline and in the immediate post-test phase, except that the numbers for each problem were different at each of the three time points. Before being thanked and greeted, children completed the mathematical anxiety questionnaire.

**Data analyses.** Descriptive statistics and bivariate correlation analyses were carried out using the SPSS 25 package. As the distribution of the observed indicators of children's math performance was expected to deviate from normality, possibly with floor effects at baseline, and a reduced variability of scores at the post-training assessment, non-parametric coefficients were used to conduct univariate and bivariate analyses. Specifically, Wilcoxon tests were used to assess change in accuracy between the baseline and the immediate post-test, and between the immediate- and the delayed post-test phases, with Bonferroni correction of significance levels for multiple comparisons. Spearman's rank correlation coefficients were used to compute bivariate associations between math performance scores and math anxiety.

To address our main research question (i.e., the effects of math anxiety on learning of new math contents) we conducted longitudinal analyses with M-Plus 8.3 (Muthèn & Muthèn, 2019). The Weighted Least Squares Means and Variances (WLSMV) estimator was used to allow reliable parameter estimations in the presence of non-normally distributed observations. Variables with observed right- or left-skewed distributions were modeled as censored indicators. The Type = Complex option provided by the Mplus software was used to take into account non-independence among observations. Specifically, the Type = Complex algorithm provides a more conservative estimation of standard errors and chi square statistics in clustered samples, that takes into account that children were nested within classes, and children within each class might be more similar to each other than to participants from other classes in certain respects that might be relevant to the study outcomes.

In detail, we estimated a bivariate autoregressive model in which we included children's accuracy scores on both math tasks (i.e., additions with tens and order invariance of addends) at baseline, immediate post-test, and at the delayed post-test phase, as well as their math anxiety score.

As in commonly used univariate autoregressive models, paths from baseline to the immediate post-test, and from the immediate- to the delayed post-test assessment, indicate stability in participants' relative positioning as compared to the rest of the sample (e.g., McArdle, 2009). Bivariate correlations between observations at the same time point are allowed, whereas lagged paths between scoring at one variable at any time point and scores at the other variable at a subsequent time point are not considered to be of interest and are therefore fixed to zero. Significant paths from math anxiety to the immediate post-test scores indicate therefore that anxiety intervenes by enhancing or lowering the relative positioning of children at the immediate post-test compared to the baseline assessment. Similarly, significant paths from math anxiety to the delayed post-test scores indicate that anxiety affects the relative positioning of children at the delayed post-test relative to the immediate post-training assessment. Due to the fact that anxiety might be either a cause of initial levels of children's mastery of each task, or a consequence of children's perception of (unsatisfactory) ability levels prior to our study (Carey et al., 2016), math anxiety was modeled as a covariate (and not as a causal predictor) of performance scores at baseline. Covariances among participants' scores on the two tasks at each time point were also freely estimated.

The fit of the model described above was evaluated by means of the $\chi^2$ test, the comparative fit index (CFI), the Tucker-Lewis Index (TLI), and the root mean square error of approximation (RMSEA), and the standardized root mean square residual (SRMR). Non-significant $\chi^2$ values are considered as indicative of a satisfactory model fit. CFI and TLI values higher than .90 and .95 are indicative of an acceptable and an excellent fit, respectively. RMSEA values below .08 and below .06 and SRMR values below .09 and below .05 are indicative of an acceptable and a good fit, respectively.

**Results**

Descriptive statistics and bivariate correlations of math performance scores with math anxiety (EES-AMAS) are reported in Table 1.

As it is evident from the data reported in Table 1, initial level of knowledge varied between the two math contents, with a relatively low mastery of addition with tens, and a fairly good preliminary understanding of the principle of order invariance of addends. Even though the latter content had not been taught in any of the schools involved in the study, more than two-thirds of the items were correctly solved at baseline. Importantly, paired-sample non parametric analyses using the Wilcoxon test revealed that children's scores on both tasks improved after the training phase. Specifically, performance on the addition with tens task improved from baseline to the immediate post-test, $Z = 2.38$, $p = .017$, and remained stable from the immediate to the delayed post-test, $Z = 0.16$, $p = 1.000$. Similarly, accuracy on the order invariance task improved from baseline to the immediate post-test, $Z = 4.06$, $p < .001$, and remained stable between the immediate and the delayed post-test, $Z = 1.73$, $p = .166$.

Significant values of Spearman's rank correlation coefficients with math anxiety emerged across all math tasks, and involved negative associations with both initial levels of knowledge and subsequent performance.

**Longitudinal model.** Results of the model testing the role of math anxiety in relation to math performance before and after the training are summarized in Figure 1.

[Insert Figure 1 here]

The fit of the model was adequate ($\chi 2$ (*df*) = 5.670(9), $p = .772$; RMSEA (95%CI) = .000(.000/.077); CFI = 1.000; TLI = 1.069, SRMR = 0.033). As predicted, anxiety was negatively related to initial performance on both math tasks, indicating that children with higher levels of math anxiety performed more poorly than their peers at baseline, even though the contents of the math tasks had not been the object of school instruction – nor evaluation – prior to the experiment. Importantly, math anxiety was negatively related to children's performance on the immediate post-training assessment on tasks tapping into the principle of order invariance of addends. In other words, even when initial levels of knowledge and the relations between initial knowledge and math anxiety were taken into account, children who reported higher levels of math anxiety benefitted less from specific training in the content, compared to their less math-anxious peers.

Finally, even though there was no direct relation between math anxiety and children's performance at delayed post-test, the analysis of the indirect effects revealed that math anxiety was indirectly related to delayed performance through its negative impact exerted on immediate post-training scores (*B*: -.080, *SE* = 0.031, $p = .010$; 95% CI: -.141/-.019), thus indicating that the disadvantage experienced by math anxious children at immediate post-test persisted after a one-week delay.

No significant direct or indirect effect of math anxiety emerged in the case of the addition with tens strategy.

**Supplementary analyses**. Because math anxiety was assessed at the end of the whole experimental procedure (i.e., at the end of session 2), it may be argued that math anxiety scores may be affected by children's performance, rather than predict their knowledge and learning gains. To address this potential limitation, we estimated an alternative model in which the math anxiety score was posited as an outcome of children's performance at the delayed post-test. Results revealed that this alternative model did not attain an adequate fit to the data ($\chi 2$ (*df*) = 36.194 (13), $p < .001$; RMSEA (95%CI) = .125(.078/.144); CFI = 0.803; TLI = 0.682, SRMR = 0.133), thus suggesting that math anxiety should not be regarded as a contingent by-product of children's performance.

## Discussion

In this study, first grade children from Italian primary schools received training in two contents that they had not encountered in their formal education before: a strategy for addition with tens and the principle of the order invariance of addends. The baseline assessments showed that, despite the lack of formal training, many children were familiar with the principle of order invariance, whereas the additions with tens strategy was unknown to most children. Training in each content lead to significant increases in children's knowledge of the content at immediate post-test, and this level of knowledge was still maintained a week later. However, the training effect was stronger for the order invariance content. Indeed, even after the training most children still performed poorly on the additions with tens tasks.

Regarding the relations with math anxiety, performance at each time point for both contents was negatively related to mathematics anxiety. Nevertheless, our main interest was in whether math anxious children benefitted less from the training than children with lower levels of anxiety. This was indeed the case for the order invariance task. Specifically, math-anxious children's performance showed less improvement between the baseline and immediate post-test, and this effect was still present at the delayed post-test (i.e., anxious children still showed a reduced effect of training at this time).

These results show that math anxiety might interfere with the learning of novel math contents in the case of young children. Nevertheless, this was only found in the case of one type of content. It is possible that this was because the level of reliability of the EES-AMAS scale used to assess math anxiety was slightly below the value generally deemed "acceptable" (i.e., .70), which may have resulted in a reduced power to detect small effects. Alternatively, it is possible that the type of training was less effective in the case of one of the two contents (i.e., improvement in performance was more modest and most children continued to perform poorly). Indeed, it might be possible that the effect of math anxiety on learning only emerges for certain contents, or if the content that is taught is not completely unfamiliar. Given the novelty of these findings, and the fact that the patterns of findings were not exactly the same in the case of the two contents, we wanted to replicate these results with a new sample of 6-year-old children from the UK.

## Study 2

The aim of Study 2 was twofold. First, we were interested in verifying whether a consistent pattern of results could be observed in a different socio-cultural and instructional system. In fact, whereas participants in Study 1 and Study 2 were of similar age (i.e., 6 years), children in Study 2 were enrolled in schools in Northern Ireland, where children start primary school soon after their 4th birthday. Consequently, children participating in Study 2 were in their 3rd primary grade, thus having a longer experience of formal schooling and evaluation at the time of the study. Second, we aimed at expanding our investigation by also including a measure of verbal working memory in our assessment. This was done because we sought to verify whether the effects of math anxiety on learning were apparent even when children's levels of working memory were taken into account, thus modulating math learning above and beyond children's cognitive resources. Indeed, a recent study found evidence for the role of verbal working memory in learning new mathematical concepts among 11-year-old children (Begolli et al., 2018). Additionally, because some previous studies suggest that the relations between math anxiety and math proficiency may vary depending on individuals' working memory resources (e.g., Beilock & Carr, 2005; Beilock & DeCaro, 2007), and that this non-linear effect may be present even in young schoolchildren (e.g., Ramirez et al., 2013), we sought to verify whether working memory may act as a moderator of the relation between math anxiety and math learning in 6-year-olds. Specifically, these studies showed that individuals with higher working memory span were disproportionately affected by math anxiety.

Given that the study was conducted in a new country where children started school two years earlier than in Italy, we first wanted to make sure that we could identify contents that were sufficiently novel to the children, and had not been formally taught to them before or during the study. Once relevant contents were identified, we also tested the materials with the following aims in mind. First, we wanted to develop training procedures that lead to measurable improvement in children's understanding of the target concepts. Second, we aimed to identify test items that were difficult for children (particularly at the pre-training phase), so that training effects could be identified, and because math anxiety is expected to affect performance on difficult items more strongly (we aimed to select items with initial accuracy levels of between 0-60%). Third, we wanted to identify pairs of test items with equal levels of difficulty, in order to create two equivalent versions of the test materials to be used in the pre- and post-test. In order to achieve this, we created two versions of the test materials where corresponding items differed only minimally. Nevertheless, we also tested empirically that corresponding items were equally difficult. Finally, to account for the possible confounding effect of socio-economic disparities on students' math anxiety and maths proficiency, an index of socio-economic deprivation at the school level was computed and used as a control variable.

**Pilot study**

The pilot study involved 26 children (16 boys) from two primary 3 classes. Preliminarily, the teachers were asked to confirm that the training tasks involved mathematical concepts which had not been taught to the children at this stage of primary school, nor would be during the following month. On this basis, three contents were selected: the principle of order invariance of addends (same as in Study 1), using the lesser/greater than symbols, and one-to-many correspondence (for example, if 4 dogs live in each house, how many dogs live in 3 houses?). The pilot study consisted of a pre-test, a training procedure, and an immediate post-test.

The results of the pilot study showed a marginal improvement on the order invariance task from 54% to 65% after the training ($Z = 1.80$, $p = .072$). Although the improvement was modest, given that math anxiety was related to rate of learning of this content in Study 1, we decided to include this content in the current study. In order to improve the effectiveness of the training procedure, an additional step was added to the instructions, whereby children were asked to not only check if the same numbers were included on both sides of the equation, but to also circle all numbers that were the same on both sides. Thirty-two test items (16 for each version of the test) were selected to be included in the main study.

On the lesser than/greater than symbol task the training resulted in a significant improvement in performance ($Z = 2.18$, $p = .029$). The pilot study also showed that the test items were difficult for children, both before ($M = .18$) and after ($M = .33$) the training. Indeed, even after the training, overall the children showed a significant bias toward giving the wrong answer (i.e., their performance was significantly below chance; $t(25) = 2.82$ $p<.001$). For this reason, the training procedure was slightly modified in the main study by asking children to perform the task in two steps. Instead of identifying the number that was larger in their head and then adding the lesser/greater than symbol, they were instructed to first circle the number that was larger, and then add the appropriate symbol. Thirty-two test items (16 for each version of the test) were retained for the purposes of the main study.

The one-to-many correspondence training did not lead to a significant improvement in children's performance ($p$ = .808), and for this reason, was not retained for the main study.

## Method

**Participants.** After approval from the Ethical Committee of the University of XXXX (blinded), parents of 120 children (59 boys; $M_{AGE}$ = 87.05 months, $SD$ = 3.70) attending the third grade of six different primary schools in XXXXXX (blinded) provided informed consent to take part in the study. Parents with university degrees were 62.30%, whereas 14.80% had a high-school diploma, and 22.20% had a lower qualification.

### Materials

***Order invariance of addends.*** To assess for children's understanding of the order invariance of addends, children completed a task, similar to that described in Study 1. The only difference was that the equations included 3 addends instead of 2, and the numbers were larger (e.g., 25 + 22 + 26 = 22 + 25 + 26). Children had to tick a yes/no box to answer the question: "Do these sums give the same answer?" There were 16 equations in total: half correct and half incorrect. In the case of incorrect equations, the two sides of the equation only differed in one number (e.g., 63 + 65 + 69 = 63 + 65 + 68) to make sure that children had to check all addends carefully. An accuracy score was calculated as the proportion of correctly-responded trials over the number of items (range: from 0 to 1). Cronbach's alpha for the measure was .81 at baseline, and .85 and .84 at immediate and delayed post-test, respectively.

***Lesser than/greater than symbols*****.** Children completed an exercise using the lesser-than/greater-than symbol, in which they were presented with a total of 16 two-digit number pairs and they had to use the lesser/greater than symbols to indicate which number was larger. On half of the trials, the number on the left was larger, on the other half, the number on the right was larger.

Also, on half of the trials, the numerical distance between the pair was small (e.g., 24 and 23); on the other half, the numerical distance was large (e.g., 46 and 94). A score of 1 was given for each correct sign drawn between the number pair. An accuracy score was calculated as the proportion of correctly-responded trials over the number of items (range: from 0 to 1). Cronbach's alpha for the measure was .94 at baseline, and .97 at immediate and delayed post-test.

***Math Anxiety.*** Children's mathematical anxiety was measured using the English version of the questionnaire used in Study 1 (EES-AMAS; Primi et al., 2020). The math anxiety score was calculated by averaging children's answers to the 9 items. Cronbach's alpha was .82.

***Working memory***. A backward letter span task was used to assess verbal working memory. The task used the stimuli and procedure developed by Ramirez et al. (2016). The task was computer-based, in which a recorded voice read out each letter (one letter per second), whilst the children had to recall the letters they had heard in reverse order. The length of sequences ranged from 2-6. Children were first presented with 2 practice items, followed by 2 test items at each level of difficulty. Testing was discontinued if a child had failed both items at a particular level of difficulty. A total score was computed by adding up the number of correctly recalled sequences. Split-half reliability for this task using the Spearman-Brown formula was .70.

***Socio-economic background***. The Multiple Deprivation Measure (MDM; Northern Ireland Statistics and Research Agency, 2010, http://www.nisra.gov.uk/deprivation/archive/NIMDM2005FullReport.pdf ), based on the schools' postcodes, was used as a proxy for participants' socio-economic background. The MDM is a weighted combination of the following domains of deprivation: income (25%); employment (25%); health and disability (15%); education, skills and training (15%); proximity to services (10%); living environment (5%); and crime and disorder (5%). The global score is computed by transforming the indicators to an exponential distribution (ranging from 0 to 100). The scores can be interpreted as percentiles, with higher scores indicating a higher level of deprivation for the area (e.g., a score of 15 means that the area is less deprived than 85% of all postcode-based areas in

Northern Ireland). Although individual participants' postcodes were not available, MDM at the schools' postcode level may be regarded as a reliable proxy for participants' socioeconomic background, as young children in Northern Ireland tend to attend schools that are very close to their homes.

**Procedure.** Data collection took place during regular school time in a quiet room made available by the schools. As in Study 1, data collection was organized into two sessions scheduled 7 days apart. In session 1, children (in pairs or triads) completed a baseline assessment of their knowledge of the two contents (i.e., order invariance of addends and using the lesser/greater than symbol). Immediately after the baseline assessment, children engaged in the training exercises. The order of the contents in the pre- and post-test materials, as well as in the training was counterbalanced across groups of children. Additionally, half of the children were given one version of the assessment at pre-test and the other version at post-test. For the other half of the sample, the order of presentation for the test materials was reversed.

One activity was concerned with the order invariance of addends. The training materials were exactly the same as in Study 1, with the exception that children in this study were given examples of two single-digit addition problems with 3 addends in each (e.g., 1 + 2 + 3 = 1 + 3 + 2), then the experimenter explained that the two sums were the same, regardless of the order of the numbers, as long as the numbers in both sums were the same. The children were then given four more addition problems (2 correct and 2 incorrect) for practice. The experimenter instructed the children to circle the numbers that appeared in both sums and not to circle any number that only appeared in one of the sums (e.g. "there is a 4 in the first sum, is there a 4 in the second sum?"). The children were then explained that the two sums were the same, regardless of the order of the numbers, as long as the numbers in both sums were the same. The children were then given four more addition problems (2 correct and 2 incorrect) to practice.

To train children in using the lesser/greater than symbol, children were first introduced a crocodile character called Crocky. The experimenter then gave the children two cards with a picture of Crocky: one with his mouth open towards the right (and was paired with the < symbol) and the other with his mouth open towards the left (and was paired with the > symbol). The children were reminded that Crocky is very greedy, so he will always open his mouth to eat the largest amount of cupcakes. Children were then presented with pairs of arrays of cupcakes, and were asked to identify the array with the larger number of cupcakes, and choose the Crocky card with the mouth opened in the correct direction. Children were then instructed to do the same, but using a pair of cards with the lesser/greater than symbols instead of the crocodile. In the final part, children were asked to perform the exercise with 16 pairs of Arabic numbers instead of the arrays of cupcakes.

As in Study 1, after completing the training for each exercise children completed an immediate post-training assessment. Session 2 was scheduled 7 days after the first session. In addition to completing a delayed post-test of their knowledge of each content in small groups, children also completed the math anxiety questionnaire and a verbal working memory assessment, which were administered individually.

**Data analyses.** As in Study 1, descriptive statistics and bivariate non-parametric analyses were conducted using the SPSS 25 package, and longitudinal analyses were carried out with M-Plus 8.3 (Muthèn & Muthèn, 2019) using the WLSMV estimation algorithm. Variables with observed right- or left-skewed distributions were modeled as censored indicators. The Type = Complex analytical procedure was adopted to adjust standard error and chi square statistics estimates to the clustered nature of our sample (i.e., with students nested within classes). An autoregressive model, similar to the model described in Study 1, was estimated, except that working memory and the interaction term between working memory and math anxiety were included as additional predictors of math performance. Because working memory is a known antecedent of math performance, the backward letter span task was modeled as a predictor, and not a mere covariate of math accuracy score at baseline, whereas math anxiety was modeled as a covariate of initial knowledge at baseline, and a predictor of subsequent performance scores. A model comparison approach was adopted to select the most adequate and parsimonious model, accounting for the relations among the observed variables (i.e., working memory, math anxiety, and math performance) over time. Specifically, we first estimated a baseline model (Model 0), in which all the paths linking working memory, math anxiety, and their interactions with math performance at each time point were fixed to 0. In model 1, we freely estimated the paths linking working memory to math performance, whereas the paths regarding math anxiety and the interaction term were fixed to 0. In model 2, we included the paths linking math anxiety to math performance measures, and in Model 3 we included the estimation of the links between the interaction term (i.e., the math anxiety by working memory product) and math performance.

The $\chi2$ test, CFI, TLI, and RMSEA were used as indices to assess the fit of the models described above. Model selection was based on the Log-likelihood $\chi2$ difference test adapted to WLSMV estimation, as well as on CFI difference (ΔCFI), RMSEA difference (ΔRMSEA), and SRMR difference (ΔSRMR). Significant differences in $\chi2$ values, and $\Delta CFI \geq .010$, $\Delta RMSEA \geq .015$, and $\Delta SMSR \geq .030$ are indicative of superiority of the more complex model relative to the more parsimonious one.

Estimates for the final selected models were computed before and after accounting for the schools' MDM.

**Results**

Descriptive statistics and relationships among measures are reported in Table 2.

Regarding the task based on the lesser than/greater than symbols, children displayed a very low level of knowledge at baseline, with 70% of children obtaining a score of zero at the first assessment. However, performance dramatically increased after training (Wilcoxon test: $Z = 9.47$, $p < .001$), reaching a ceiling effect with 70% of the children correctly performing on all tasks at immediate post-test. There was a slight decrease in accuracy from the immediate to the delayed post-test, but it was not significant, $Z = 1.09$, $p < .552$, and 58% of the children still obtained the highest score after a 7-day delay. Correlational analyses indicated that performance on the task after the training was unrelated to working memory capacity (that is, the training was effective regardless of children's working memory capacity). However, there was a relationship between math anxiety and performance on the task at immediate post-test.

Regarding the principle of order invariance of addends, performance was very high at baseline, with all the children displaying at least a minimal understanding of the concept (minimum score: .25), and 29% obtaining the highest score even before receiving any training. Nevertheless, paired-sample non parametric analyses revealed that children's scores improved after the training phase, $Z = 6.70$, $p < .001$, and remained stable from the immediate to the delayed post-test, $Z = 1.80$, $p = .144$.

At the bivariate level, the index of socio-economic deprivation (MDM) displayed a moderate positive association with math anxiety, and a negative association with math accuracy in the case of both tasks and all time points, except for the lesser/greater than task at baseline.

**Model selection.** Fit indices regarding the four alternative nested models tested to account for the relations among the observed variables are reported in Table 3.

The baseline model is a pure bivariate autoregressive model, in which all links between working memory, math and anxiety, and their interaction, on the one hand, and math performance score before and after training, on the other, are hypothesized to be null. As it is evident from the reported data, the fit of the model is not acceptable. When the contribution of working memory is allowed (Model 1), fit indices improve, but still remain inadequate. The model offers an adequate representation of the data when the contribution of math anxiety is also allowed (Model 2). When the interaction term between math anxiety and working memory is also estimated (Model 3), the global fit of the model remains adequate. However, the estimation of 6 more parameters does not improve the adequacy of the model as compared to Model 2. Therefore, the model not including the interactive effect of working memory and math anxiety on math performance provides a comparatively adequate - but more parsimonious - account of the observed data, and will be retained for subsequent analyses.

**Longitudinal model.** Results for the longitudinal model including working memory and math anxiety – but not their interaction term – and their relations with learning of the two novel math contents are reported in Figure 2.

[Insert Figure 2 here]

The results showed a different pattern of relations between working memory and math anxiety with children's performance on each task. Regarding the task tapping into the lesser than/greater than symbols, baseline performance – which was on average extremely low – was negatively related to children's working memory resources, but not to math anxiety. By contrast, performance immediately after training was unrelated to working memory, but it was negatively affected by math anxiety. In other words, although improvement after training was, on average, very large and unrelated to children's cognitive resources, math anxious children improved less than their non-anxious peers. Performance on the delayed post-test did not appear to depend either on working memory or anxiety. However, the indirect path from math anxiety to delayed post-test – through reduced learning at the immediate post-test – was significant (*B*: -.027, *SE* = .011, *p* = .017; 95%CI: -.049/-.005).

Regarding the principle of order invariance of addends, verbal working memory emerged as a significant predictor of both prior knowledge at baseline, and performance immediately after training. Children's mastery of the principle at the baseline assessment was also negatively related to their math anxiety level, whereas no relation emerged between math performance and anxiety at either the immediate or the delayed post-test.

The pattern of path coefficients for this model did not change when schools' MDM score was added as a control variable. Parameter estimates computed before and after adjusting for MDM are reported in the supplemental materials (see Supplemental Tables A2 and A3, respectively).

**Supplementary analyses**. We estimated an alternative model in which the math anxiety score was posited as an outcome of children's performance at the delayed post-test. Working memory was instead retained as a predictor of children's performance, due to its well-established unidirectional link with math proficiency. As in Study 1, results revealed that this alternative model did not attain an adequate fit to the data ($\chi2$ (df) = 21.287 (12), $p$ = 0.046; RMSEA (95%CI) = .080(.010/.145); CFI = 0.739; TLI = 0.390, SRMR = 0.102).

**Discussion**

In this study, 6-year-old children from the UK attending the 3rd grade of primary school received training in two contents that they had not encountered in their formal education before: using the lesser/greater than sign and the principle of the order invariance of addends. The baseline assessments showed that, despite the lack of formal training, most children were familiar with the principle of order invariance, and performance at baseline was already high (78% on average). By contrast, children were unfamiliar with the lesser/greater than sign. Despite the large difference in initial level of knowledge of the two concepts, the training for each was successful at increasing children's knowledge at immediate post-test, and this level of knowledge was still maintained a week later. The training effect was larger for the lesser/greater than sign (81% increase in the proportion of correct responses on average), but it was also substantial (17%) in the case of the order invariance content.

Regarding the relations with math anxiety and working memory, the patterns differed across contents. We discuss these two effects separately, as there was no evidence of an interaction between them. Math anxiety was weakly and negatively correlated with performance on the lesser/greater than task at all time points, but this effect only reached significance at immediate post-test. Indeed, the longitudinal model indicated that math anxious children learnt less from the training in the case of this content. Regarding the order invariance content, math anxiety was related to initial performance, but this effect was eliminated after the training, as indicated by simple correlational analyses, as well as the longitudinal model, which showed no effect of math anxiety on mathematics learning in this case.

Next we consider the effects of working memory. For the lesser/greater than sign, performance prior to training negatively correlated with working memory. Although this finding might seem counterintuitive, several children reported that they thought the symbol represented an arrow head that had to point at the larger number. Thus, the results show that children with higher working memory capacity were more consistent in interpreting the sign in this seemingly logical (although incorrect) way before the training. Nevertheless, there was no effect of working memory on performance after the training. By contrast, there was a significant positive correlation between working memory and initial performance in the case of the order invariance content, and children with higher working memory capacity also benefitted more from the training. This finding is in line with Begolli et al. (2018) who showed similar effects in the case of 11-year-old children who received instruction in solving mathematical word problems related to proportional reasoning. Additionally, Begolli et al. (2018) also found a significant effect of inhibition skills on children's learning. Inhibition skills seem particularly relevant in the case of learning about the lesser/greater than sign, as in this case, children had to suppress their initial tendency to interpret the symbol as an arrow head. Future studies could investigate the possibility that inhibition skills might interact with math anxiety in shaping children's learning.

Although we have found evidence for the effect of both math anxiety and working memory on learning novel mathematics contents, there was no interaction between these factors. That is, although it is possible that higher working memory individuals are disproportionately affected by math anxiety in test situations (e.g., Beilock & Carr, 2005; Beilock & DeCaro, 2007; Ramirez et al., 2013), we did not find evidence for a similar interaction between math anxiety and working memory in the case of learning situations. Nevertheless, as we have only investigated this possibility in a single study, this question could be further explored in the future.

Finally, it should be noted that findings were robust to variability in socio-economic background across schools. Even though the school-level socio-economic deprivation index was significantly associated with higher levels of math anxiety and lower levels of math proficiency, the observed pattern of relations between math anxiety, working memory, and math learning remained stable even after accounting for variability in socio-economic background across schools.

## General discussion

This study investigated the effect of mathematics anxiety on math learning in 6-year-old children in two countries, Italy and the UK, that differ in school starting age, as well as in their mathematics curriculum. Our results confirmed that math anxiety interfered with mathematics learning, as assessed immediately after the training session, in the case of two out of four contents on which our participants were trained, and this effect persisted after a one-week delay. That is, we can assume that math anxious children were less able to encode novel, math-related information, a finding that is similar to the patterns reported in the case of stereotype threat in older participants (Appel & Kronberger, 2012; Rydell et al., 2010a, 2010b), as well as in research on the relations between achievement-related emotions and conceptual change with undergraduate students (Muis et al., 2015). The fact that this pattern can already be observed in the case of 6-year-old children with limited exposure to school education strengthens recent claims that mathematics anxiety is negatively related to mathematics performance already in the case of early elementary school pupils (cf., Ramirez et al., 2013). We should also note the robustness of this finding, as the pattern was observed in both studies, and in relation to different types of math content (in the case of the principle of order invariance of addends in the Italian sample, and in learning to use the lesser/greater than sign in the case of the UK children).

Nevertheless, we should also note that the finding did not generalize across all contents, which hints at some potential boundary conditions (i.e., that in some cases math anxiety does not interfere with mathematics learning). The simplest interpretation is that in these cases we did not have sufficient statistical power to detect the effects of math anxiety on learning, because the training effects were not substantial enough. Nevertheless, there might be other possibilities as well, for example relating to the novelty or familiarity of the training approach, the complexity of the strategies that are being taught, and the way the training is delivered (for example, whether the training is delivered in a group setting or on a one-to-one basis). In Study 2, we also found evidence for the role of working memory in learning novel mathematics contents, although this effect did not interact with the effect of mathematics anxiety. The effects of working memory and other potential moderating factors should be further investigated in future studies, as these investigations could provide hints as to how the negative effects of math anxiety on learning could be avoided in applied contexts. They could also help in identifying children who might be more susceptible to experiencing negative outcomes relating to their mathematics anxiety.

Although this was not the main focus of the current paper, our findings showed that children's initial knowledge of the contents was also related to children's math anxiety in the case of three out of the four contents. A potential interpretation of this pattern is that children with math anxiety benefit less from informal learning opportunities outside the classroom, although other interpretations are also possible. For example, that math-anxious children are less able to spontaneously extract higher-level meaning and more general rules from specific contents, a possibility, which is consistent with the reduced competency account of math anxiety (see Ramirez, Shaw & Maloney, 2018 for a recent review). Another possibility is that, even at this young age, anxious children already display avoidance behaviors relating to math, which reduce their opportunities for informal learning. Moreover, evidence also exists that, to some extent, children's math anxiety may be related to parent's math anxiety (Maloney, Ramirez, Gunderson, Levine & Beilock, 2015), and math-anxious parents – by avoiding math themselves – may provide children with less opportunities to practice and learn math in the home environment (Del Rio, Susperreguy, Strasser & Salinas, 2017). This proposal appears to be in line with our finding in Study 2 that lower socio-economic status was linked to higher anxiety and lower math proficiency in children (assuming that lower socio-economic status is associated with more negative feelings about math in the case of the parents). Indeed, these possibilities deserve further attention in future studies with children.

**Theoretical and educational implications**

Research into mathematics anxiety in young children is limited (although see Cargnelutti et al., 2017b; Gunderson et al., 2018; Harari et al., 2013; Jameson, 2014; Ramirez et al., 2013, 2016; Sorvo et al., 2017; Wu et al., 2012, 2014), and the cause and effect relationships between mathematics anxiety and mathematics performance are not fully understood (for recent reviews, see Carey et al., 2016; Ramirez et al., 2018). This study addressed an important missing piece of this puzzle, i.e., whether math anxiety might interfere with the acquisition of new knowledge, in addition to its potential to disrupt the recall and use of already mastered math skills in test situations (e.g., Ashcraft & Kirk 2001; Beilock & Carr, 2005). Indeed, findings revealed that this is the case. This evidence could help in explaining why the relationship between mathematics anxiety and mathematics performance appears to get stronger over the primary school years (see e.g., Ashcraft & Moore, 2012; Stevenson et al., 1990; Zhang et al., 2019). This would also make a strong case for the importance of early intervention for mathematics anxiety, as it would support the long-term negative effects of mathematics anxiety, in addition to its potential to interfere with performance in test situations.

The fact that the current studies focused on 6-year-old children has important implications from an educational perspective, as this is the typical age when children enter formal education in various countries around the world (c.f., Gunderson et al., 2018; Ramirez et al., 2013). Nevertheless, our results revealed strikingly similar effects of math anxiety in two countries where 6-year-old children have either just entered the formal education system (i.e., in Italy), or were already attending the third grade of school (i.e., in Northern Ireland). Future studies could indeed further deepen our understanding of the negative effect of math anxiety on learning by involving other age groups, as well as in relation to more advanced aspects of the mathematics curriculum, such as performing arithmetic operations with fractions or solving numerical equations.

It has been shown that individuals with math anxiety tend to rely on simpler solution strategies (e.g., Beilock & DeCaro, 2007; Morsanyi et al., 2014). Although this could be the consequence of experiencing working memory load as a consequence of focusing on anxious thoughts, our findings also suggest another possibility, i.e., that individuals with math anxiety are restricted in their ability to learn and apply more complex solution strategies for some problems in the first place.

**Limitations and future directions**

As a limitation of our study, we should note that even though we sought to reproduce as closely as possible a procedure of teaching and learning of novel math contents that are commonly encountered during the first years of mathematical education (albeit slightly later in the school year), we should acknowledge that our experimental procedure diverged from an ordinary classroom situation in some important ways. For instance, the contents were presented by experimenters instead of the classroom teacher, and learning of novel math contents at school does not commonly take place in pairs or triads. All these aspects may indeed affect the impact of math anxiety on math learning, and limit the generalizability of our findings to ordinary classroom settings.

Another important limitation of this work is that individual differences measures (i.e., math anxiety in Studies 1 and 2, and working memory in Study 2) were assessed at the end of the whole procedure. One may indeed argue that children's level of math anxiety might have been affected by their previous performance, rather than the reverse. It is important to consider, however, that math anxiety is a relatively stable trait, and that the math anxiety instrument we used in this study (Primi et al., 2020) asked children to report their level of anxiety in relation to some common classroom events (e.g., When your math teacher gives you homework that is long and difficult.), and not in relation to the present situation. More importantly, our findings revealed that alternative models in which math anxiety was included as an outcome – instead than a predictor – of children's math performance provided a non-adequate fit to the data in both studies, thus suggesting that math anxiety should not be regarded as a contingent by-product of children's attainment.

Beyond stressing limitations, future directions of work should also be sketched. Our findings suggest, for example, that socio-economic disparities across schools are related to both math anxiety and math proficiency at the children's individual level. Unfortunately, our sample did not include a sufficiently large number of schools to warrant a multilevel analysis, which would provide more compelling evidence regarding the role of school-level properties in individual students' emotional experiences of maths. However, these findings parallel results from a prior multilevel study with high-school students (Radišić, Videnović & Baucal, 2015), in which indicators of economic, social, and cultural status emerged as the only variables measured at the school level that accounted for individual differences in math anxiety across students. This seminal evidence undoubtedly calls for further studies to better clarify the role of socio-economic deprivation not only in shaping math anxiety, but also in modulating its effects on math learning.

Another important direction of future work should be to clarify the specific processes through which math anxiety interferes with learning, and the conditions under which such interference occurs. In the present work, we included working memory as a plausible moderator of the link between math anxiety and math learning (Study 2). Yet, a number of other factors may play a role. In a recent review, Ramirez and colleagues (2018) highlighted that students' subjective appraisals of their emotional states (i.e., interpreting physiological arousal as fear vs. excitement), of mathematics (i.e., viewing math tasks as a threat vs. a challenge), or of themselves (i.e., feeling sufficiently vs. scarcely skilled in maths) may dramatically change the impact of math anxiety on math achievement. Future studies should seek to determine whether such or other factors may also shape the link between math anxiety and the ability to learn novel math contents.

**Conclusion**

Overall, the current results are both novel and important, given the relative lack of research into math anxiety in the case of young children, and the general focus on correlational studies within the math anxiety literature, which results in a limited understanding of cause and effect relationships between math anxiety and math performance. The current results also suggest that, in the long term, there are cumulative effects of mathematics anxiety, as it was linked to reduced initial knowledge, as well as reduced improvement after training. Parents and teachers might not be enthusiastic about the possibility to assess young children's math anxiety, as they might feel that this could give some children the idea that math could be an anxiety-provoking subject. Nevertheless, the current results showed that even young children tend to report moderate levels of math anxiety on average. This suggests that it is important to identify children who are anxious about math already in the first school years. Specific interventions for math anxiety should also be developed for this age group, and should be started from the earliest school grades.

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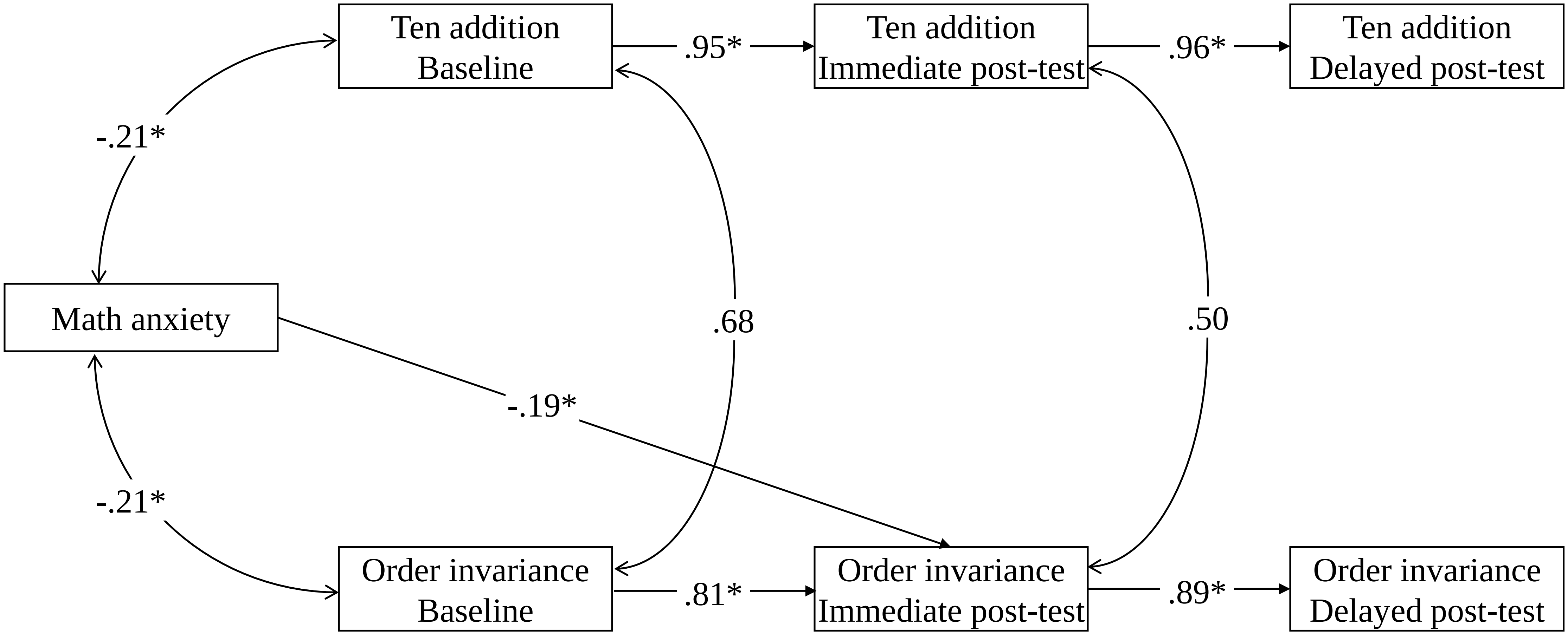
Figure captions

*Figure 1*. Relations between math anxiety and math performance before and after learning novel contents (Study 1; $N = 115$). Standardized values are reported and only parameters with $p$ values lower than .10 are displayed. * $p < .05$.

*Figure 2*. Relations between math anxiety, working memory and math performance before and after learning novel contents (Study 2; $N = 120$). Standardized values are reported and only parameters with $p$ values lower than .10 are displayed. † $p < .10$; * $p < .05$.


Ten addition Baseline
.95*
Ten addition Immediate post-test
.96*
Ten addition Delayed post-test
-.21*
.68
.50
Math anxiety
-.19*
-.21*
Order invariance Baseline
.81*
Order invariance Immediate post-test
.89*
Order invariance Delayed post-test

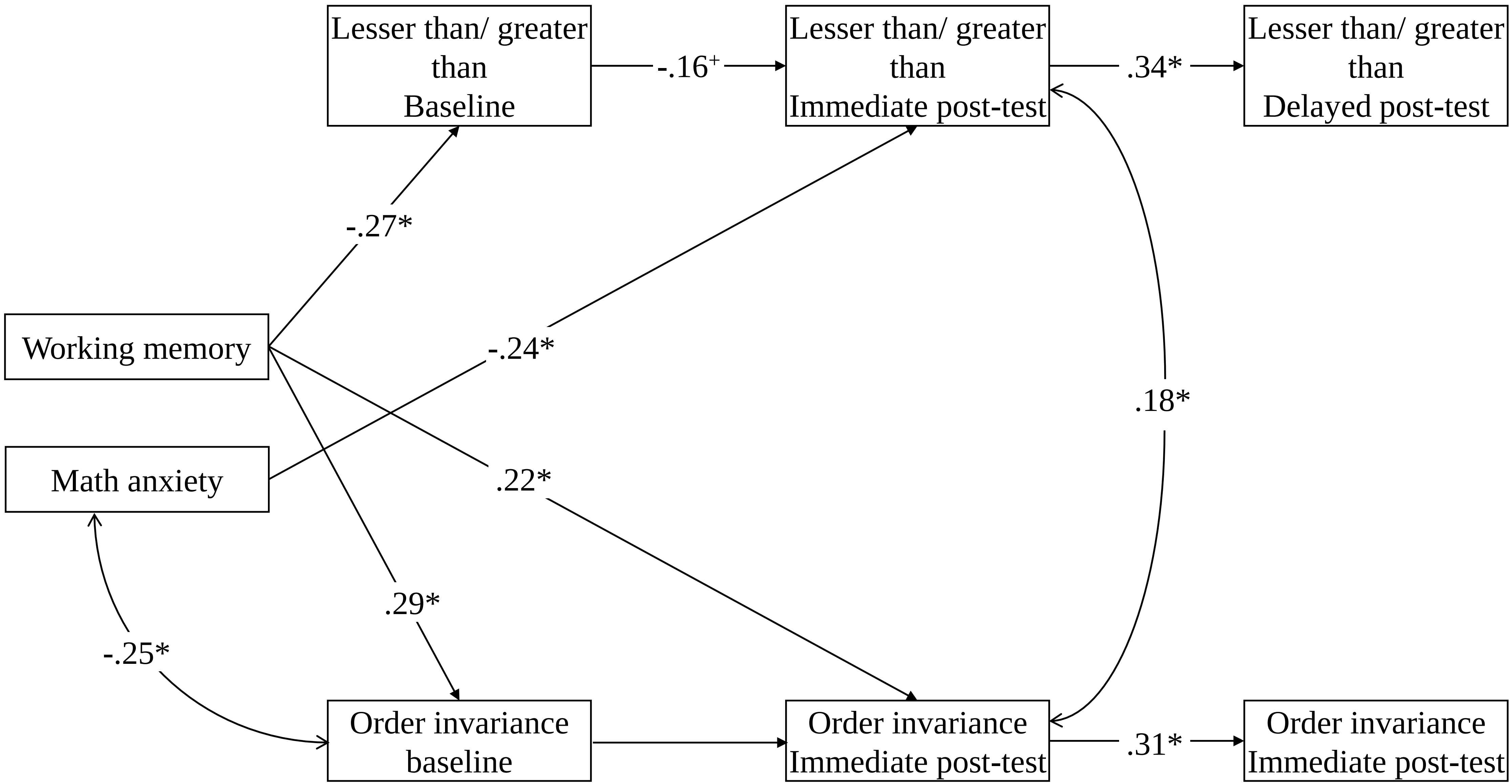

Lesser than/ greater than Baseline
-.16+
Lesser than/ greater than Immediate post-test
.34*
Lesser than/ greater than Delayed post-test
-.27*
Working memory
-.24*
.18*
Math anxiety
.22*
.29*
-.25*
Order invariance baseline
Order invariance Immediate post-test
.31*
Order invariance Immediate post-test

Table 1. *Descriptive statistics and intercorrelations among variables (Study 1 - N = 115).*

| | Descriptive statistics | | | | Correlations | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (SD) | Min-max | Skewness | Kurtosis | 1. | 2. | 3. | 4. | 5. | 6. |
| Additions with tens | | | | | | | | | | |
| 1. Baseline | .34 (.42) | 0-1 | 0.69 | -1.29 | - | | | | | |
| 2. Immediate post-test | .37 (.43) | 0-1 | 0.52 | -1.57 | .92** | - | | | | |
| 3. Delayed post-test | .39 (.43) | 0-1 | 0.45 | -1.22 | .88** | .87** | - | | | |
| Order invariance of addends | | | | | | | | | | |
| 4. Baseline | .69 (.32) | 0-1 | -0.52 | -0.57 | .60** | .59** | .61** | - | | |
| 5. Immediate post-test | .78 (.29) | 0-1 | -1.30 | -0.46 | .48** | .53** | .55** | .73** | - | |
| 6. Delayed post-test | .83 (.23) | .29-1 | -1.00 | -0.52 | .48** | .49** | .51** | .68** | .69** | |
| 7. Math anxiety | 2.52 (0.71) | 1-4.44 | -0.02 | -0.43 | -.21* | -.24* | -.26* | -.22* | -.33** | -.24* |

*Note*. Theoretical values for math accuracy scores (Additions with tens and Order invariance of addends) range from 0 to 1. Theoretical values for math anxiety score range from 1 to 5. Spearman ranks correlation coefficients (rho) are reported. *$p < .05$; ** $p < .001$.

Table 2. *Descriptive statistics and intercorrelations among variables (Study 2 - N = 120).*

| | Descriptives | | | | Intercorrelations | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (*SD*) | Min-max | Skewness | Kurtosis | 1. | 2. | 3. | 4. | 5. | 6. | 7. | 8. |
| Lesser than/greater than symbols | | | | | | | | | | | | |
| 1. Baseline | .08 (.19) | 0-1 | 3.69 | 10.08 | - | | | | | | | |
| 2. Immediate post-test | .89 (.26) | 0-1 | -2.63 | -5.86 | -.21* | - | | | | | | |
| 3. Delayed post-test | .80 (.28) | 0-1 | -2.20 | 3.46 | -.26** | .28** | - | | | | | |
| Order invariance of addends | | | | | | | | | | | | |
| 4. Baseline | .78 (.21) | .25-1 | -0.52 | -0.57 | -.21** | .21* | .25** | - | | | | |
| 5. Immediate post-test | .95 (.12) | .27-1 | -1.30 | -0.46 | -.10 | .20* | .10 | .12 | - | | | |
| 6. Delayed post-test | .92 (.15) | .28-1 | -1.00 | -0.52 | -.08 | .10 | .29** | .24* | .23* | - | | |
| 7. Math anxiety | 2.35 (0.87) | 1-4.22 | 0.24 | -0.91 | .15 | -.21* | -.10 | -.24* | -.01 | -.07 | - | |
| 8. Working memory | 4.62 (1.62) | 1-8 | -1.16 | 0.44 | -.20* | .04 | .07 | .28* | .17† | .14 | -.03 | - |
| 9. School deprivation score | 41.30 (17.61) | 5.04-67.23 | -0.42 | -0.62 | .34** | -.36** | -.33** | -.14 | -.28* | -.15 | .37** | -.09 |

*Note*. Theoretical values for math accuracy scores (Lesser than/greater than symbols and Order invariance of addends) range from 0 to 1. Theoretical values for math anxiety score range from 1 to 5. Theoretical values for School deprivation score range from 0 to 100. Spearman ranks correlation coefficients (rho) are reported. †$p < .10$; *$p < .05$; **$p < .001$.

Table 3. *Fit indices of competing models accounting for the relations among working memory, math anxiety, and math performance over time (Study 2 - N = 120).*

| Model | $\chi^2_{(df)}$ (*p*) | CFI | TLI | RMSEA (95%CI) | SMSR | Log-likelihood $\Delta\chi^2_{(df)}$ (*p*) | ΔCFI | ΔRMSEA | ΔSMSR |
|---|---|---|---|---|---|---|---|---|---|
| Model 0 | $47.553_{(29)}$ (*p* = .016) | 0.637 | 0.550 | 0.073 (0.032/0.109) | 0.107 | - | - | - | - |
| Model 1 | $38.076_{(23)}$ (*p* = .025) | 0.705 | 0.539 | 0.074 (0.42/0.126) | 0.082 | $13.773_{(6)}$ (*p* = .032) | 0.068 | -0.011 | 0.025 |
| Model 2 | $17.451_{(17)}$ (*p* = .424) | 0.991 | 0.981 | 0.015 (0.00/0.085) | 0.045 | $17.164_{(6)}$ (*p* = .008) | 0.286 | 0.059 | 0.037 |
| Model 3 | $10.110_{(11)}$ (*p* = .520) | 1.000 | 1.057 | 0.000 (0.00/0.090) | 0.034 | $9.239_{(6)}$ (*p* = .160) | .009 | 0.015 | 0.011 |

*Note*. Model 0: all paths from working memory, math anxiety, and their interaction term fixed to 0. Model 1: paths from working memory to math scores freely estimated; paths from math anxiety and the interaction term fixed to 0. Model 2: paths from working memory and math anxiety freely estimated; paths from the interaction term fixed to 0. Model 3: all paths from working memory, math anxiety, and their interaction term freely estimated. CFI = Comparative Fit Index. TLI = Tukey-Lewis Index. RMSEA = Root Mean Squares Error Approximation. SMSR = Standardized root Mean Square Residual.

Supplementary Table A1. Unstandardized and Standardized Path Coefficients and Correlations between Math Anxiety and Math Performance before and after learning novel contents (Study 1, $n$ = 115).

| | Estimate | *SE* | Lower/upper 95%CI | Standardized estimate | *p* |
|---|---|---|---|---|---|
| *Path coefficients* | | | | | |
| Math anxiety ⟶ Addition with tens - Immediate post-test | -0.026 | 0.025 | -0.076/0.023 | -.038 | .312 |
| Math anxiety ⟶ Addition with tens - Delayed post-test | -0.036 | 0.033 | -0.101/.0030 | -.049 | .203 |
| Math anxiety ⟶ Order invariance - Immediate post-test | -0.096 | 0.045 | -0.184/-0.008 | -.192 | . 044* |
| Math anxiety ⟶ Order invariance - Delayed post-test | 0.039 | 0.028 | -0.017/0.095 | .084 | .248 |
| Addition with ten – Baseline ⟶ Addition with tens - Immediate post-test | 0.902 | 0.162 | 0.584/1.219 | .954 | .000** |
| Addition with tens - Immediate post-test⟶ Addition with tens - Delayed post-test | 1.013 | 0.224 | 0.575/1.451 | .966 | .000** |
| Order invariance – Baseline ⟶ Order invariance - Immediate post-test | 0.853 | 0.094 | 0.668/1.037 | .814 | .000** |
| Order invariance - Immediate post-test ⟶ Order invariance - Delayed post-test | 0.837 | 0.170 | 0.505/1.170 | .898 | .000** |
| *Correlations* | | | | | |
| Math anxiety ⟷ Addition with tens - Baseline | -0.158 | 0.058 | -0.272/-0.043 | -.214 | .000** |
| Math anxiety ⟷ Order invariance - Baseline | -0.103 | 0.015 | -0.132/-0.074 | -. 216 | .000** |
| Addition with tens – Baseline⟷ Order invariance – Baseline | 0.242 | 0.071 | 0.103/0.380 | .689 | .000** |

| | | | | | |
|---|---|---|---|---|---|
| Addition with tens - Immediate post-test↔ Order invariance - Immediate post-test | 0.023 | 0.018 | -0.012/0.058 | .505 | .038* |
| Addition with tens - Delayed post-test↔ Order invariance - Delayed post-test | 0.016 | 0.029 | -0.040/0.073 | .480 | .418 |

*Note*: *$p$ < .05; **$p$ < .001.

Supplementary Table A2. Unstandardized and Standardized Path Coefficients and Correlations between Math Anxiety and Math Performance before and after learning novel contents (Study 2, $n$ = 120).

| | Estimate | *SE* | Lower/upper 95%CI | Standardized estimate | *p* |
|---|---|---|---|---|---|
| *Path coefficients* | | | | | |
| Math anxiety ⟶ Lesser than/greater than - Immediate post-test | -0.065 | 0.024 | -0.112/-0.019 | -.242 | .002* |
| Math anxiety ⟶ Lesser than/greater than - Delayed post-test | -0.016 | 0.036 | -0.087/0.055 | -.049 | .658 |
| Math anxiety ⟶ Order invariance - Immediate post-test | 0.021 | 0.036 | -0.049/0.091 | .072 | .549 |
| Math anxiety ⟶ Order invariance - Delayed post-test | -0.030 | 0.033 | -0.095/0.036 | -.111 | .403 |
| Working memory ⟶ Lesser than/greater than - Baseline | -0.123 | 0.054 | -0.228/-0.017 | .274 | .038 |
| Working memory ⟶ Lesser than/greater than - Immediate post-test | -0.008 | 0.013 | -0.034/0.018 | -.029 | .546 |
| Working memory ⟶ Lesser than/greater than - Delayed post-test | 0.012 | 0.040 | -0.066/0.090 | .037 | .759 |
| Working memory ⟶ Order invariance - Baseline | 0.083 | 0.023 | 0.039/0.127 | .297 | .000** |
| Working memory ⟶ Order invariance - Immediate post-test | 0.065 | 0.021 | 0.024/0.106 | .224 | .005* |
| Working memory ⟶ Order invariance - Delayed post-test | 0.042 | 0.036 | -0.029/0.112 | .155 | .242 |
| Lesser than/greater than – Baseline ⟶ Lesser than/greater than - Immediate post-test | -0.100 | 0.049 | -0.196/-0.004 | -.166 | .091† |

| | | | | | |
|---|---|---|---|---|---|
| Lesser than/greater than - Immediate post-test ⟶ Lesser than/greater than - Delayed post-test | 0.407 | 0.095 | 0.220/0.594 | .345 | .000** |
| Order invariance – Baseline ⟶ Order invariance - Immediate post-test | 0.252 | 0.168 | -0.078/0.582 | .242 | .134 |
| Order invariance - Immediate post-test ⟶ Order invariance - Delayed post-test | 0.291 | 0.113 | 0.069/0.513 | .313 | .002* |
| *Correlations* | | | | | |
| Math anxiety ⟷ Lesser than/greater than - Baseline | 0.048 | 0.052 | -0.055/0.150 | .113 | .326 |
| Math anxiety ⟷ Order invariance - Baseline | -0.067 | 0.021 | -0.108/-0.026 | -.257 | .000** |
| Math anxiety ⟷ Working memory | -0.131 | 0.093 | -0.312/0.051 | -.133 | .143 |
| Lesser than/greater than – Baseline ⟷ Order invariance – Baseline | -0.025 | 0.017 | -0.059/0.008 | -.226 | .147 |
| Lesser than/greater than - Immediate post-test ⟷ Order invariance - Immediate post-test | 0.013 | 0.006 | 0.001/0.024 | .186 | .016* |
| Lesser than/greater than - Delayed post-test ⟷ Order invariance - Delayed post-test | 0.001 | 0.008 | -0.014/0.017 | .020 | .856 |

Note: †$p < .10$; *$p < .05$; **$p < .001$.

Supplementary Table A3. Unstandardized and Standardized Path Coefficients and Correlations between Math Anxiety and Math Performance before and after learning novel contents, adjusted for socio-economic deprivation (Study 2, *n* = 120).

| | Estimate | *SE* | Lower/upper 95%CI | Standardized estimate | *p* |
|---|---|---|---|---|---|
| *Path coefficients* | | | | | |
| Math anxiety ⟶ Lesser than/greater than - Immediate post-test | -0.093 | 0.046 | -0.184/-0.003 | -.151 | .012* |
| Math anxiety ⟶ Lesser than/greater than - Delayed post-test | -0.004 | 0.055 | -0.112/0.103 | -.008 | .936 |
| Math anxiety ⟶ Order invariance - Immediate post-test | 0.057 | 0.039 | -0.019/0.134 | .199 | .128 |
| Math anxiety ⟶ Order invariance - Delayed post-test | -0.048 | 0.034 | -0.114/0.018 | -.177 | .185 |
| Working memory ⟶ Lesser than/greater than - Baseline | -0.095 | 0.053 | -0.199/0.009 | -.211 | .122 |
| Working memory ⟶ Lesser than/greater than - Immediate post-test | 0.016 | 0.040 | -0.063/0.095 | .026 | .685 |
| Working memory ⟶ Lesser than/greater than - Delayed post-test | 0.036 | 0.073 | -0.107/0.180 | .065 | .608 |
| Working memory ⟶ Order invariance - Baseline | 0.079 | 0.024 | 0.031/0.127 | .284 | .000** |
| Working memory ⟶ Order invariance - Immediate post-test | 0.053 | 0.025 | 0.004/0.103 | .186 | .051[†] |
| Working memory ⟶ Order invariance - Delayed post-test | 0.036 | 0.033 | -0.029/0.102 | .135 | .279 |
| Lesser than/greater than – Baseline ⟶ Lesser than/greater than - Immediate post-test | -0.124 | 0.147 | -0.413/0.165 | -.090 | .437 |

| | | | | | |
|---|---|---|---|---|---|
| Lesser than/greater than - Immediate post-test ⟶ Lesser than/greater than - Delayed post-test | 0.299 | 0.115 | 0.075/0.524 | .329 | .001* |
| Order invariance – Baseline ⟶ Order invariance - Immediate post-test | 0.202 | 0.165 | -0.122/0.526 | .197 | .224 |
| Order invariance - Immediate post-test ⟶ Order invariance - Delayed post-test | 0.334 | 0.136 | 0.067/0.601 | .357 | .003* |
| *Correlations* | | | | | |
| Math anxiety ⟷ Lesser than/greater than - Baseline | 0.009 | 0.047 | -0.083/0.101 | .024 | .848 |
| Math anxiety ⟷ Order invariance - Baseline | -0.054 | 0.020 | -0.093/-0.014 | -.221 | .002* |
| Math anxiety ⟷ Working memory | -0.082 | 0.073 | -0225/0.061 | -.089 | .256 |
| Lesser than/greater than – Baseline ⟷ Order invariance – Baseline | -0.017 | 0.018 | -0.052/0.019 | -.160 | .358 |
| Lesser than/greater than - Immediate post-test ⟷ Order invariance - Immediate post-test | 0.014 | 0.019 | -0.024/0.052 | .110 | .440 |
| Lesser than/greater than - Delayed post-test ⟷ Order invariance - Delayed post-test | 0.027 | 0.016 | -0.004/0.058 | .227 | .038* |

*Note*. Coefficients reported in parentheses are adjusted for School deprivation as measured by the Multiple Deprivation Measure (Northern Ireland Statistics and Research Agency, 2010, http://www.nisra.gov.uk/deprivation/archive/NIMDM2005FullReport.pdf) associated at the school postcode. †$p < .10$; *$p < .05$; **$p < .001$.