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Abstract

The positive relationship between spatial ability and mathematical skills is a classical result in developmental and cognitive psychology. Given this correlational relationship, researchers have tried to establish whether spatial training can increase mathematical ability. Such research has provided mixed results. In this study, we analysed the effects of two types of spatial training and handedness on primary school children's arithmetical ability. The participants were pre-tested on a test of arithmetic and assigned to one of three groups: (a) one hour of mental rotation and translation training, (b) one hour of mental translation training only, or (c) a no-contact group. The results showed no significant difference between training groups and a significant interaction between training group and category of handedness. Interestingly, only extremely right-handed children in the mental rotation and translation group seemed to benefit from the training. These outcomes suggest that any spatial training needs to include mental rotation activities to be effective, and that the relationship between spatial training and achievement mathematics appears to be moderated by handedness.

Keywords: mathematics; mental rotation; spatial ability, handedness; STEM.

Introduction

Concerns have been raised about young people's low achievements in mathematics, both in Europe (Greg, 2009) and the United States (Hanushek, Peterson, & Woessmann, 2012; Richland, Stigler, & Holyoak, 2012). Students' insufficient mathematical ability has serious implications, as the likelihood of graduating in Science, Technology, Engineering, and Mathematics (STEM) subjects is limited by one's mathematical ability. The job market increasingly demands workforce with STEM expertise and requires increasingly higher competencies, making competition fiercer worldwide (Halpern et al., 2007).

Students' attainment in mathematics is thus a matter of crucial practical importance. For this reason, an impressive amount of research has been devoted to pinpointing the cognitive correlates of mathematical ability (e.g., Deary, Strand, Smith, & Fernandes, 2007; Lubinski, 2010; Peng, Namkung, Barnes, & Sun, 2016; Rohde & Thompson, 2007; Wai, Lubinski, & Benbow, 2009) and finding effective methods to improve students' mathematical skills.

These methods not only include traditional school interventions (for a review, see Hattie, 2009), but also cognitive-training based treatments. Examples of such treatments to foster students' attainment in mathematics and other academic and cognitive skills include working memory training (Sala & Gobet, 2017a), chess instruction (Gobet & Campitelli, 2006; Sala, Foley, & Gobet, 2017; Sala & Gobet, in press-a; Sala & Gobet, 2016; Sala, Gobet, Trinchero, & Ventura, 2016; Sala, Gorini, & Pravettoni, 2015; Trinchero & Sala, 2016), and music training (Sala & Gobet, 2017b). The results show either minimal overall effects on academic achievement and overall cognitive ability (music and working memory training) or medium effects possibly due to placebo effects (chess). These results are in line with Thorndike and Woodworth's (1901) *common element* theory according to which *far transfer* – i.e., the generalization of a set of skills across domains only loosely related – rarely occurs (Gobet, 2016; Sala & Gobet, 2017c; Sala & Gobet, in press-b).

Spatial Training

Another, relatively understudied, type of intervention to enhance mathematical ability is spatial training. Spatial training includes activities such as 2D and 3D mental rotation, spatial reasoning and visualizations (Sorby, 2011). However, given the difficulty of far transfer to take place, why should spatial training increase mathematical ability?

The Relationship between Spatial and Mathematical Abilities

Problem solving in mathematics and STEM disciplines largely relies on spatial ability (Stieff & Uttal, 2015). Mechanical physics and engineering deal with movement and interaction between elements in a geometrical space. Mathematicians work with functions represented in 2D and 3D space. More generally, several branches of mathematics – necessary to master disciplines such as physics and engineering – require the manipulation of spatial relationships (e.g. geometry, calculus, topology).

The tight relation between spatial ability and mathematical ability has been established empirically. These two separate constructs are highly correlated to each other (Mix et al., 2016). Spatial abilities – such as mental rotation ability (Mix et al., 2016; Wai, Lubinski, & Benbow, 2009) – are thus strong predictors of achievement in mathematics, both in children (Lauer & Lourenco, 2016) and in undergraduate and doctorate students (Wai et al., 2009). Thus, several researchers have suggested that training spatial ability causes improvement in mathematics achievement.

Spatial Training to Train Spatial and STEM Abilities: The Empirical Evidence

Before asking whether spatial training leads to improving mathematical skills such as arithmetic or geometry, one has to verify whether spatial ability can be trained. A meta-analysis carried out by Uttal et al. (2013) suggests that this is the case. Spatial training appears to transfer both to the trained tasks and other spatial tasks not directly trained.[1] Crucially, from a practical point of view, spatial ability seems to be malleable enough to be significantly boosted by a short-term training (Uttal et al., 2013).

The evidence supporting the effectiveness of spatial training at improving performance on spatial tasks appears to be quite solid. Regrettably, it is not possible to reach the same conclusion for non-spatial tasks. The research on spatial training to improve STEM achievement has provided promising results, but the number of studies is still relatively limited.

In His, Linn, and Bell (1997), a group of undergraduates improved their attainment in an engineering course after attending a voluntary spatial training (3D orthographic projections). However, the fact that the sample was self-selected casts serious doubts upon the reliability of the outcome. More recently, Sorby (2009) reported that a group of undergraduates in engineering with low spatial ability improved their course grades after spatial training (Sorby, 2011), whereas a control group with no training did not show any amelioration. These positive findings were replicated two years later (Sorby, Casey, Veurink, & Dulaney, 2013). Less clear were the results in Miller and Halpern's (2013) study. They did find a moderate positive effect after delivering spatial training, but only in items related to Newtonian mechanics. No benefits occurred in other courses.

The studies mentioned above dealt with university students. Cheng and Mix (2014) focused on the effects of short-term (40 minutes) spatial training on children's basic arithmetical ability. The training consisted of 40 minutes of mental rotation and mental translation exercises suitable for children (Ehrlich, Levine, & Goldin-Meadow, 2006). The treatment group showed a small improvement (approximatively d = 0.20) in the test of arithmetic, limited to one particular type of items (missing-term problems). A study by Hawes, Moss, Caswell, and Poliszczuk (2015) found no significant effects of mental rotation training on a group of primary school children's arithmetical ability. Finally, Xu and LeFevre (2016) reported no transfer from spatial training to a number line task in a sample of kindergarten children.

The Potential Moderating Role of Handedness

Several researchers have argued that the relation between mathematical and spatial ability may be moderated by handedness (Casey, Pezaris, & Nuttall, 1992). Handedness is believed to affect achievement in mathematics because it represents the degree of dominance and development of the right hemisphere, which is involved in cognitive tasks such as spatial reasoning (Ganley & Vasilyeva, 2011) and mental rotation ability (O'Boyle et al., 2005). Some non-right-handers (i.e., left-handed and ambidextrous people) have a more developed right hemisphere than right-handers (Gutwinski et al., 2011). Such a condition may explain why non-right-handers excel in domains where spatial ability is required. For example, non-right-handers are present among chess players in significantly greater ratio than the general population (Gobet & Campitelli, 2007). The same pattern has been found in artists (Preti & Vellante, 2007).

Whether non-right-handers are better than right-handers in mathematics is still a matter of debate (e.g., Benbow, 1986; Cheyne, Roberts, Crow, Leask, & García-Fiñana, 2010; McManus, 2002). However, it appears that among right-handers, those who show a consistent preference for using the right hand (hereafter, extreme right-handers) underperform in mathematics (e.g., Annett & Manning, 1989; Cheyne et al., 2010; Peters, 1991). The possible explanation relies again on the degree of development of the right hemisphere in comparison to the left hemisphere. According to Annett (2002), a strong dominance of the left hemisphere may lead to both being extremely right-handed and suffering from some deficits in spatial ability and, hence, in mathematics. In line with this idea, in a recent large study (total N = 2,314), extreme right-handers obtained a poorer score on a variety of tests of mathematics compared to moderate right-handers (Sala, Signorelli, Barsuola, Bolognese, & Gobet, submitted).

The Present Study

In this study, we replicated and extended Cheng and Mix's (2014) study. There were two crucial additions. First, we tested whether the effects of training (if any) on mathematical ability interact with handedness. We expected extreme right-handers to perform more poorly on the pre-test of arithmetic than the moderate right-handers and non-right-handers. Most importantly, given that the extreme right-handers are believed to have a lower mathematical ability because of a

[1] It must be noticed that transfer of training to multivariate measures of a particular skill (e.g., spatial ability) does not necessarily mean that that skill has been successfully enhanced (Shipstead, Redick, & Engle, 2012). In fact, the improvement in a variety of tasks may stem from some general ability at performing spatial tasks (e.g., better strategies). In any case, this important theoretical issue is beyond the aims of this article.

spatial deficit, we also expected them to benefit most from the spatial training task. Second, along with the treatment and no-contact groups, another treatment group practicing only mental translation was included. The rationale was to understand whether mental translation training alone (i.e., no mental rotation) could positively influence attainment in mathematics (see below for details).

Method

Participants

A total of 159 first, second, and third graders in nine classes of a primary school in northern Italy took part in this experiment. The mean age of the participants was 7.61 years (SD = 0.89). Parental consent was asked and obtained for all the participants.

Materials

The participants were administered (a) the Edinburgh Handedness Inventory (EHI),[2] (b) a spatial ability task (mental rotation and translation) suitable for children (score range 0 – 16; Ehrlich et al., 2006), and (c) a test of arithmetic, designed by the experimenters (score range 0 – 27; Cronbach Alpha = .96).

EHI is a multiple-item questionnaire that provides a continuous measure of handedness (h), which is calculated using the formula $h = \frac{R-L}{R+L}$, where R and L indicate the number of preferences for the right and left hand, respectively. The range of values is between -1, for extreme left-handedness, and +1, for extreme right-handedness. The participants were categorized according to their h-values (Casey, 1995):

a) Extreme right-handers: $h \geq .90$ ($N = 48$).
b) Moderate right-handers: $.40 < h < .90$ ($N = 81$).
c) Non-right-handers: $h \leq .40$ ($N = 30$).

The test of mental rotation and translation ability consists of 16 items. The participant is shown four whole pictures and two parts of a flat shape. The participant has to mentally put the two pieces together and choose one of the four whole pictures (Figure 1).

In the test of arithmetic, finally, the participants solved simple mathematical equations (e.g., 3 + 4 = ?) and missing-term problems (e.g., 3 + ? = 7).

Design

All the nine classes were pre-tested in arithmetic, spatial ability (rotation/translation), and EHI. A week later, the nine classes were randomly assigned to three groups:

a) Three classes (one first-, one second-, one third-grade) attended 60 minutes of mental rotation and translation exercises. This training consisted of 16 rotation items and 16 translation items. Analogously to the testing session, the participants were asked to choose one of the pictures. Finally, children were given the two parts of the picture on separate pieces of cardstock and requested to confirm or change the choice after putting them together (Figure 2).
b) Three classes (one first-, one second-, one third-grade) attended 60 minutes of 32 translation exercises only (translation group; Figure 3). The training procedure was analogous to that in the previous group.
c) Three classes (one first-, one second-, one third-grade) did not carry any activity (no-contact group).

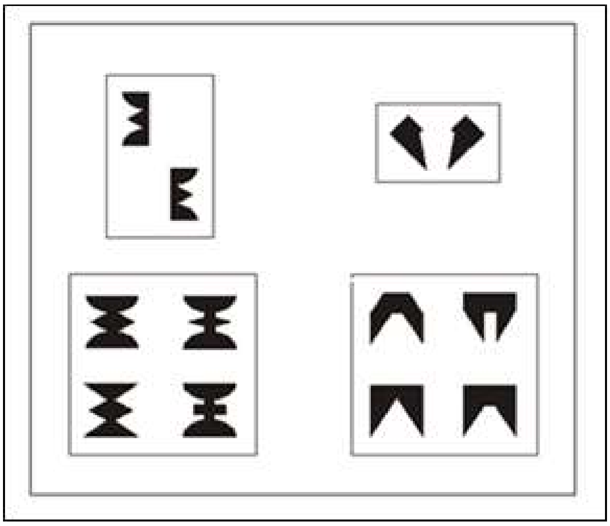

Figure 1. Two examples of the items used in the spatial test (translation and rotation).

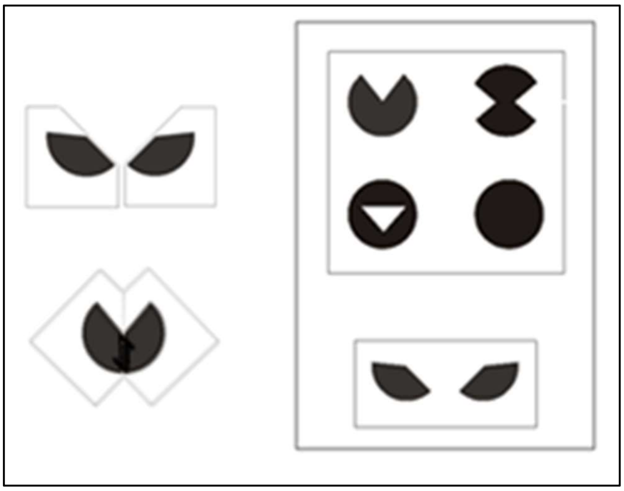

Figure 2. An example of rotation item used in the full-training group.

[2] The item “striking a match” was considered inappropriate for primary school children and thus replaced with the item “dealing cards” (Groen, Whitehouse, Badcock, & Bishop, 2013).

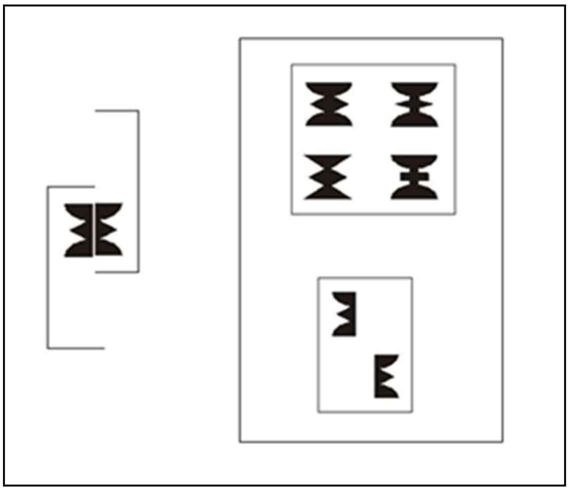

Figure 3. An example of translation item used in both the training groups.

Finally, the three groups were post-tested in arithmetic and spatial ability immediately after the end of the training.

Results

Preliminary Analyses

The three groups did not differ in terms of age ($p = .970$) or pre-test arithmetic test scores ($p = .391$). As expected, the category of handedness had a significant effect on the pre-test scores in arithmetic ($F(2, 156) = 6.50$, $p = .002$). Extreme right-handers were outperformed by both moderate right-handers ($p < .001$) and non-right-handers ($p = .048$).

The pre-post test correlations for arithmetical ability and spatial ability were $r = .94$ and $r = .60$, respectively (both *p*s $< .001$).

Finally, an ANCOVA (pre-test scores as the covariate) confirmed that the spatial training had a significant effect on the score of spatial ability. In fact, the two training groups (full and translation) outperformed the no-contact group ($p = .030$ and $p = .004$, respectively).

Main Analysis: Scores in Arithmetical Ability

The pre- test and post-test scores in arithmetical ability are summarized in Table 1.

Table 1. Scores in arithmetical ability the three groups.

Group	*N*	*Pre-test*	*Post-test*
Full-training	56	16.73 (9.20)	18.04 (7.98)
Translation	53	18.81 (7.02)	18.79 (6.79)
No-contact	50	17.18 (8.32)	18.40 (8.17)

Note. Standard deviations are shown in brackets.

An ANCOVA (Table 2) was run to analyse the effects of the independent variables (group and category of handedness) on the results of the post-test of arithmetical ability, using pre-test score and age as covariates. The results showed no significant effect of age (in years, $p = .176$), category of handedness (*h*-cat; $p = .846$), or group ($p = .491$). As expected, a significant effect of the pre-test scores was found ($p < .001$). Interestingly, a significant interaction between group and category of handedness was reported ($p = .013$).

Table 2. The ANCOVA model of the scores in arithmetic

Variable	*Df*	*F-value*	*p-value*
Group	2	0.72	.491
h-cat	2	0.17	.846
Age	1	1.85	.176
Pre-test scores	1	333.69	**.000**
Group**h*-cat	4	3.27	**.013**

The extreme right-handers in the full-training group showed the greatest mean improvement in the test of arithmetic compared to the other extreme right-handers. The pre- and post-test mean scores are summarized in Table 3.

Table 3. Extreme right-handers' scores in the three groups.

Group	*N*	*Pre-test*	*Post-test*
Full-training	14	10.71 (8.32)	13.57 (7.80)
Translation	17	18.41 (7.98)	18.47 (7.54)
No-contact	17	12.88 (8.35)	14.76 (8.88)

Note. Standard deviations are shown in brackets.

Discussion

The results of this experiment show no significant impact of the one-hour spatial training on children's arithmetical ability. In fact, most of the variance in the post-test of arithmetical ability is explained by pre-test scores ($r = .94$; $r^2 \times 100 = 88\%$). This outcome is in accordance with previous experimental studies (e.g., Cheng & Mix, 2014; Hawes et al., 2015; Xu & LeFevre, 2016) examining the effects of spatial training on arithmetical ability. In a wider perspective, our results are consistent with substantial research on far transfer (Burgoyne et al., 2016; Sala et al., 2017; Sala & Gobet, 2016, 2017a, 2017b).

However, the significant role played by handedness, predicted by Annett (2002), sheds light on the potential benefits of spatial training on arithmetical ability. The extreme right-handers in the full-training group reported the best improvement in mathematical ability compared to both the whole groups and the sub-samples of extreme right-handers. This pattern of results suggests that short-term mental spatial training may be effective for a particular subsample of underachievers in arithmetic (i.e., extreme right-handers), as long as mental rotation activities are included.

Recommendations for Future Research

This study highlights the possible benefits of mental rotation training for extreme right-handers' arithmetical ability. In order to confirm (or disconfirm) our results, future investigations should replicate and extend the design of the current study. First, even if the total sample was large (*N* = 159), the subgroup of extreme right-handers consisted of only a few tens of individuals (*N* = 48) distributed across three groups. Given the importance of that subgroup for the main hypothesis of this study, future experiments should include more participants (e.g., as twice as many) to increase the statistical power, and hence the reliability, of the analysis and outcomes. Second, the future investigations should systematically manipulate the duration of training and administer both immediate and delayed post-test assessments. This way, it would be possible to evaluate whether the effects of spatial training on extreme right-handers' on mathematical ability increase with the duration of training and last after its end. Third, we collected only one measure of mathematical ability (i.e., arithmetic). The use of multivariate measures of mathematical ability and spatial ability would contribute to establishing whether spatial training benefits for extreme right-handers goes beyond basic arithmetic ability.

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References

Annett, M. (2002). *Handedness and brain asymmetry: The right shift theory*. Hove, East Sussex, UK: Psychology Press.

Annett, M., & Manning, M. (1989). The disadvantage of dextrality for intelligence. *British Journal of Psychology, 80*, 213–226.

Benbow, C. P. (1986). Physiological correlates of extreme intellectual precocity. *Neuropsychologia, 24*, 719–725.

Burgoyne, A. P., Sala, G., Gobet, F., Macnamara, B. N., Campitelli, G., & Hambrick, D. Z. (2016). The relationship between cognitive ability and chess skill: A comprehensive meta-analysis. *Intelligence, 59*, 72–83.

Casey, M. B. (1995). Empirical support for Annett's conception of the heterozygotic advantage. *Cahiers de Psychologie Cognitive, 14*, 520–528.

Casey, M. B., Pezaris, E., & Nuttall, R. L. (1992). Spatial ability as a predictor of math achievement: The importance of sex and handedness patterns. *Neuropsychologia, 30*, 35–45.

Cheng, Y. L., & Mix, K. S. (2014). Spatial training improves children's mathematics ability. *Journal of Cognition and Development, 15*, 2–11.

Cheyne, C. P., Roberts, N., Crow, T. J., Leask, S. J., & García-Fiñana, M. (2010). The effect of handedness on academic ability: A multivariate linear mixed model approach. *Laterality, 15*, 451–464.

Deary, I. J., Strand, S., Smith, P., & Fernandes, C. (2007). Intelligence and educational achievement. *Intelligence, 35*, 13–21.

Ehrlich, S., Levine, S., & Goldin-Meadow, S. (2006). The importance of gestures in children's spatial reasoning. *Developmental Psychology, 42*, 1259–1268.

Ganley, C. M., & Vasilyeva, M. (2011). Sex differences in the relation between math performance, spatial skills, and attitudes. *Journal of Applied and Developmental Psychology, 32*, 235–242.

Gobet, F. (2016). *Understanding expertise: A multi-disciplinary approach.* London: Palgrave/Macmillan.

Gobet, F., & Campitelli, G. (2006). Educational benefits of chess instruction. A critical review. In T. Redman (Ed.), *Chess and education. Selected essays from the Koltanowski Conference* (pp. 124–143). Dallas, TX: University of Texas at Dallas.

Gobet, F., & Campitelli, G. (2007). The role of domain-specific practice, handedness and starting age in chess. *Developmental Psychology, 43*, 159–172.

Grek, S. (2009). Governing by numbers: The PISA 'effect' in Europe. *Journal of Education Policy, 24*, 23–37.

Groen, M. A., Whitehouse, A. J. O., Badcock, N. A., & Bishop, D. V. M. (2013). Associations between handedness and cerebral lateralisation for language: A comparison of three measures in children. *PLoS ONE 8*: e64876.

Gutwinski, S., Löscher, A., Mahler, L., Kalbitzer, J., Heinz, A., & Bermpohl, F. (2011). Understanding left-handedness. *Deutsches Arzteblatt International, 108*, 849–853.

Halpern, D. F., Benbow, C. P., Geary, D. C., Gur, R. C., Hyde, J. S., & Gernsbacher, M. A. (2007). The science of sex differences in science and mathematics. *Psychological Science in the Public Interest, 8*, 1–51.

Hanushek, E. A., Peterson, P. E., & Woessmann, L. (2012). *Achievement growth: International and US state trends in student performance*. Harvard's Program on Education Policy and Governance.

Hattie, J. (2009). *Visible learning: A synthesis of over 800 meta-analyses relating to achievement*. New York: Routledge.

Hawes, Z., Moss, J., Caswell, B., & Poliszczuk, D. (2015). Effects of mental rotation training on children's spatial and mathematics performance: A randomized controlled study. *Trends in Neuroscience and Education, 4*, 60–68.

Hsi, S., Linn, M. C., & Bell, J. E. (1997). The role of spatial reasoning in engineering and the design of spatial instruction. *Journal of Engineering Education, 86*, 151–158.

Lauer J. E., & Lourenco, S. F. (2016). Spatial processing in infancy predicts both spatial and mathematical aptitude in childhood. *Psychological Science, 27*, 1–8.

Lubinski, D. (2010). Spatial ability and STEM: A sleeping giant for talent identification and development. *Personality and Individual Differences, 49*, 344–351.

McManus, I. C. (2002). *Right hand, left hand*. London: Orion Books Ltd.

Miller, D. I., & Halpern, D. F. (2013). Can spatial training improve long-term outcomes for gifted STEM

undergraduates? *Learning and Individual Differences, 26*, 141–152.
Mix, K. S., Levine, S. C., Cheng, Y. L., Young, C., Hambrick, D. Z., Ping, R., & Konstantopoulos, S. (2016). Separate but correlated: The latent structure of space and mathematics across development. *Journal of Experimental Psychology: General, 145*, 1206–1227.
O'Boyle, M. W., Cunnington, R., Silk, T. J., Vaughan, D., Jackson, G., Syngeniotis, A., &, Egan, G. F. (2005). Mathematically gifted male adolescents activate a unique brain network during mental rotation. *Cognitive Brain Research, 25*, 583–587.
Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia, 9*, 97–113.
Peng, P., Namkung, J., Barnes, M., & Sun, C. Y. (2016). A meta-analysis of mathematics and working memory: Moderating effects of working memory domain, type of mathematics skill, and sample characteristics. *Journal of Educational Psychology, 108*, 455–473.
Peters, M. (1991). Sex, handedness, mathematical ability, and biological causation. *Canadian Journal of Psychology, 45*, 415–419.
Preti, A., & Vellante, M. (2007). Creativity and psychopathology: Higher rates of psychosis proneness and nonright-handedness among creative artists compared to same age and gender peers. *Journal of Nervous & Mental Disease, 195*, 837–845.
Richland, L. E., Stigler, J. W., & Holyoak, K. J. (2012). Teaching the conceptual structure of mathematics. *Educational Psychologist, 47*, 189–203.
Rohde, T. E., & Thompson, L. A. (2007). Predicting academic achievement with cognitive ability. *Intelligence, 35*, 83–92.
Sala, G., Burgoyne, A. P., Macnamara, B. N., Hambrick, D. Z., Campitelli, G., & Gobet, F., (2017). Checking the "academic selection" argument. Chess players outperform non-chess players in cognitive skills related to intelligence: A meta-analysis. *Intelligence, 61*, 130–139.
Sala, G., Foley, J., & Gobet, F. (2017). The effect of chess instruction on pupils' cognitive and academic skills: State of the art and theoretical challenges. *Frontiers in Psychology, 8*:238.
Sala, G., & Gobet, F. (in press-a). Does chess instruction improve mathematical problem-solving ability? Two experimental studies with an active control group. *Learning & Behavior*.
Sala, G., & Gobet, F. (in press-b). Does far transfer exist? Negative evidence from chess, music, and working memory training. *Current Directions in Psychological Science*.
Sala, G., Gobet, F. (2016). Do the benefits of chess instruction transfer to academic and cognitive skills? A meta-analysis. *Educational Research Review, 18*, 46–57.
Sala, G., & Gobet, F. (2017a). Working memory training in typically developing children: A meta-analysis of the available evidence. *Developmental Psychology, 53*, 671–685.
Sala, G., & Gobet, F. (2017b). When the music's over. Does music skill transfer to children's and young adolescents' cognitive and academic skills? A meta-analysis. *Educational Research Review, 20*, 55–67.
Sala, G., & Gobet, F. (2017c). Experts' memory superiority for domain-specific random material generalizes across fields of expertise: A meta-analysis. *Memory & Cognition, 45*, 183–193.
Sala, G., Gobet, F., Trinchero, R., & Ventura, S. (2016). Does chess instruction enhance mathematical ability in children? A three-group design to control for placebo effects. *Proceedings of the 38th Annual Meeting of the Cognitive Science Society*.
Sala, G., Gorini, A., & Pravettoni, G. (2015). Mathematical problem-solving abilities and chess. *SAGE Open*, 5.
Sala, G., Signorelli, M., Barsuola, G., Bolognese, M., & Gobet, F. (submitted). The relationship between handedness and mathematics is non-linear and is moderated by gender, age, and type of task.
Shipstead, Z., Redick, T. S., & Engle, R. W. (2012). Is working memory training effective? *Psychological Bulletin, 138*, 628–654.
Sorby, S. A. (2009). Education research in developing 3-D spatial skills for engineering students. *International Journal of Science Education, 31*, 459–480.
Sorby, S. A. (2011). *Developing spatial thinking*. Independence: Cengage.
Sorby, S. A., Casey, B., Veurink, N., & Dulaney, A. (2013). The role of spatial training in improving spatial and calculus performance in engineering students. *Learning and Individual Differences, 26*, 20–29.
Stieff, M., & Uttal, D. (2015). How much can spatial training improve STEM achievement? *Educational Psychology Review, 27*, 607–615.
Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin, 139*, 352–402.
Trinchero, R., & Sala, G. (2016). Chess training and mathematical problem-solving: The role of teaching heuristics in transfer of learning. *Eurasia Journal of Mathematics, Science & Technology Education, 12*, 655–668.
Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology, 101*, 817–835.
Xu, C., & LeFevre, J. A. (2016). Training young children on sequential relations among numbers and spatial decomposition: Differential transfer to number line and mental transformation tasks. *Developmental Psychology, 52*, 854–866.