Journal of Cognitive Enhancement
https://doi.org/10.1007/s41465-026-00344-w

Better Together: Harnessing Social Interactions to Improve Spatial Skills in the Classroom

Nina Peleg[1] · Hannah McAuley[1] · Charlotte Pelter[1] · Cecilia Aguilar[1] · Ori Ossmy[1]

Received: 6 January 2025 / Accepted: 13 October 2025

Abstract
Spatial skills—the ability to represent, organise, and navigate the environment, mentally manipulate objects, and communicate information about the external world—are fundamental cognitive abilities that support everyday problem-solving and underlie competencies in fields such as science, technology, engineering, and mathematics. Research shows these skills can be enhanced through targeted training, yet optimal strategies for training are not clear. This pre-registered study examined whether learning in a group enhances spatial training more than individual-focused approaches. Forty-five reception-year children were tested in a six-week training programme where they either completed a spatial task with others ('social' condition), completed the task themselves ('individual') or completed a non-spatial task ('control'). Children in the social group showed significantly greater improvements in spatial assessments, including mental rotation and spatial reasoning, as well as spatial vocabulary. These gains were associated with engagement levels within the group. Our findings highlight that incorporating collaborative learning into spatial training programmes can yield stronger outcomes than individual practice alone. This proof-of-concept suggests that harnessing the social, communicative, and interactive dynamics of the classroom can amplify the benefits of spatial skill interventions and pave the way for larger, more comprehensive educational interventions.

Keywords Spatial skills · Social cognition · Education · Spatial language · Collaborative learning

Introduction

In most daily-life activities, humans rely on their spatial skills—the ability to represent, organise, and navigate their environment, mentally manipulate objects, and communicate information about the external world. These skills are not only essential for everyday problem-solving but also serve as important cognitive building blocks for success in science, technology, engineering, and mathematics (STEM). Indeed, strong spatial skills correspond to understanding abstract concepts and problem-solving strategies in STEM fields (Hawes & Ansari, 2020) and share underlying neural mechanisms with numerical cognition (Hawes et al., 2019).

Despite their significance, many educational systems do not formally target spatial skill development. However, numerous studies demonstrate that spatial abilities are malleable, and that training can lead to substantial improvements (Uttal et al., 2013; Yang et al., 2020). Spatial training has been shown to increase achievement in mathematics by the equivalent of about half a year's progress in that subject (Hawes et al., 2022), and to foster gains in other STEM disciplines as well (Bower & Liben, 2021; Sorby et al., 2018). Moreover, spatial training can help close attainment gaps in early childhood (Bower et al., 2020). These findings highlight the potential value of well-designed interventions that can be realistically integrated into early education settings.

However, existing spatial training interventions vary widely, spanning different ages, skills, and tasks. Because of this wide range, choosing an intervention type is more related to resources, intervention context, or specific goals (Uttal et al., 2013). Traditionally, interventions focused on one specific spatial skill. For example, the use of mental rotation tasks for training and then testing improvements in mental rotation and related educational outcomes, such as

✉ Ori Ossmy
ori.ossmy@bbk.ac.uk

1 Centre for Brain and Cognitive Development, Department of Psychological Sciences, Birkbeck, University of London, London, United Kingdom

mathematical ability (Cheng & Mix, 2014). Others created training tasks that combine several skills together including block-building tasks, mental rotation, spatial visualisation, and spatial perspective-taking. Spatial language exposure has also been found to relate to better spatial skills, even if the language is unrelated to the specific skill (Casasola et al., 2020; Hawes et al., 2017). Although effective, these approaches rarely consider *how the learning environment itself—particularly its social dimension—may shape the acquisition and transfer of spatial skills*.

Educators use different learning approaches to address or even leverage the learning environment. One such approach is *collaborative learning (CL)*, an educational approach where children work together without predefined roles, engaging in joint reasoning and negotiating shared understandings (Laal & Laal, 2012). CL is rooted in the seminal theories of Piaget and Vygotsky (Lisi & Golbeck, 1999; Piaget & Inhelder, 1956; Vygotsky & Cole, 1978). Vygotsky's zone of proximal development supports CL by arguing that collaboration with more-capable peers provides scaffolding that extends a child's competence beyond what could be achieved alone (Vygotsky & Cole, 1978). Complementarily, Piaget's theory of socio-cognitive conflict argues that encountering and resolving discrepant peer viewpoints drives accommodation and deeper conceptual change (Piaget, 2013). Taken together, CL has long been validated in developmental psychology and pedagogy as a driver of learning through social interaction, where learning evolves (O'Donnell & King, 1999). In the case of spatial training, CL may be particularly beneficial because it exposes children to diverse spatial language and viewpoints, requires them to integrate conflicting perspectives, and may increase motivation and cognitive engagement. By fostering richer interactions, CL could support children to form more robust mental representations of space and improve general spatial cognition (Tolmie et al., 2010).

Recently, research has turned to creating spatial training embedded into science or mathematics classes, or "spatialising the classroom" (Lowrie & Logan, 2023; Newcombe, 2016). The motivation for these studies, that transfer is most likely if training occurs within the framework of learning, provides further motivation for CL in spatial training. Yet, few studies have tested the impact of collaborative group work on spatial training in early education, as opposed to general study (Blau et al., 2020; Schwarz et al., 2021). Presumably, this may have an enhanced and differential effect from full-class trainings, as it provides the additional benefits discussed above, as well as occurring within the framework of learning. To address this, this *pre-registered study examined the effectiveness of collaborative versus individual spatial training in reception-year children*.

We hypothesised that (H1) extensive early training of spatial skills facilitates subsequent spatial, mathematical and science skills; (H2) collaborative learning is more effective for training spatial skills compared to individual training; and (H3) within the collaborative-learning condition, children who devote a larger proportion of the session to active, on-task engagement will also show greater gains from CL training. To test these hypotheses, reception-year children completed spatial training once a week (35 min) for six weeks at their school. They were randomly assigned to one of three groups: Social group that completed puzzle tasks as a group (CL approach), Individual group that completed puzzle tasks by themselves, and Control group that completed an active control phonics session.

Thus, this pre-registered study (https://osf.io/ayvn2) provides a much-needed exploration into how collaborative learning can be applied to improving early spatial skills. By situating this research within *real classroom practice*, we offer insights for developing larger-scale programmes that harness the inherently social nature of early learning environments. As educational settings increasingly emphasise active and collaborative experiences, identifying strategies that capitalise on social interaction could more effectively nurture the spatial and STEM-related competencies foundational to children's future academic and career paths.

Materials and Methods

Participants

We tested 45 reception-year children (4.3 to 5.51 years; M_{age} = 5.05 years; 19 girls). Children were recruited from two Reception classes at Underhill School, Chipping Barnet, UK. The school is located in a suburban area with a diverse student population and no formal spatial curriculum.

Children and their parents were informed of the research verbally by their class teacher, and by emails and letters explaining the programme. All parents signed consent forms for their children to participate in the study. No incentives were offered for participation. The support of the school provided us with *a rare opportunity to conduct a multi-session intervention*. Nevertheless, our sample was limited by the size of the school and therefore we were not able to have more participants.

Design

Children underwent a six-week training programme in their classroom. They were randomly assigned to one of three groups (Fig. 1A): (1) Social group (n = 16): children completed a group training programme in which subgroups of

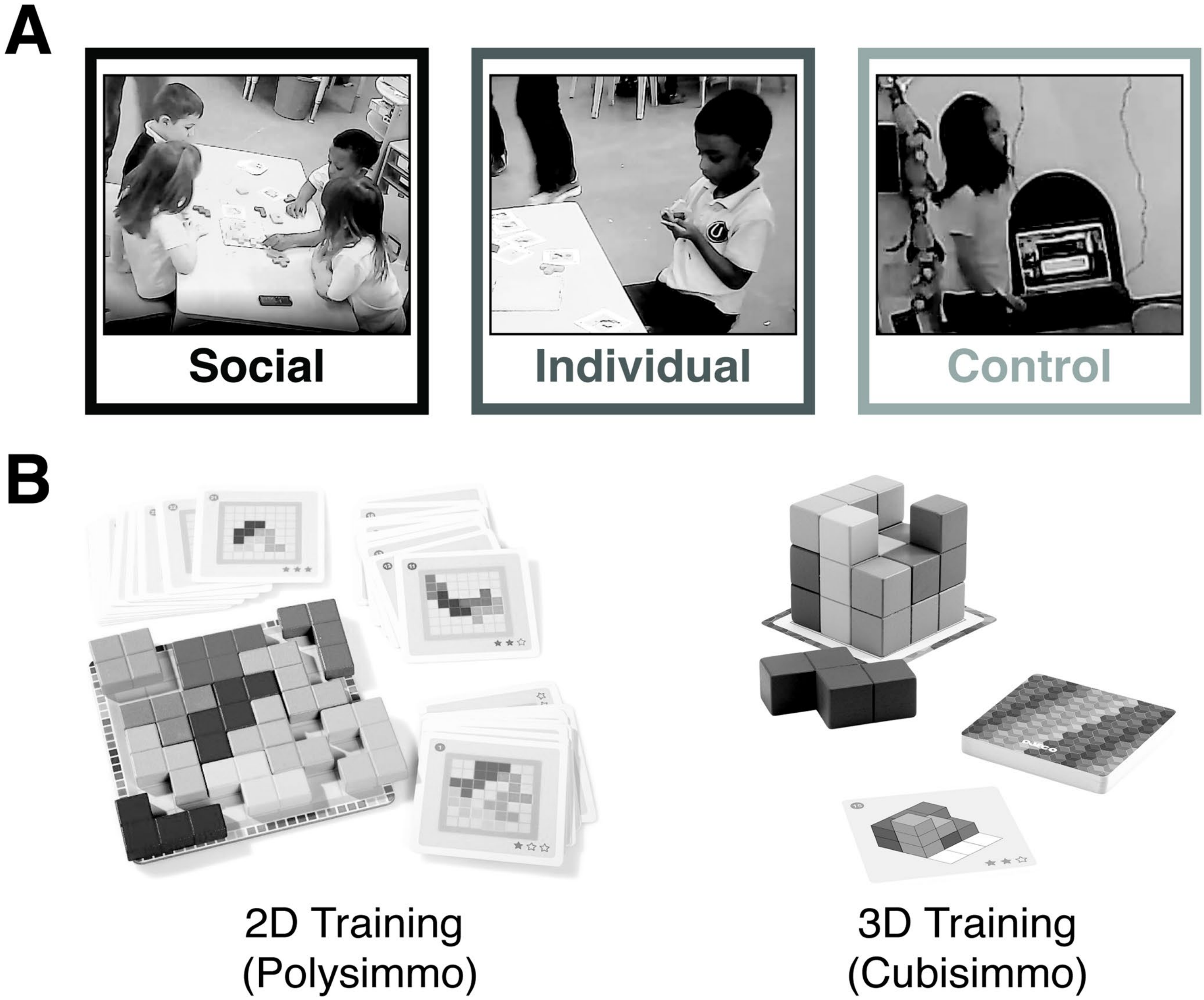

Fig. 1 Experimental design. (A) children were assigned to three experimental condition—social (completing spatial tasks in groups of four), individual (completing spatial tasks by themselves), and control (phonics lesson). (B) Each training session involved 2D and 3D puzzles (see Supporting Information).

four children played the spatial games; (2) Individual group ($n = 16$): children played an individual version of the same spatial games; and (3) Control group ($n = 13$): children completed a non-spatial activity (active control phonics session). The groups were matched for age. Training included overall 6 weekly sessions; each training session lasted 35 min (see Supporting Information for further details on the procedure). The groups were distributed equally across the two classes. To evaluate their improvement in spatial skills, children completed established spatial tests (see Assessments) in two testing sessions, *one week before* the training programme started (pre-training test) and *one week after* the end of the training programme (post-training test). Assessors were blind to children's group assignments to minimize expectancy effects.

Training Procedure and Materials

In each training session, children in the Social and Individual groups were provided with an off-the-shelf puzzle game. In the Social group, four children worked together; in the Individual group, each child worked alone. Before each session, the teachers (who had been trained in standardised instructions by the researchers) asked the Social group to work together to solve the puzzle, talk to each other, and help each other find the right pieces. The Individual group was instructed to solve the puzzle by themselves without asking others for help. In the Control group, children engaged in routine phonics activities unrelated to spatial challenges under similar time constraints. All sessions ran concurrently and no other information from the teachers was provided. The Social and Individual groups were instructed by the same teacher but then moved to different locations. The same teacher was in charge across the training sessions. The small groups in the Social condition included the same children for all training sessions.

Throughout all groups, children were not given substantive instructional support, teachers left children to work through puzzles either alone or in their groups. The groups were located in different rooms, and no communication was allowed between children who were not partners. Children were allowed to ask the teacher questions and get support regarding the instruction, and the goal of the puzzle. No hints or strategies were provided, ensuring that problem-solving emerged naturally from the children's interaction with the materials. When completed, children raised their hands to have their puzzle checked by their teacher. If correct, they moved to the next puzzle card. If incorrect, children were told to try again. The difficulty of puzzle cards gradually increased within the session, ensuring progression in spatial complexity.

In the first three weeks, children were given 'Polysimmo'—a two-dimensional puzzle developed by Djeco Toys (Fig. 1B, left panel). Polysimmo consists of a set of cards with various geometric patterns and a collection of coloured geometric shapes. Children were challenged to replicate the 2D structures on the cards by arranging the geometric shapes on a flat surface. The same set of cards was used across training sessions. To do so, children must perceive the shapes through manipulation, understand their required spatial orientation, and visualise the end result before execution, lending it a proper tool for training spatial skills.

In the second half of the programme, during the last three weeks, children were provided with 'Cubisimmo'—a three-dimensional puzzle developed by Djeco Toys (Fig. 1B, right panel). Cubissimo includes a set of wooden blocks of different shapes and sizes. The goal of the game is to assemble these blocks into structures according to a set of cards with various 3D geometric shapes. The same set of cards was used across training sessions. To do so, children must engage in mental rotation and spatial transformation to determine how the pieces fit together.

Therefore, the use of both Polysimmo and Cubissimo in the training programme supported a range of key spatial skills. We started with the Polysimmo puzzles due to their relatively simpler design, which is well-suited to introduce children in reception class to spatial challenges. As the children progressed through the first half of the training programme, they developed a foundational competence to solve the more complex "Cubissimo" puzzles.

The Social group's training sessions were recorded in video to measure children's interaction and engagement during training. Each child quartet was recorded with one HD camera in a side view. All videos are shared at https://nyu.databrary.org/volume/1457. Unfortunately, administrative challenges meant other groups were not recorded.

Assessments

All assessments were conducted in one-on-one sessions by a trained experimenter, following the standardized protocols detailed in the cited validation studies. Specifically: (1) The Children's Mental Transformation Task (CMTT; Frick et al., 2014) tested children's spatial reasoning by requiring them to choose the correct transformed shape from alternatives, with strong internal consistency ($\alpha > 0.80$) and approximately 10–15 min to complete; (2) The Picture Rotation Task tested children's mental rotation skills (Quaiser-Pohl, 2003) and involved identifying rotated images matching a target, with high reliability ($\alpha = 0.89$) and completion within about 10 min; (3) The Spatial Vocabulary Assessment testing children's spatial vocabulary (receptive and expressive; (Casasola et al., 2020) assessed expressive and receptive vocabulary through spatial language comprehension and production tasks, showing high reliability (Cronbach's α ranging from 0.80 to 0.89), and typically completed in about 15 min; (4) The Science-K Inventory testing scientific reasoning (Koerber & Osterhaus, 2019) tested basic scientific reasoning via practical and theoretical questions, demonstrating robust internal consistency ($\alpha = 0.87$), and administered in about 15–20 min; and (5) the Reception Class Math Assessment assessed foundational mathematical reasoning skills with good reliability, typically completed within approximately 10–15 min. Further details and example items are provided in the original studies.

To measure the effects of the training programme, we calculated children's performance gains in each assessment by dividing their score in the post-training test by their score in the pre-training test and multiply it by 100.

Video Coding

A primary coder scored videos frame by frame using Datavyu software (www.datavyu.org) to time-lock engagement of children from the Social group. The coder identified frame by frame whether children were engaged with the spatial task during the training session and if so–how. To ensure interobserver reliability, a second coder independently scored 33.3% of the data. Disagreements between coders were resolved by discussion. Coding manual coders followed can be found at https://nyu.databrary.org/volume/1457.

Engagement. In principle, children were free to take any actions during the training session, including not taking part in the activity at all. So, coders considered each time the child was engaged in the training in terms of their presence in the group work including when they led their own partners' work, pointed at own partners, acted on the spatial task, touched the materials, showed the materials to group partners, followed the work of partners on the task, or participated in a discussion with the teacher. Each frame of the training session was coded and we calculated the training engagement as a percentage of frames children were engaged from the overall training session. Interobserver agreement for accumulated durations of engagement was high, rs(14) > 0.89, ps < 0.01.

Engagement Types. Children could have been engaged in different manners. For each of the coded training engagements, coders determined whether the type of engagement was (1) looking (the child looked at the puzzle or the activity of solving it); (2) touching (the child touched at least one of the puzzle parts); (3) solving (the child actively solved the puzzle by moving the puzzle part on the board); and (4) consulting (the child actively engaged in a conversation with the teacher about the task). Engagement segments could be coded by more than one type of engagement. The interactions with the teachers were coded whenever a child verbally addressed the teacher about the puzzle; teachers, who were instructed not to provide hints or demonstrations, responded only with neutral acknowledgements. Because the recorded audio could not be transcribed clearly (the classroom audio was too noisy), this category is best interpreted as child-initiated on-task engagement rather than adult instructional support. Coders agreed on the type of engagement in 98.00% of activities, *kappa* = 0.84, $p < .01$.

Results

Preliminary analyses showed no effects of children's age or gender on the differences in their assessments, all ps > 0.42, so these factors were collapsed in all analyses. Preliminary analyses also confirm no group differences across all tests in pre-test scores, all *ps* > 0.06 (Table S1). One of the children from the Social group did not complete the post-training assessments and therefore was excluded from further analysis.

Group Practice is Better for Training Spatial Skills

Figure 2 shows the differences between the groups in each assessment (Table S2). As we expected, we found differences between groups in assessments of expressive spatial vocabulary ($F(2,41) = 6.53$, $p = .003$, $\eta^2 = 0.241$; one-way ANOVA using group as independent variable), receptive spatial vocabulary ($F(2,41) = 3.79$, $p = .031$, $\eta^2 = 0.156$), spatial reasoning ($F(2,41) = 11.98$, $p < .001$, $\eta^2 = 0.369$), and mental rotation ($F(2,41) = 13.12$, $p < .001$, $\eta^2 = 0.390$).

LSD-corrected post hoc comparisons confirmed that these differences are driven by greater improvements in children from the Social group compared to both the Individual and Control groups in expressive spatial vocabulary ($p = .028$, $p < .001$, respectively), receptive spatial vocabulary ($p = .030$, $p = .017$, respectively)), spatial reasoning ($p = .009$, $p < .001$, *respectively*), and mental rotation ($p = .006$, $p < .001$, respectively). In addition, the LSD-corrected post-hoc comparisons revealed that improvements in the Individual group were greater than the Control group in spatial reasoning and mental rotation ($p = .027$, $p = .021$, respectively).

In contrast to our predictions, we did not find significant differences in scientific reasoning and mathematical assessments ($F(2,41) = 2.88$, $p = .068$ and $F(2,41) = 0.93$, $p = .404$, respectively; Fig. 2E-F). However, both improvements in scientific reasoning and mathematics were correlated with improvements in expressive vocabulary, which was significantly better in children from the Social group ($r(42) = 0.38$, $p = .011$, $r(42) = 0.43$, $p = .004$, *respectively;* Table S3).

Engagement in Group Work is Associated with Training Outcomes

Children from the Social group (see Methods and Supporting Information for details on video coding) were engaged in $M = 67.44\%$, $SD = 5.53$ of the session. Figure 3A shows change in engagement across the first four sessions and the two following ones. The line suggests an increase in engagement that follows a decrease. Yes, a repeated measures ANOVA confirmed that these differences were not significant $F(5,13) = 4.03$, $p = .076$. Figure 3B shows that children's most prominent type of engagement was looking ($M = 91.92\%$ of engagement time, $SD = 3.31$), then touching ($M = 79.77\%$, $SD = 5.85$), solving ($M = 66.69\%$, $SD = 2.34$), and interactions with the teacher ($M = 39.12\%$, $SD = 6.65$).

Children's overall engagement was correlated with their improvements in expressive and receptive vocabulary ($r(13) = 0.649$, $p = .009$ and $r(13) = 0.522$, $p = .046$, respectively) and spatial reasoning ($r(13) = .522$, $p = .046$) but not with the other assessments (rs < 0.46, ps>0.05; Fig. 3C-D). Finally, using multiple linear regression, we were able to significantly predict children's improvements in expressive vocabulary ($R^2 = 0.78$, $F(4,10) = 3.95$, $p = .036$), and mental transformation ($R^2 = 0.80$, $F(4,10) = 4.30$, $p = .028$). We failed to predict improvements in other assessments (Fs < 2.1, $p > .15$). In terms of individual predictors, the solving, looking and teacher engagements significantly contributed to the prediction in expressive vocabulary ($\beta = 1.81$, $p = .012$, $\beta = 3.97$, $p = .011$, $\beta = 1.31$, $p = .042$, respectively) whereas solving and teacher engagement significantly contributed to the prediction of mental transformation ($\beta = 1.42$, $p = .022$, $\beta = 1.03$, $p = .004$, respectively).

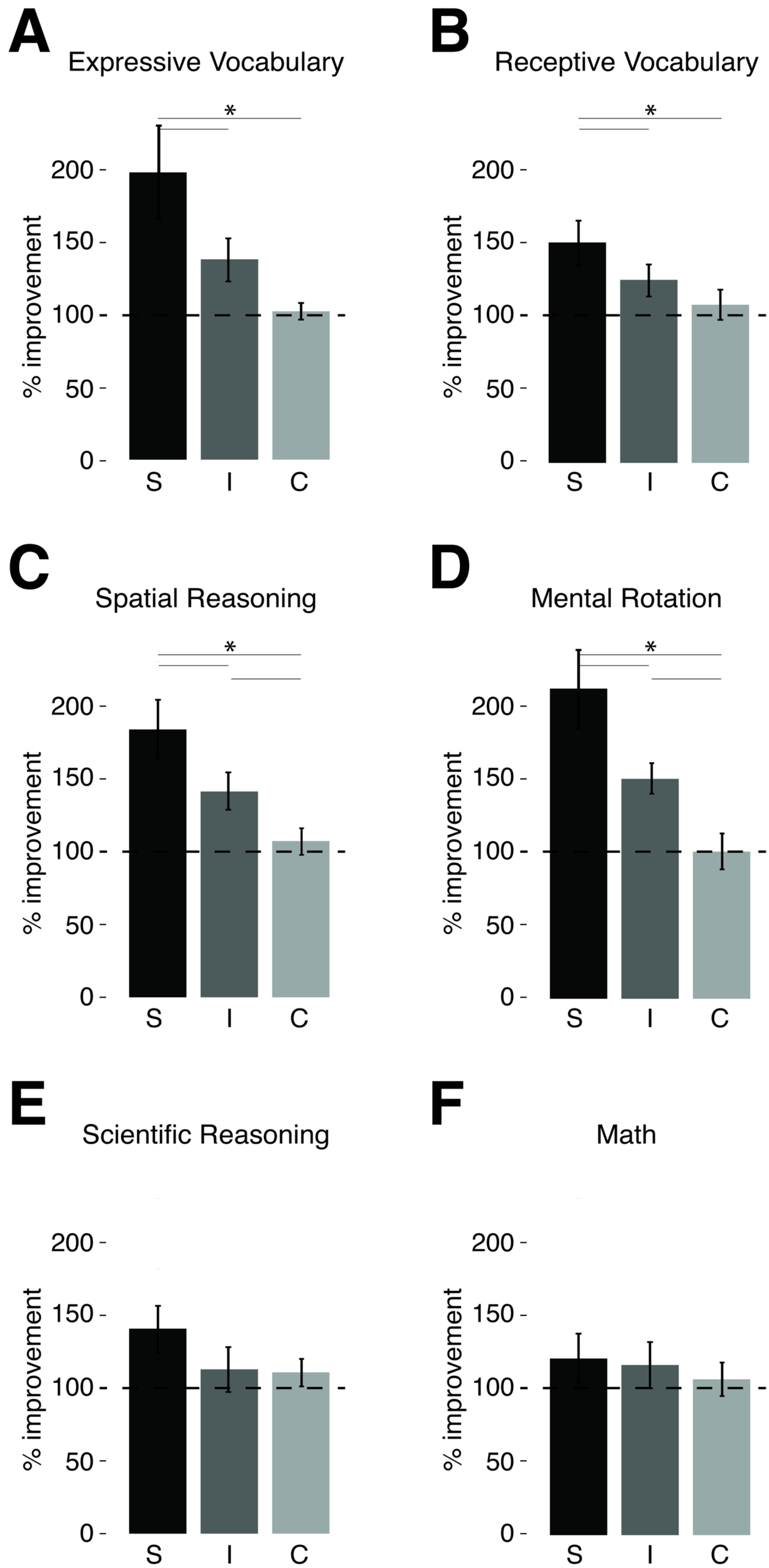

Fig. 2 Differences across groups in post-training improvements. By comparing post-training assessment with pre-training assessment, we assessed children's improvements (See Methods) in **(A)** expressive vocabulary, **(B)** receptive vocabulary, **(C)** spatial reasoning, **(D)** mental rotation, **(E)** scientific reasoning, and **(F)** math. Asterisks indicate significant difference and dashed line indicates no improvement from pre-training assessment to post-training assessment

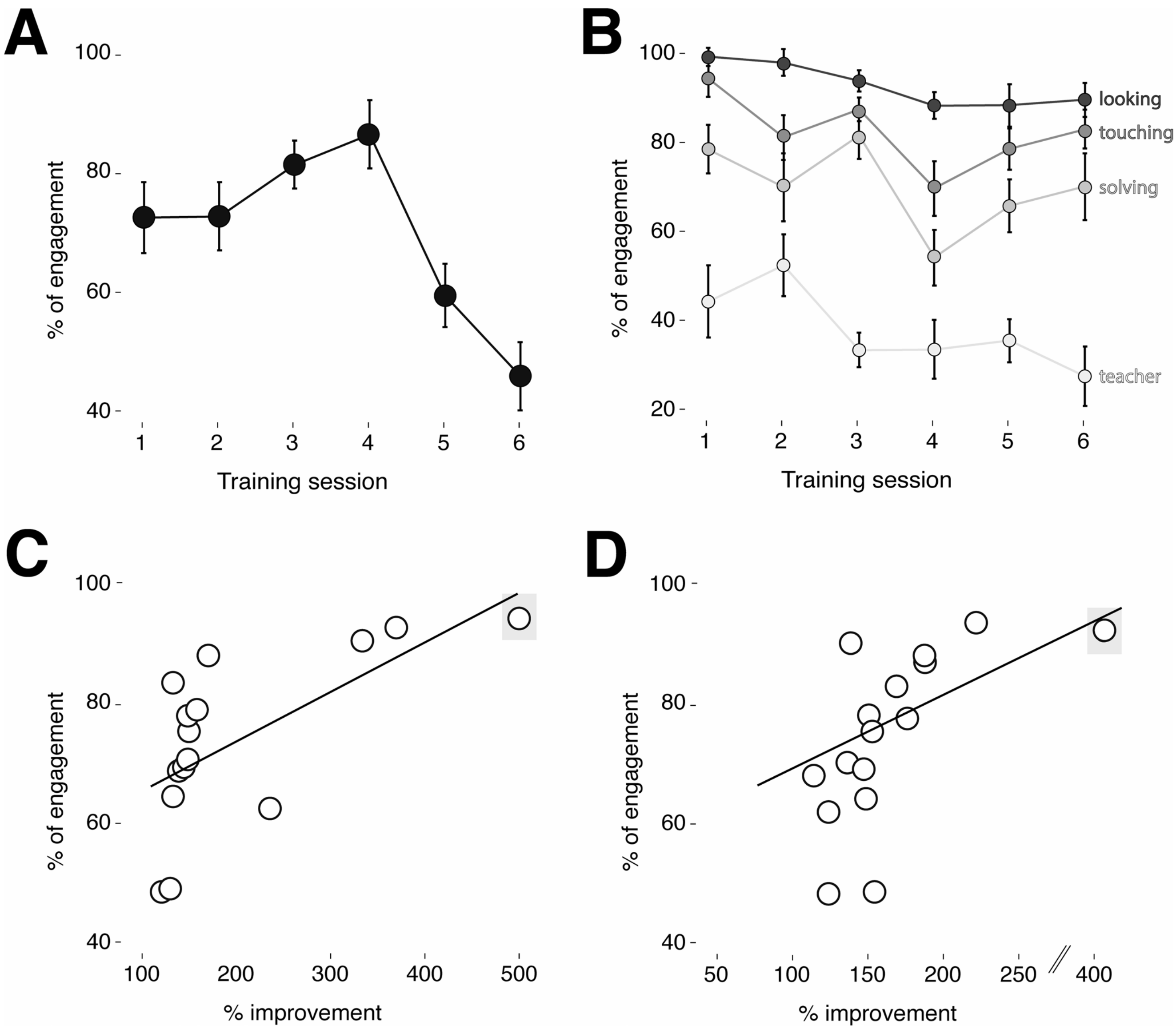

Fig. 3 Engagement in the Social group. **(A)** percentage of engagement changes from on session to another, with decrease after the fourth session; **(B)** Changes in engagement across sessions per engagement type; **(C-D)** Significant correlations between engagement and improvements in expressive (**C**) and receptive (**D**) vocabulary respectively ($r(13) = 0.649$, $p = .009$ and $r(13) = 0.522$, $p = .046$), respectively. Correlations were still significant after removing the yellow-marked data point ($r(12) = 0.592$, $p = .026$, $r(12) = 0.630$, $p = .016$, respectively)

Discussion

This pre-registered study tested the impact of collaborative learning (CL) on spatial training in reception-year children. As expected, children who completed the spatial training improved more in spatial assessments compared to those who were not trained. Moreover, as expected, children who completed collaborative training significantly improved compared to children who completed the training individually. The level of engagement in the group work predicted improvements in expressive vocabulary and mental transformation. Taken together, our results motivate larger scale studies, which can further affirm our demonstration of how CL may be harnessed for improving spatial skills. Our study aligns with existing research demonstrating the effectiveness of spatial training in children as young as 4-years-old. Unlike previous training programmes for this age group (Hawes et al., 2017), we used a single task and found significant effects for generalised spatial tests (mental rotation and spatial reasoning). This finding suggests that spatial training programmes can be more accessible and easier to implement by using only basic puzzle tasks.

The main novelty in this study is the use of a CL approach. Similar to previous studies, we also show associations between spatial language exposure and improvements in general spatial skills (Casasola et al., 2020). Although no significant gains were found in spatial vocabulary tests for the individual and control groups, the social group's progress is attributed to CL, which bolsters skill advancement through both spatial tasks and enriched language interaction. Active engagement within the group was a crucial predictor of this advancement, with the time spent actively solving the tasks as a key predictor of children's improvements in mental transformation.

Several complementary mechanisms likely account for the CL effects we found. First, socio-cognitive elaboration: when children work jointly they must articulate their reasoning, confront discrepant viewpoints, and negotiate a shared plan of action. Such "transactive" discourse is known to deepen conceptual understanding by making implicit spatial representations explicit and by forcing learners to integrate multiple perspectives (Coleman, 1998; Slavin, 1983). This interpretation fits our data, where engagement time was associated with improvement in the spatial vocabulary tests. Second, linguistic mediation: CL dramatically increases both the quantity and the sophistication of spatial talk. Exposure to—and production of—terms such as behind, rotate, or mirror-image provides children with linguistic tools that scaffold the encoding and manipulation of spatial relations, a link documented across several large-scale studies (Casasola et al., 2020; Pruden et al., 2011). Third, motivational affordances: working with peers typically elevates task engagement through shared goals, peer accountability, and social enjoyment (Johnson & Johnson, 2009). Higher engagement was indeed associated with larger learning gains in our social group, suggesting that affective-motivational factors amplify the cognitive benefits afforded by explanation and language. Finally, a more speculative route—cognitive off-loading. Because puzzle pieces are physically shared in the group condition, each child has fewer direct manipulations and must rely more heavily on mental transformation, potentially intensifying spatial practice (Cherry et al., 2024). Together, these intertwined mechanisms—elaboration, language, motivation, and cognitive off-loading—provide a rich explanatory framework for the advantages of CL in early spatial learning. Future research should on comparing those alternative mechanisms and their interactions during spatial training.

Our results did not confirm generalisation of the CL effect to mathematics or science skills. However, we did find that improvements in mathematics and scientific reasoning correlated with improvements in spatial vocabulary tests. A possible explanation concerns the simplicity of the task and instructional support. Children in the social condition were not obligated, nor explicitly encouraged, to exchange or discuss viewpoints to complete the task, thus they spent less time facilitating processes such as integration of information from different sources (which relates to conceptual learning and thereby mathematics and science reasoning). Prior research, for example, indicates that group discussion effectively improves outcomes in science lessons (Howe & Tolmie, 2003). Alternatively, our lack of generalisation may be due to our inability to detect effects due to our sample size. Past studies have found transfer effects to be smaller than effects on spatial skills, thus we may have not been appropriately sized to detect them (Gilligan et al., 2020; Lowrie et al., 2020). To test generalization of spatial skills to other domains, future research must increase the sample size and use tasks that require perspective-taking and sharing of viewpoints to examine whether those lead to the generalisation of CL effects from spatial skills to mathematics and scientific reasoning skills.

Designing training programs that align with learning approaches is crucial for translating research into effective educational practice. It is essential to differentiate between the efficacy of spatial skills interventions in controlled environments and their effectiveness in real-world classrooms, as highlighted by Schoenwald and Hoagwood (2001). Proven by our concept, using classroom learning approaches like CL not only boosts training outcomes but also facilitates seamless integration into the collaborative nature of primary school classrooms, thus enhancing practical effectiveness over mere laboratory efficacy.

The applied benefit of our approach is that it aligns well with contemporary educational frameworks that emphasise 21st-century skills such as communication, creativity, and critical thinking. CL in spatial tasks might serve as a microcosm for more complex, domain-general problem-solving abilities. If these social-based training methods prove scalable, schools could implement them as a low-cost, sustainable strategy to enhance early STEM education. Indeed, the relative simplicity and low-resource nature of puzzle-based interventions make them appealing for widespread classroom use, especially if ongoing teacher training or substantial resource investments are minimized. Thus, although our findings should be interpreted with caution as this is a small-scale study, we believe our intervention serves as an important proof-of-concept and paves the way for future programmes to use the collaborative-learning approach.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s41465-026-00344-w.

Acknowledgements We would like to thank Jack Hayward for his contribution in collecting the data.

Authors' Contributions NP: formal analysis, writing—original draft and editing; HM, CP and CA: data analysis; OO: supervision, conceptualization, study design, analyses, writing—review and editing, funding acquisition.

Funding This work was supported by the ESRC New Investigator grant ES/W009242/1, the BA Talent Award TDA21\210038, the Waterloo Foundation grant 917–4975, and the Birkbeck/Wellcome Trust Institutional Strategic Support Fund to Ori Ossmy.

Data Availability Videos and aggregated data are shared at https://nyu.databrary.org/volume/1457. The rest of the data is available on request to the corresponding author.

Declarations

Ethics Approval and Consent to Participate The study was approved by the Psychology Ethics Committee at Birkbeck, University of London (reference #2122035) and was pre-registered (https://osf.io/ayvn2). All Caregivers provided a signed consent form.

Consent for Publication All participants provided a written consent form and publication form.

Competing Interests The authors declare no competing interests.

References

Blau, I., Shamir-Inbal, T., & Hadad, S. (2020). Digital collaborative learning in elementary and middle schools as a function of individualistic and collectivistic culture: The role of ICT coordinators' leadership experience, students' collaboration skills, and sustainability. *Journal of Computer Assisted Learning*, *36*(5), 672–687. https://doi.org/10.1111/jcal.12436

Bower, & Liben, L. S. (2021). Can a Domain-General Spatial intervention facilitate children's science learning? A lesson from astronomy. *Child Development*, *92*(1), 76–100. https://doi.org/10.1111/cdev.13439

Casasola, M., Wei, W. S., Suh, D. D., Donskoy, P., & Ransom, A. (2020). Children's exposure to Spatial language promotes their Spatial thinking. *Journal of Experimental Psychology: General*, 149(6), 1116–1136. https://doi.org/10.1037/xge0000699

Cheng, Y. L., & Mix, K. S. (2014). Spatial training improves children's mathematics ability. *Journal of Cognition and Development*, *15*(1), 2–11. https://doi.org/10.1080/15248372.2012.725186

Cherry, L. K. R., Cheng, M., Ghilardi, T., & Ossmy, O. (2024). Automatic Real-Time Hand Tracking Enhances Adolescents' Spatial Skills by Eliminating Haptic Feedback. *2024 IEEE International Conference on Development and Learning* (ICDL), 1–6. https://doi.org/10.1109/ICDL61372.2024.10644469

Coleman, E. B. (1998). Using explanatory knowledge during collaborative problem solving in science. *Journal of the Learning Sciences*, *7*(3–4), 387–427. https://doi.org/10.1207/s15327809jls0703amp;4_5

Frick, A., Möhring, W., & Newcombe, N. S. (2014). Development of mental transformation abilities. *Trends in Cognitive Sciences*, *18*(10), 536–542. https://doi.org/10.1016/j.tics.2014.05.011

Gilligan, K. A., Thomas, M. S. C., & Farran, E. K. (2020). First demonstration of effective Spatial training for near transfer to Spatial performance and Far transfer to a range of mathematics skills at 8 years. *Developmental Science*, *23*(4), e12909. https://doi.org/10.1111/desc.12909

Hawes, Z., & Ansari, D. (2020). What explains the relationship between Spatial and mathematical skills? A review of evidence from brain and behavior. *Psychonomic Bulletin & Review*, *27*(3), 465–482. https://doi.org/10.3758/s13423-019-01694-7

Hawes, Z., Moss, J., Caswell, B., Naqvi, S., & MacKinnon, S. (2017). Enhancing children's Spatial and numerical skills through a dynamic Spatial approach to early geometry instruction: Effects of a 32-Week intervention. *Cognition and Instruction*, *35*(3), 236–264. https://doi.org/10.1080/07370008.2017.1323902

Hawes, Z., Sokolowski, H. M., Ononye, C. B., & Ansari, D. (2019). Neural underpinnings of numerical and Spatial cognition: An fMRI meta-analysis of brain regions associated with symbolic number, arithmetic, and mental rotation. *Neuroscience & Biobehavioral Reviews*, *103*, 316–336. https://doi.org/10.1016/j.neubiorev.2019.05.007

Hawes, Z., Gilligan-Lee, K. A., & Mix, K. S. (2022). Effects of Spatial training on mathematics performance: A meta-analysis. *Developmental Psychology*, *58*(1), 112–137.

Howe, C., & Tolmie, A. (2003). Group work in primary school science: Discussion, consensus and guidance from experts. *International Journal of Educational Research*, *39*(1), 51–72. https://doi.org/10.1016/S0883-0355(03)00073-9

Johnson, D. W., & Johnson, R. T. (2009). An educational psychology success story: Social interdependence theory and cooperative learning. *Educational Researcher*, *38*(5), 365–379. https://doi.org/10.3102/0013189X09339057

Koerber, S., & Osterhaus, C. (2019). Individual differences in early scientific thinking: Assessment, cognitive Influences, and their relevance for science learning. *Journal of Cognition and Development*, *20*(4), 510–533. https://doi.org/10.1080/15248372.2019.1620232

Laal, M., & Laal, M. (2012). Collaborative learning: What is it? *Procedia - Social and Behavioral Sciences*, *31*, 491–495. https://doi.org/10.1016/j.sbspro.2011.12.092

Lisi, R. D., & Golbeck, S. L. (1999). Implications of Piagetian theory for peer learning. *Cognitive perspectives on peer lear ning*. Routledge.

Lowrie, T., & Logan, T. (2023). Spatial visualization supports students' math: Mechanisms for Spatial transfer. *Journal of Intelligence*, *11*(6), 127. https://doi.org/10.3390/jintelligence11060127

Lowrie, T., Resnick, I., Harris, D., & Logan, T. (2020). In search of the mechanisms that enable transfer from Spatial reasoning to mathematics Understanding. *Mathematics Education Research Journal*, *32*(2), 175–188. https://doi.org/10.1007/s13394-020-00336-9

Newcombe, N. S. (2016). Thinking spatially in the science classroom. *Current Opinion in Behavioral Sciences*, *10*, 1–6. https://doi.org/10.1016/j.cobeha.2016.04.010

O'Donnell, A. M., & King, A. (1999). *Cognitive perspectives on peer learning*. Taylor & Francis Group. https://doi.org/10.4324/9781410603715

Piaget, J. (2013). Play, Dreams And Imitation In Childhood. Routledge. https://doi.org/10.4324/9781315009698

Piaget, J., & Inhelder, B. (1956). *The child's conception of space*. Routledge & K. Paul.

Pruden, S. M., Levine, S. C., & Huttenlocher, J. (2011). Children's Spatial thinking: Does talk about the Spatial world matter? *Developmental Science*, *14*(6), 1417–1430. https://doi.org/10.1111/j.1467-7687.2011.01088.x

Quaiser-Pohl, C. (2003). The mental cutting test 'Schnitte' and the picture rotation test-Two new measures to assess Spatial ability. *International Journal of Testing*, *3*(3), 219–231. https://doi.org/10.1207/S15327574IJT0303_2

Schoenwald, S. K., & Hoagwood, K. (2001). Effectiveness, transportability, and dissemination of interventions: What matters when? *Psychiatric Services (Washington D C)*, *52*(9), 1190–1197. https://doi.org/10.1176/appi.ps.52.9.1190

Schwarz, B. B., Swidan, O., Prusak, N., & Palatnik, A. (2021). Collaborative learning in mathematics classrooms: Can teachers understand progress of concurrent collaborating groups? *Computers & Education*, *165*, 104151. https://doi.org/10.1016/j.compedu.2021.104151

Slavin, R. (1983). When does cooperative learning increase achievement. *Psychological Bulletin*, *94*(3), 429–445.

Sorby, S., Veurink, N., & Streiner, S. (2018). Does Spatial skills instruction improve STEM outcomes? The answer is 'yes'. *Learning and Individual Differences*, *67*, 209–222. https://doi.org/10.1016/j.lindif.2018.09.001

Tolmie, A. K., Topping, K. J., Christie, D., Donaldson, C., Howe, C., Jessiman, E., Livingston, K., & Thurston, A. (2010). Social effects of collaborative learning in primary schools. *Learning and Instruction*, *20*(3), 177–191. https://doi.org/10.1016/j.learninstruc.2009.01.005

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*(2), 352. https://doi.org/10.1037/a0028446

Vygotsky, L. S., & Cole, M. (1978). *Mind in society: Development of higher psychological processes*. Harvard university press.

Yang, W., Liu, H., Chen, N., Xu, P., & Lin, X. (2020). Is early Spatial skills training effective? A Meta-Analysis. *Frontiers in Psychology*, *11*(1938). https://doi.org/10.3389/fpsyg.2020.01938

Bower, C. A., Odean, R., Verdine, B. N., Medford, J. R., Marzouk, M., Golinkoff, R. M., & Hirsh-Pasek, K. (2020). Associations of 3-year-olds' block-building complexity with later spatial and mathematical skills. *Journal of Cognition and Development, 21*(3), 383–405. https://doi.org/10.1080/15248372.2020.1741363