Abstract

Construction play is thought to develop logico-mathematical skills, however the underlying mechanisms have not been defined. In order to fill this gap, this study looks at the relationship between Lego construction ability, cognitive abilities and mathematical performance in 7-year-old, Year 2 primary school children ($N = 66$). While studies have focused on the relationship between mathematics performance and verbal memory, there are limited studies focusing on visuospatial memory. We tested both visuospatial and verbal working memory and short term memory, as well as non-verbal intelligence. Mathematical performance was measured through the WIAT-II numerical operations, and the word reading subtest was used as a control variable. We used a Lego construction task paradigm based on four task variables found to systematically increase construction task difficulty. The results suggest that Lego construction ability is positively related to mathematics performance, and visuospatial memory fully mediates this relationship. Future work of an intervention study using Lego construction training to develop visuospatial memory, which in turn may improve mathematics performance, is suggested.
Introduction

Children learn through play. Construction play is defined by Piaget as activities producing symbolic products, and is thought to develop logico-mathematical knowledge (Wolfgang & Phelps, 1983). However, the mechanisms of how construction play can develop logico-mathematical skills are not defined. Baddeley’s (1986, 2000) influential memory model differentiated between verbal and visuospatial memory systems. Ever since, there has been high interest in analysing the relationship between memory systems and learning. Previous studies on construction play and mathematics have focused on the relationship with verbal memory (Richardson & Richardson, 2011), but there are no studies on construction play and visuospatial memory, which may be more relevant. In fact, there is a general paucity of research on visuospatial memory, in comparison to the research on verbal memory (Raghubar, Barnes, & Hecht, 2010). In this study we analyse the relationship between construction play and mathematics performance and test whether visuospatial memory is a mechanism mediating this relationship.

Construction Play, Spatial Ability, and Mathematics Performance

Studies analysing the relationship between construction play and cognitive abilities have focused on spatial ability (Connor & Serbin, 1977; Caldera, McCulp, O'Brien, Truglio, Alvarez, & Huston, 1999; Robert & Heroux, 2004). Spatial ability has been further divided into static (fixed objects) or dynamic (movement of objects), and intrinsic (comparison within an object) or extrinsic (comparison between objects) (Uttal et al., 2013).
Studies have found correlations between construction play and spatial abilities. Connor and Serbin (1977) first asked undergraduate students to categorize toys as masculine or feminine, and then analyzed play preferences of children according to the categorization. They found boys playing with masculine activities (blocks, and large motor toys) were correlated with higher performance of spatial ability as measured by the Wechsler Preschool and Primary Scale of Intelligence Block Design and Preschool Embedded Figures Test (EFT). However for girls, they did not find significant relationships between cognitive development and play preferences for either masculine or feminine activities (Connor & Serbin, 1977). In a study with older children (9-year-old), past experience in playing with Lego did not correlate with any of the spatial measures. There was a negative relationship between the mental rotation ability, and the number of errors and the time taken to construct the Lego model (Brosnan, 1998). Similarly, in another study, although preference for construction play was not significantly correlated with any of the spatial tests, accuracy on the structured block play was correlated with Block Design and Copying Blocks, but not with the Children’s EFT (Caldera, McCulp, O'Brien, Truglio, Alvarez, & Huston, 1999). In 9 and 12-year-old children, construction play was significantly related to Water Level tasks and Block Design but not EFT (Robert & Heroux, 2004). It is important to note that two of the studies (Brosnan, 1998; Caldera, McCulp, O'Brien, Truglio, Alvarez, & Huston, 1999) correlating construction ability and spatial ability found that accuracy, rather than preference for construction play, was positively correlated with spatial ability. The other studies only looked at preference of construction play, but did not have a measure to test accuracy in construction ability.
There are a few studies analysing the relationship between construction ability and mathematics. In adolescents, a study analysing the relationship between block building and mathematical performance found that structural balance of a block building activity was correlated to mathematics performance (Casey, Pezaris, & Bassi, 2012). In younger children, a study found that building a model according to instructions was correlated to early maths ability in 3-year-olds (Verdine et al., 2013). Another study on the adaptiveness and complexity of construction play and mathematics performance was conducted by observing and recording construction play with manipulatives (blocks, Lego, carpentry) in a child care program with preschool children 3-4 years of age (Stannard, Wolfgang, Jones, & Phelps, 2001). They found that the correlation between the children’s construction play and mathematics performance was not significant at younger years, but the correlation was significant in grade 7 (12-year-old) and beyond. The researchers suggest this as evidence that construction play in preschool can have long term effects on logico-mathematical knowledge (Stannard, Wolfgang, Jones, & Phelps, 2001). In a subsequent study, researchers looked at the relationship between block construction and reading and mathematical abilities, using Tests of Early Mathematics and Reading Abilities in preschool children (Hanline, Milton, & Phelps, 2012). Children played once a week for 90 minutes and their block constructions were scored according to a 19-point scale based on the complexity and symbolic representational properties of the constructions. They did not find a relationship between block construction and mathematics performance, but with reading performance at 8 years of age (Hanline, Milton, & Phelps, 2012). These findings may be a result of the study focusing on symbolic play, defined by Piaget as transforming objects into make-
believe play through motor or verbal actions (Wolfgang & Phelps, 1983), more than construction play. Both the studies mentioned found a relationship between construction ability and mathematics performance (Stannard, Wolfgang, Jones, & Phelps, 2001) or reading performance (Hanline, Milton, & Phelps, 2012) several years after construction ability was tested. It could be that construction ability develops more complex academic skills that are not tested till later years. Nevertheless, with the time lapse between the observations of construction ability and the measures of academic performance, it is difficult to assess whether the findings relate specifically to construction ability or as a result of general cognitive development, which was not tested. Another study with children (10-year-old) found that spatial ability is uniquely correlated to scientific reasoning, when taking into account verbal and non-verbal intelligence (Mayer, Sodian, Koerber, & Schwippert, 2014). This suggests that spatial ability may be a unique underlying mechanism accounting for individual differences in academic performance.

The only study on construction play and mathematics that accounts for cognitive skills is by Richardson and Richardson (2011) who tested the relationship between Lego construction ability, spatial ability, verbal memory and mathematics performance in 3 groups of children (7-8-year-old, 10-11-year-old, and 13-14-year-old). Lego construction ability was measured using the Lego construction paradigm (Richardson, Jones, & Torrance, 2004) in which eighteen different single coloured Lego construction tasks of progressive difficulty were used (see Methodology section). Instructions were provided on a one page isometric view of the models, that children had to create with Lego blocks, while their construction time was recorded. They found significant correlations between Lego construction time and mathematical performance as well as spatial ability, but not
with verbal memory. They found that in older children (10-11-year-old, and 13-14-year-old) the relationship between construction time and mathematical performance was mediated by spatial ability. Richardson and Richardson (2011) was the only study to date to analyze construction play together with mathematical performance and verbal memory. However, a control task such as linguistic performance, was not included to test whether the observed relationship with mathematics performance was domain general, or specific to Lego construction ability and mathematics development. They tested Digit Span, a measure of verbal memory, however visuospatial memory may be more relevant to construction tasks. In fact, no studies have so far measured visuospatial working memory in relation to construction tasks.

Miyake and colleagues analyzed the relationship between spatial abilities, visuospatial memory, and executive functions. They found that although the results show a higher unique correlation between spatial abilities and executive functions, visuospatial memory accounted for some of the variance found in spatial abilities (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). Taking this as theoretical support, we focused our study on the relationship between visuospatial memory and construction ability.

**Verbal and Visuospatial Memory Models, and Mathematics**

The Baddeley (1986, 2000) memory model describes verbal and visuospatial memory as slave systems, with the central executive as an overarching umbrella term. Verbal memory has been further subdivided into verbal short term memory (STM), defined as simple storage, while verbal working memory (WM) is thought to involve STM as well as controlled attention, which is a domain of executive functions (Miyake,
Friedman, Rettinger, Shah, & Hegarty, 2001). Researchers suggest that the most parsimonious model is the one in which STM is domain specific to verbal or visuospatial domains, while WM is domain general (Alloway, Gathercole, & Pickering, 2006). In contrast, others suggest that visuospatial memory should be divided along characteristics different than that of verbal memory. For example, some suggest that a visual cache stores information about form and color, whereas the inner scribe would store information about movement sequences (Logie & Pearson, 1997). Yet, other models divide visuospatial memory into visual or spatial domains (Pickering, Gathercole, Hall, & Lloyd, 2001; Passolunghi & Mammarella, 2012; Mammarella, Cornoldi, Pazzaglia, Toso, Grimoldi, & Vio, 2006). Visual tasks require recognition of form, shape and color of objects, whereas spatial tasks require the recognition of location, position and configuration of objects, while processing them simultaneously or sequentially (Mammarella, Cornoldi, Pazzaglia, Toso, Grimoldi, & Vio, 2006).

Visuospatial working memory has been correlated with mathematics performance in several studies (Holmes & Adams, 2006; McKenzie, Bull, & Gray, 2003; Passolunghi & Mammarella, 2012; Meyer, Salimpoor, Wu, Geary, & Menon, 2010; Ashkenazi, Rosenberg-Lee, Metcalfe, Swigart, & Menon, 2013). One study analyzed specific visual and spatial memory impairments and mathematics ability (Passolunghi & Mammarella, 2012). The tasks consisted of visual and spatial tasks at both simple and complex levels, and intrusion errors (test of inhibition) were also measured. Children with mathematics learning disability were selectively poorer at spatial tasks, with more intrusion errors, but were not significantly different on visual tasks from typical populations (Passolunghi & Mammarella, 2012). Likewise, children with developmental dyscalculia (diagnosed as
children with poor mathematical performance, with normal IQ and reading performance) were found to have impairments in visuospatial WM, STM and inhibition ability compared to typically developing populations (Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013a). This highlights the relationship between inhibition, visuospatial processing and mathematics performance, in isolation from other memory measures and the executive functions of attention, and task switching (Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013b).

Studies have compared verbal memory and visuospatial memory in relations to mathematics performance. In a study of children (8-9-year-old), only visuospatial working memory, and not verbal working memory, remained significantly correlated with mathematics performance when age-related variance was controlled (Holmes & Adams, 2006). Visuospatial working memory measures predicted unique variance in younger (8-year-old) children’s mathematics performance, but only predicted unique variance in older children (9-year-old) for difficult mathematics questions. The researchers suggest that younger children have a higher dependency on visuospatial working memory than older children, who revert back to visuospatial working memory for more difficult tasks (Holmes & Adams, 2006). In another study, younger children (6-year-old) performed significantly poorer on mathematics tasks during the visuospatial interference, but not the phonological interference. Older children’s (8-year-old) performance was significantly disrupted during the phonological interference, as well as the visuospatial interference, but not to the same extent as the younger children (McKenzie, Bull, & Gray, 2003). This suggests that younger children are more reliant on visuospatial working memory for their mathematics performance than older children. On
the other hand, when verbal STM, WM, and visuospatial memory were compared to WIAT-II numerical operations and mathematical reasoning scores, younger children (7-8-year-old) showed a correlation between verbal STM scores and mathematical reasoning, while older children (8-9-year-old) showed a correlation between visuospatial memory and numerical operations (Meyer, Salimpoor, Wu, Geary, & Menon, 2010). They conclude that younger children are more reliant on verbal processing and then shift to visuospatial processing. It could also be that WIAT-II mathematical reasoning is based on word problems which may be more salient to younger children, than older children who are more proficient readers. The authors (Meyer, Salimpoor, Wu, Geary, & Menon, 2010) suggest that verbal processing may play a larger role in initial learning and performance, while visuospatial processing may facilitate development of mathematics at later stages. In all the studies comparing and contrasting verbal and visuospatial memory, the unique role of visuospatial memory in the development of mathematics has not been disputed. Taking this as evidence, we tested whether visuospatial memory could be the underlying mechanism in the relationship between construction ability and mathematics performance.

**Overview of Current Study**

Construction play is thought to develop logico-mathematical skills, however the underlying mechanisms have not been defined. Studies have found a relationship between performance on construction play and spatial abilities (Caldera, McCulp, O’Brien, Truglio, Alvarez, & Huston, 1999; Connor & Serbin, 1977; Robert & Heroux, 2004) as well as mathematics performance (Richardson & Richardson, 2012; Stannard, Wolfgang,
Jones, & Phelps, 2001). Although there are studies that have factored in cognitive abilities of IQ (Stannard, Wolfgang, Jones, & Phelps, 2001), and verbal memory (Richardson & Richardson, 2011), there is no study that compares construction ability and visuospatial memory. Given the visuospatial processing characteristics inherent in construction ability, it is more relevant to test visuospatial memory than verbal memory as previously done (Richardson & Richardson, 2011). Visuospatial memory has been correlated with spatial abilities (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001) as well as mathematics performance, particularly in younger children (6-8-year-old) (Holmes & Adams, 2006; McKenzie, Bull, & Gray, 2003). With this rationale, we hypothesized that visuospatial memory as the mechanism underlying the relationship between construction play and mathematics performance. Here we operationally tested construction ability in a Lego construction task paradigm (Richardson, Jones, & Torrance, 2004). For the first time in a construction task setting we tested several measures of verbal STM and WM, as well as visuospatial STM and visuospatial WM. We used standardized measures of WIAT-II mathematics and reading performance, as well as standardized measures of memory (AWMA). Reading performance was measured to test whether construction ability is domain specific to mathematics, or a domain general cognitive ability. We also tested general non-verbal intelligence by using Raven’s Coloured Progressive Matrices (CPM). We recruited children 7 years of age. We hypothesized that Lego construction ability (LegoCA) would be correlated with mathematics performance (Hypothesis 1), with visuospatial WM and STM mediating this relationship (Hypothesis 2), and tested this using mediational analysis. We did not expect to find a relationship between LegoCA and verbal WM and STM (Hypothesis 3).
Methodology

Participants

There were 66 participants in total (M= 7.4 years, SD= 3.7 months, 30 females). Ethical approval was provided by the Cambridge Psychology Research Ethics Committee. After the study, children were given gift vouchers and sweets to thank them for participating in our study.

Tests

The Wechsler Individual Achievement Test - Second UK Edition (WIAT-II) numerical operations and reading subtests were used as they are specific to the UK population. The Raven’s Coloured Progressive Matrices (CPM) was used as it is designed for children, and the scores can be standardized. The CPM tests non-verbal abstract reasoning.

Memory Tasks

The Automated Working Memory Assessment-1 (AWMA-1) was used since it consists tests of verbal STM, verbal WM, visuospatial STM and visuospatial WM (corresponding to the phonological loop, visuospatial sketch pad and central executive components of Baddeley and Hitch’s 1974 model of working memory), which are factors of particular interest to this study (Alloway, 2007). Scores were standardized across individuals (M=100, SD =15). The test reliability of the AWMA-1 was between α= 0.69 to α=0.90 when tested across 128 individuals ranging in age from 4-year-old to 23-year-old (Alloway, 2007).
The AWMA-I consisted of four pre-recorded tasks. In Digit Recall (verbal STM) participants had to recall numbers presented aurally. In Listening Recall (verbal WM) participants had to first process whether the sentence was true or false, and then recall the last word of the sentences in the order they were presented. In Dot Matrix (visuospatial STM) participants had to recall the position of a dot in a matrix in the order that it was presented. This task is akin to the simple spatial-sequential task as there is a recall of the order (Passolunghi & Mammarella, 2012). In Odd One Out (visuospatial WM) participants had to identify the odd shape, and then recall the position of the odd shape in the order they were presented. This task is akin to the complex spatial-sequential task as it requires processing of the stimuli followed by recall of the order (Passolunghi & Mammarella, 2012). In all the AWMA-I tests, four correct answers led to the next level, while failing three consecutive answers self-terminated the subtest.

Construction Ability Tasks

To measure Lego construction ability (LegoCA), participants were given Lego pieces and given instructions on building the model. The instructions were displayed on one page, and consisted of exploded isometric models. The highest level of the Lego model constructed accurately was used as the participants’ construction ability score in the data analysis. The instructions for the Lego construction tasks were provided by Miles Richardson (see figure 1 for example). Only one colour was used for each Lego model. Accuracy and construction time was recorded, and a picture of the constructed model was taken.
The Lego construction task paradigm was formulated by Richardson, Jones, and Torrance, (2004). They found that the four construction task variables of 1) symmetrical planes (number of orientations required to find correct placement), 2) novel assemblies (number of unique assemblies), 3) components (number of pieces to create structure), and 4) selections (total number of components to select required components from) were systematically correlated with the time taken to construct the structure. Through regresional analysis, the researchers derived a mathematical formula to model task difficulty:

\[
\text{Task Difficulty} = 10^{(0.020 \text{ components}) + (-0.117 \text{ symmetrical planes}) + (0.047 \text{ novel assemblies}) + (0.028 \text{ selections}) + 1.464}
\]

The task is more difficult with a higher number of novel assemblies, components and selections. The task is easier with a higher number of symmetrical planes since there are fewer restrictions on the orientation of the component.

The Lego construction task paradigm has been validated in adults and children as young as 7 years of age \((\alpha= 0.83)\) through replication studies (Richardson, Jones, Croker,
& Brown, 2011). The construction tasks were made easier than the tasks used by Richardson and Richardson (2011) by not including components other than those required to construct the structure. For example, if a construction task required 4 Lego components, then only 4 Lego components were provided, so that children did not have to choose the correct 4 Lego components out of a selection of 6 Lego components. Using the mathematical model of Richardson and Richardson (2011) the 7 Lego construction tasks were presented in order of task difficulty (see table 1 for example).

<table>
<thead>
<tr>
<th>Model</th>
<th>Components</th>
<th>Symmetrical Planes</th>
<th>Novel Assemblies</th>
<th>Selections</th>
<th>Task Difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>38.55</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.2</td>
<td>1</td>
<td>5</td>
<td>40.79</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2</td>
<td>2</td>
<td>7</td>
<td>45.71</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.8</td>
<td>4</td>
<td>5</td>
<td>48.02</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.8</td>
<td>4</td>
<td>6</td>
<td>53.20</td>
</tr>
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<tr>
<td></td>
<td>8</td>
<td>1</td>
<td>5</td>
<td>8</td>
<td>92.47</td>
</tr>
</tbody>
</table>

Table 1: Lego Models in Order of Task Difficulty (Richardson, Jones, & Torrance, 2004)
The testing session took approximately an hour and a half. All tasks were tested in individual sessions. Children were given breaks between tasks. The tasks were administered in randomised order.

**Statistical Analysis**

The relationship between performance on LegoCA, WM tasks, STM tasks, CPM, and WIAT-II (Reading and Numerical Operations), were tested using Spearman’s ranked correlation, since the Lego task was ranked by level. A mediation analysis was used to test if cognitive abilities mediated the relationship between the performance on LegoCA and WIAT-II numerical operations. Mediation analysis followed the recommendations of Baron, and Kenny (1986) and Preacher, and Hayes (2008) of four steps in the procedure to test for mediation: (1) testing if the relationship between the independent variable and the dependent variable is significant, (2) testing if the relationship between the independent variable and the mediator variable is significant, (3) testing if the relationship between the mediator variable and the dependent variable while controlling for the independent variable is significant, and (4) if the relationship between the independent variable and the dependent variable becomes non-significant after running the analysis, there is a full mediation (Baron & Kenny, 1986; Preacher & Hayes, 2008). The mediation analysis had LegoCA as the independent variable, CPM visuospatial WM and STM as the mediator variables, and WIAT-II numerical operations as the dependent variable. The data was standardized, and so the mediational analysis reports standardized beta values. Since the raw order data consists variables that were not normally distributed, bootstrapping was used to assess the significance of the mediation analysis results as recommended by Preacher and Hayes (2008). For this purpose we used the
SPSS script provided by Hayes (2013). For bootstrapping analysis the data was resampled 5000 times. The outcome of the test can be considered significant if the 95% confidence interval of computed statistics does not include zero. Only the bootstrapping results of tests which fully satisfied the requirements of mediational analysis are presented. All statistical testing was done using SPSS Statistics Version 20.

Results

None of the children could complete the last Lego construction task of the highest task difficulty level, and so there were no ceiling effects. The last Lego construction task was removed from analysis. Maximum level of Lego construction task was used in the data analysis. The recall and processing scores of the Odd-One-Out test were strongly correlated $r = 0.94, p < .001$. Hence, in order to avoid multicollinearity problems they were combined into an average and named Visuospatial WM (VSWM) score. Likewise, the recall and processing scores of the Listening Recall test were strongly correlated $r = 0.94, p < .001$, they were combined into an average and named Verbal WM score.

Descriptive statistics are provided in Table 2. Spearman’s rank correlations between measures are shown in Table 3. WIAT-II numerical operations was significantly correlated with visuospatial STM and WM, CPM, verbal WM and WIAT-II word reading, but not significantly correlated to verbal STM. LegoCA was significantly correlated with WIAT numerical operations, visuospatial WM and STM, and CPM. The correlation between performance on LegoCA and verbal memory scores, and reading scores were not significant.
Table 2: Descriptive Statistics

<table>
<thead>
<tr>
<th>Task</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIAT-II Numerical Operations</td>
<td>111.65</td>
<td>18.48</td>
</tr>
<tr>
<td>Lego Max Level (LegoCA)</td>
<td>4.12</td>
<td>1.22</td>
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<tr>
<td>Visuospatial Working Memory (VSWM)</td>
<td>114.20</td>
<td>11.85</td>
</tr>
<tr>
<td>Dot Matrix (Visuospatial STM)</td>
<td>103.74</td>
<td>15.85</td>
</tr>
<tr>
<td>Verbal Working Memory (Verbal WM)</td>
<td>111.70</td>
<td>13.54</td>
</tr>
<tr>
<td>Digit Recall (Verbal STM)</td>
<td>108.82</td>
<td>11.58</td>
</tr>
<tr>
<td>Raven’s Colored Progressive Matrices (CPM)</td>
<td>104.77</td>
<td>14.56</td>
</tr>
<tr>
<td>WIAT-II Word Reading</td>
<td>112.97</td>
<td>11.51</td>
</tr>
</tbody>
</table>

A mediation analysis was used to test for group mediation, with LegoCA as the independent variable, CPM, visuospatial WM and STM as the mediator variables, and

Table 3: Spearman’s Rho Correlation Matrix for All Variables

<table>
<thead>
<tr>
<th></th>
<th>Numerical Operations</th>
<th>Lego CA</th>
<th>VSWM</th>
<th>Visuospatial STM</th>
<th>vWM</th>
<th>Verbal STM</th>
<th>CPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>LegoCA</td>
<td>Correlation</td>
<td>.298*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>.014</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VSWM</td>
<td>Correlation</td>
<td>.357**</td>
<td>.377**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>.003</td>
<td>.002</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visuospatial STM</td>
<td>Correlation</td>
<td>.373**</td>
<td>.311*</td>
<td>.516**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>.002</td>
<td>.011</td>
<td>.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VWM</td>
<td>Correlation</td>
<td>.250*</td>
<td>.066</td>
<td>.295*</td>
<td>.203</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>.043</td>
<td>.597</td>
<td>.016</td>
<td>.102</td>
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<tr>
<td>Verbal STM</td>
<td>Correlation</td>
<td>.034</td>
<td></td>
<td>.132</td>
<td>.042</td>
<td>.128</td>
<td>.276*</td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>.786</td>
<td>.292</td>
<td>.740</td>
<td>.304</td>
<td>.025</td>
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<tr>
<td>CPM</td>
<td>Correlation</td>
<td>.256*</td>
<td>.265*</td>
<td>.424**</td>
<td>.431**</td>
<td>.148</td>
<td>-.064</td>
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<tr>
<td></td>
<td>p</td>
<td>.038</td>
<td>.031</td>
<td>.000</td>
<td>.000</td>
<td>.235</td>
<td>.608</td>
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<tr>
<td>Word Reading</td>
<td>Correlation</td>
<td>.498**</td>
<td>.066</td>
<td>.026</td>
<td>.108</td>
<td>.409**</td>
<td>.222</td>
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<td>.619</td>
<td>.847</td>
<td>.416</td>
<td>.001</td>
<td>.092</td>
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</table>
WIAT-II numerical operations as the dependent variable. The mediation models are shown in Figure 2.

Figure 2. Mediation Analysis, (A) The mediation analysis model used in all analyses, with the paths labelled (a), (b), (c) and (c'). Path (a) represents the standardized beta coefficient of the direct relationship between the independent variable and the mediator variable(s). Path (b) represents the standardized beta coefficient of the indirect relationship between the mediator variable(s) and the dependent variable, while controlling for the independent variable. Path (c) represents the standardized beta coefficient of the direct relationship between the independent variable and the dependent variable. The notation (c') represents the standardized beta coefficient of the indirect relationship between the independent variable and the dependent variable, while controlling for the mediator variables. (B) Mediation analysis of visuospatial memory and CPM, (C) Mediation analysis of CPM, (D) Mediation analysis of VSWM, (E) Mediation analysis of Visuospatial STM.
Figure 2B presents the results of the mediation analysis of visuospatial memory and CPM. LegoCA was significantly related to the dependent variable WIAT-II numerical operations, thus satisfying the first step of the mediation analysis procedure. LegoCA was significantly related to all three mediators, thus satisfying the second step of the mediation analysis procedure. The mediators were not significantly related to WIAT-II numerical operations when LegoCA was controlled, and so the model does not satisfy the third step of the mediation analysis procedure. These results suggest that there was no group mediation effect in the relationship between LegoCA and WIAT-II numerical operations. CPM, Visuospatial WM and STM, were then analysed individually to test for unique mediation effects.

Figure 2C presents the results of the mediation analysis used to test whether CPM mediated the relationship between LegoCA and WIAT-II numerical operations. LegoCA was significantly related to the dependent variable WIAT-II numerical operations, thus satisfying the first step of the mediation analysis procedure. LegoCA was significantly related to the mediator variable CPM, thus satisfying the second step of the mediation analysis procedure. The mediator CPM was not significantly related to WIAT-II numerical operations when LegoCA was controlled, and so the model does not satisfy the third step of the mediation analysis procedure. These results suggest that CPM does not mediate the relationship between LegoCA and WIAT-II numerical operations.

Figure 2D presents the results of the mediation analysis used to test whether VSWM mediated the relationship between LegoCA and WIAT-II numerical operations. LegoCA was significantly related to the dependent variable WIAT-II numerical operations, thus satisfying the first step of the mediation analysis procedure. LegoCA was significantly related to the dependent variable WIAT-II numerical operations, thus satisfying the first step of the mediation analysis procedure. LegoCA was
significantly related the mediator variable VSWM, thus satisfying the second step of the mediation analysis procedure. The mediator VSWM was significantly related to WIAT-II numerical operations when LegoCA was controlled, satisfying the third step of the mediation analysis procedure. The relationship between LegoCA and WIAT-II numerical operations becomes non-significant when VSWM is controlled, satisfying the fourth step of the mediation analysis procedure. These results suggest full mediation by VSWM between LegoCA and WIAT-II numerical operations. Since not all variables were normally distributed, bootstrapping was used. The confidence interval (.040 to .282) at 95% suggests that these findings are significant.

Figure 2E presents the results of the mediation analysis used to test whether visuospatial STM mediated the relationship between LegoCA and WIAT-II numerical operations. LegoCA was significantly related to the dependent variable WIAT-II numerical operations, thus satisfying the first step of the mediation analysis procedure. LegoCA was significantly related the mediator variable visuospatial STM, thus satisfying the second step of the mediation analysis procedure. The mediator visuospatial STM was significantly related to WIAT-II numerical operations when LegoCA was controlled, satisfying the third step of the mediation analysis procedure. The relationship between LegoCA and WIAT-II numerical operations becomes non-significant when visuospatial STM is controlled, satisfying the fourth step of the mediation analysis procedure. These results suggest full mediation by visuospatial STM between LegoCA and WIAT-II numerical operations. Since not all variables were normally distributed, bootstrapping was used. The confidence interval (.025 to .235) at 95% suggests that these findings are significant.
Discussion

The aim of this study was to assess the relationship between Lego construction ability and mathematics performance, while testing visuospatial memory as a mechanism mediating this relationship. We hypothesized that Lego construction ability would be correlated with mathematics performance (Hypothesis 1), with visuospatial WM and STM mediating this relationship (Hypothesis 2), and tested it using mediational analysis. We did not expect to find a relationship between Lego construction ability and verbal WM and STM (Hypothesis 3).

Lego construction ability was significantly related to, visuospatial memory, CPM and mathematics performance, but not to verbal memory and reading performance. These findings support our Hypothesis 1 and 3. This suggests that Lego construction ability is uniquely correlated with mathematics performance, and not driven by general cognitive ability or intelligence. A mediation analysis was run to account for cognitive abilities in the relationship between Lego construction ability and mathematics performance. The model inclusive of both CPM and visuospatial memory did not find mediation effects. The mediators were then tested individually. We found that the relationship between Lego construction ability and mathematics performance is uniquely mediated by both visuospatial WM and STM, but not CPM. These findings support our Hypothesis 2. This suggests that visuospatial short-term and working memory is the mechanism mediating the relationship between Lego construction ability and mathematics performance. Since the CPM was not a mediating factor, the relationship between Lego construction ability
and mathematics is not explained as a general non-verbal intelligence, but a relationship specifically mediated by visuospatial memory.

There seems to be a disassociation between the relationship of Lego construction ability, visuospatial memory and CPM to mathematics performance and between the relationship of verbal memory and word reading abilities to mathematical performance. Lego construction ability is only correlated to the visuospatial memory and CPM, but not to verbal memory or word reading ability. Several studies analysing the relationship between both verbal and visuospatial memory, mathematics and reading, have found that visuospatial memory is correlated only to mathematics (Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013b; Kyttälä, 2008; Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013a; Passolunghi, Mammarella, & Altoè, 2008). Our data finds the same. Although mathematics and reading performance are correlated, visuospatial measures are only correlated to mathematics performance and not reading performance. This suggests that Lego construction ability is correlated with a unique visuospatial aspect of mathematics that is not transferable to word reading and verbal memory.

Mathematics performance was correlated with word reading, CPM, visuospatial STM and WM, and verbal WM. Mathematics performance was not significantly correlated with verbal STM. A study comparing children in grade 2 (7-8-year-old) and grade 3 children (8-9-year-old) (Meyer, Salimpoor, Wu, Geary, & Menon, 2010), found mathematical reasoning was correlated with verbal WM, and not verbal STM in younger children, but not in older children. The same study, found WIAT-II numerical operations correlated with visuospatial memory only in older children (Meyer, Salimpoor, Wu, Geary, & Menon, 2010). In our study, we found WIAT-II numerical operations correlated
with visuospatial memory measures in 7-year-old children. These conflicting results question the suggestion that younger children rely on verbal processing and then switch to visuospatial processing, with mathematical development. The authors (Meyer, Salimpoor, Wu, Geary, & Menon, 2010) suggest that verbal processing facilitates initial learning, whereas visuospatial processing is involved with long term mathematical development.

Going further, since WM is thought to include STM and controlled attention, future work can test executive functions to theoretically isolate the visuospatial aspects and differentiate it from generalized executive functions. This has been previously done by testing inhibition, attention and task switching (Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013b), intrusion tasks (Passolunghi & Mammarella, 2012), and a latent variable approach comparing STM, WM and fluid intelligence (Engle, Tuholski, Laughlin, & Conway, 1999). Such a study would allow us to further differentiate whether Lego construction ability is uniquely correlated to visuospatial memory, or generalized executive functions.

Intervention studies have found training with manipulatives improves performance in visuospatial memory. A study compared musical training and mental abacus training on verbal WM and STM, and spatial simultaneous and spatial sequential at simple and complex levels (Lee, Lu, & Ko, 2007). Children (12-year-old) with mental abacus training showed improved performance on spatial tasks compared to the control group, while children with musical training showed improved performance on both verbal and spatial tasks (Lee, Lu, & Ko, 2007). Another intervention study with children (9-10-year-old), has shown that it is possible to improve visuospatial memory through
training of spatial sequential tasks (Caviola, Mammarella, Cornoldi, & Lucangeli, 2009). The intervention was presented as a game where a protagonist carried out several spatial sequential tasks. Teachers discussed strategies of coding and analyzing the stimuli, creating chunks of visuospatial stimuli and using mental images, followed by a discussion on recognizing the best strategy to use. The intervention group showed marked improvement on spatial sequential tasks, while spatial simultaneous tasks and verbal memory remained comparable to the control group (Caviola, Mammarella, Cornoldi, & Lucangeli, 2009). The Lego construction task paradigm and isometric model instructions require the usage of similar strategies of coding and analysing the components to build Lego construction models with increasing task difficulty, and may be a valuable intervention tool to fine tune visuospatial memory.

Visuospatial memory is correlated with mathematics performance, particularly in younger children 6-year-old (Holmes & Adams, 2006) to 8-year-old (McKenzie, Bull, & Gray, 2003). Children begin to rely on verbal working memory and revert back to visuospatial memory for more difficult mathematics questions (Holmes & Adams, 2006). A reason for this development may be the educational system that enforces verbal memory above and beyond visuospatial memory. There is a paucity of research on visuospatial memory in comparison with verbal memory. Studies do show a unique correlation between visuospatial memory and mathematics, and that children with mathematics learning disabilities and developmental dyscalculia have visuospatial memory impairments (Passolunghi & Mammarella, 2012; Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013b). Previous research has shown that visuospatial memory can be specifically trained (Caviola, Mammarella, Cornoldi, & Lucangeli, 2009; Lee, Lu, & Ko,
These findings highlight educational implications for using intervention tools for children with visuospatial memory impairments, which are correlated with mathematics performance. The results from this study suggest that the relationship between mathematics performance and Lego construction ability is uniquely mediated by visuospatial memory. The benefit of using the Lego construction paradigm (Richardson, Jones, & Torrance, 2004) as an intervention tool is that the task difficulty can be systematically increased in increments. This raises the possibility that Lego construction tasks may be used to facilitate visuospatial memory, and thus the development of mathematical performance. Future work with an intervention study will be required to test this hypothesis.

In conclusion we found that Lego construction play is strongly related to mathematical performance in primary school children and this relationship is mediated by visuospatial memory. Our results raise the possibility that construction play may be effectively used to train and strengthen mathematical skill in young children and future studies can investigate using construction play for the remediation of specific mathematical learning difficulties, like developmental dyscalculia.
References


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