International Journal of Developmental Science 9 (2015) 95–114
DOI 10.3233/DEV-14154
IOS Press

Keeping It in Three Dimensions: Measuring the Development of Mental Rotation in Children with the Rotated Colour Cube Test (RCCT)

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Abstract
This study introduces the new Rotated Colour Cube Test (RCCT) as a measure of object identification and mental rotation using single 3D colour cube images in a matching-to-sample procedure. One hundred 7- to 11-year-old children were tested with aligned or rotated cube models, distracters and targets. While different orientations of distracters made the RCCT more difficult, different colours of distracters had the opposite effect and made the RCCT easier because colour facilitated clearer discrimination between target and distracters. Ten-year-olds performed significantly better than 7- to 8-year-olds. The RCCT significantly correlated with children's performance on the Raven's Coloured Progressive Matrices Test (RCPM) presumably due to the shared multiple-choice format, but the RCCT was easier, as it did not require sequencing. Children from families with a high socio-economic status performed best on both tests, with boys outperforming girls on the more difficult RCCT test sections.

Keywords
Development of mental rotation, perceptual matching, 3D, task difficulty, colour salience, measurement

Mental rotation is the psychological process of spatially changing an object's orientation in the mind (Shepard & Metzler, 1971). This ability was a crucial landmark in the imagery debate in cognitive psychology (Kosslyn, 1996; Kosslyn, Ganis, & Thompson, 2006; Pylyshyn, 1977, 2003) as it demonstrated that people form mental images in their minds rather than just following a verbal command script. In developmental psychology, Piaget and Inhelder (1956, 1971) had acknowledged the role of imagery much earlier. They proposed that children would not be able to demonstrate dynamic imagery before reaching the concrete-operational stage at about age seven. However, studies have found that young children could mentally rotate (Kosslyn, Margolis, Barrett, Goldknopf, & Daly, 1990) albeit at a much slower rate than adults (Frick, Hansen, & Newcombe, 2013; Frick & Möhring, 2013; Krüger, Kaiser, Mahler, Bartels, & Krist, 2013; Marmor, 1975, 1977; Schwarzer, Freitag, Buckel, & Lofruthe, 2012).

A common approach to adapting Shepard and Metzler's (1971) complex three dimensional cube aggregates for use with school children is through a reduction in dimensionality and by changing item characteristics, for instance, either 2D animal pictures (Quaiser-Pohl, 2003) or letters (Kosslyn et al., 1990). The current study investigates whether this omission of the third dimension is necessary and offers a new test where complexity was reduced, but without resorting to two-dimensional object images. We designed the Rotated Colour Cube Test (RCCT) in an effort to reduce task complexity without sacrificing the three dimensions: We simplified the Shepard and Metzler's classic cube aggregates to one single coloured 3D cube.

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ISSN 2192-001X/15/$35.00

The Mental Rotation Test

In Shepard and Metzler's (1971) pioneering work, participants were presented with pairs of perspective drawings of 3D cube aggregates and asked to identify whether the second image was either the same or a mirror image. They found a linear relationship between reaction time and the degree of rotation, similar to that found when physically rotating objects – a small rotation of an object takes less time than a large rotation. This suggested that mental image transformations correspond to transformations in the real world (Shepard & Cooper, 1982).

Vandenberg and Kuse (1978) used these black-and-white 3D cube aggregates to produce the Mental Rotation Test (MRT) with a response format that consisted of two targets and two distracters. Participants had to identify two structurally identical, but differently rotated cube aggregates from a multiple-choice selection of four cube aggregates. This test format has become widely applied in research with adults (Geiser, Lehmann, & Eid, 2008; Peters, 2005; Peters et al., 1995; Peters, Manning, & Reimers, 2007; Voyer & Saunders, 2004).

Differences in the characteristics of stimuli, such as using animate objects instead of cubes facilitated mental rotation in women and children (Alexander & Evardone, 2008; Neuburger, Jansen, Heil, & Quaiser-Pohl, 2011; Rosser, Ensing, & Mazzeo, 1985). This indicates that a key difficulty may be related to stimulus identification and encoding (Bialystok, 1989). Mental rotation of an object's encoded image (Jolicoeur, 1988; Moreau, 2012) may be either matched with a more abstract, structural representation (Hyde, 1981), or directly compared with the nearest and most similar stored view (Hedges & Nowell, 1981). Hence, the initial two sections of our new test assessed perceptual matching of model and target as a baseline ability for mental rotation; only thereafter were the model and target cube differently rotated.

A further facilitating factor in mental rotation performance is colour information (Alington, Leaf, & Monaghan, 1992). Since colour is one of the fundamental properties of an object, it might be perceived pre-attentively like other features such as line orientation (Enns & Rensink, 1991; Treisman, 1986) and may therefore provide less able participants with an additional 'processing channel'. Children are especially sensitive to colour signals in early stages of retinal perception, whereas size and orientation features are processed in later processing stages (Donnelly et al., 2007). Hence, as in the coloured version of the Raven's Standard Progressive Matrices Test for children, we used coloured cube images. However, we gradually reduced the relevance of colour differences as a helpful cue in each section. The rationale behind this approach was similar to a visual search task where increased colour similarities resulted in a reduction of feature uniqueness between target and distracters (Gerhardstein & Rovee-Collier, 2002; Treisman, 1988; Treisman & Gelade, 1980).

Developmental Differences in Mental Rotation

Mental rotation is correlated with academic success in topics such as geometry, mathematics, and chemistry (Harris, Hirsh-Pasek, & Newcombe, 2013; Hyde & Linn, 1986). Piaget and Inhelder assumed that children in the preoperational stage until about age seven would only use static imagery. In particular, young children would not understand how changing an object's direction also changes its features in a coordinated way (dynamic imagery) (Piaget & Inhelder, 1971, p. 120). However, subsequent research demonstrated that this widely accepted assumption was incorrect and underestimated young children's ability to process rotated objects. The ability to mentally rotate develops in infancy (e.g. Moore & Johnson, 2008, 2011; Quinn & Liben, 2008) and during early childhood, and continues to do so into adolescence (e.g. Kail, 1986; Kosslyn et al., 1990).

Marmor (1975) showed that 5-year-old children were able to rotate the original cube aggregates (Shepard & Metzler, 1971) and found a similar linear increase in reaction time related to angular disparity. Likewise, in a forced choice paradigm study of rotated 2D object shapes, 4- and 5-year-old's accuracy decreased with the angle of the rotation, but 3-year-old's accuracy did not (Frick, Hansen, et al., 2013). However, in a different study, 3-year-olds demonstrated the ability to rotate a 2D object although at very slow speeds of 2,500 ms, increasing up to 3,000 ms at larger angles (Krüger et al., 2013; see also Kosslyn et al. 1990). In a Tetris game with dynamic 2D rotated shapes, error rates of 4- and 5-year-olds did not suggest mental rotation ability, but 5-year-olds' response times increased with greater rotation from 2,200 ms to 3,200 ms (Frick, Ferrara, & Newcombe, 2013). Interestingly, these reaction time studies demonstrated a transition from static to dynamic imagery in very young children already in terms of speed and not just accuracy.

Moreover, recently Schwarzer et al. (2012) used the original Shepard and Metzler cube aggregates in a dynamic video film with 9-months-old infants. Importantly for the assumption that mental rotation mirrors motoric real-life object rotation, the results suggested an active motor component insofar as the more mobile crawlers looked longer at the mirror image of cube aggregates in a habituation task than static infants who could only sit. When using simpler letter stimuli, the motor component was found to be important in a linear fashion in 8- to 10-month-olds, with walkers being more likely to distinguish impossible letter rotation outcomes compared to crawlers, belly crawlers, and sitting infants, respectively (Frick & Möhring, 2013). If manual exploration was permitted, even 6-month-olds showed increased looking time for impossible rotations in a habituation experiment (Möhring & Frick, 2013). This motoric component was also found in adults who were low performers in the Vandenberg and Kuse (1978) test (redrawn version of Peters et al., 1995) as they would gesture more in their explanations regarding differences in the structure of a wooden 3D model of Shepard and Metzler's cube aggregates (Göksun, Goldin-Meadow, Newcombe, & Shipley, 2013).

Individual Differences in Mental Rotation

Gender differences in mental rotation are widely reported (Linn & Petersen, 1985). In a meta-analysis by Voyer, Voyer, and Bryden (1995), men outperformed women on the MRT by nearly one standard deviation. Other research suggests that gender differences on the MRT tended to disappear with practice in computer games (Haier et al., 1992; Okagaki & Frensch, 1994), through sports activities (Blüchel, Lehmann, Kellner, & Jansen, 2012; Quaiser-Pohl & Lehmann, 2002), by lifting time constraints (Goldstein, Haldane, & Mitchell, 1990; Peters, 2005; Voyer, 2011) and with extensive item-specific practice (Kail, 1986; Kass, Ahlers, & Dugger, 1998), as well as 2D-3D dimensional transformation training (Moreau, 2012; Tzuriel & Egozi, 2007, 2010). Hence many factors influence gender differences in mental rotation performance. We expected that in the current study, gender differences would not show as a main effect because the many trials in the test would give girls sufficient practice with the rotated items and reaction times were not measured.

Socio-economic status (SES) is another variable that influences cognitive development. Children with low SES can fall behind on very early measures of cognitive development such as the Bayley Infant Behaviour Scales (Farah, 2010), school readiness tests (Brooks-Gunn & Duncan, 1997) and executive attention (Mezzacappa, 2004). SES, especially in boys, has been identified as an important factor in influencing spatial cognition and the development of visuo-spatial memory (Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005). Whereas girls and boys with a low SES showed no difference in performance on measures of aerial maps and mental rotation ability, boys from families with middle- and high-SES performed better (Levine et al., 2005). We controlled SES in the current sample of children by considering whether the London council, or their parents, paid for their school meals and included this factor in the statistical analyses. We expected that especially boys from lower SES backgrounds would not perform as well as boys from families that were able to pay for their children's school meals.

Training Studies and Dimensionality in Mental Rotation

Kail (Kail, 1986; Kail & Park, 1990) indicated that with extensive practice children could reach adult levels of performance on mental rotation tasks, but the training effect was limited to item-specific features of just one object, with no transfer of the practice effect to other objects. This suggested that children stored unique view-specific images of an object without developing an abstract ability to rotate. It is likely that the mental rotation task can be solved with the storage of visual snapshots, similar to visual priming in children (Lange-Küttner, 2010b; Enns & Cameron, 1987). Recent studies on practice and training of mental rotation have focused on dimensionality of the object, in particular on the 2D versus 3D task difficulty (Tzuriel & Egozi, 2007, 2010). The visual information processing system finds 2D stimuli easier to process than 3D (Jansen, Schmelter, Quaiser-Pohl, Neuburger, & Heil, 2013) and this difference appeared to increase with age (Hoyek et al., 2012). This may be the case because degree of rotation is less influential in two dimensions (Bauer & Jolicoeur, 1996; Jolicoeur, Regehr, Smith, & Smith, 1985). Hoyek et al. (2012) found no correlation between 2D stimuli and 3D cubes in 7- to 8-year-olds, which supports the notion of dimension-specific processing.

Two-dimensional stimuli are not really realistic, but flat. However, children favour 3D pictures, become progressively more interested in depth depiction and develop their ability to represent three dimensions in their own graphic constructions (Kosslyn, Heldmeyer, & Locklear, 1980; Lange-Küttner, 1994, 2004, 2009). Girls preferred to unfold cube faces and drew large amounts of surface detail that could distort the overall view of the cube, whereas boys appeared to favour keeping a cube's visual appearance intact (Lange-Küttner & Ebersbach, 2012). Children of kindergarten age were already able to estimate the volume of 3D cubes (Ebersbach, 2009). Hence, it is both appropriate and beneficial to measure young children's mental rotation ability in a test with three-dimensional cube images.

What is the particular difficulty when processing three-dimensional stimuli? 2D perception requires the processing of stimuli only within a single plane based on straightforward similarity judgements, whereas three-dimensional perception requires more complex spatial inferences about visually incomplete, hidden-from-view information, where object features have to be interpolated. Superior 2D-3D "dimensionality crossing" (spatial transformations) was identified in males who outperformed women on most mental rotation tasks (Voyer et al., 1995); especially the occluded parts of the cube aggregates were more difficult to process for women (Voyer & Hou, 2006). However, training in 2D-3D spatial transformations successfully improved girls' performance (Tzuriel & Egozi, 2007, 2010). In adults, 2D training led only to improvements in 2D tasks, whereas 3D training led to improvements in both 2D and 3D tasks (Moreau, 2012). This clearly demonstrates the importance and specificity of dimensionality in the mental rotation task.

The Current Study

A widely used approach for studying children's mental rotation ability is the reduction of cognitive load through the simplification of stimulus complexity. For instance, outline drawings of human figures provided children with an apparently more simple and socially more suitable test items compared to the classic complex geometric cube aggregates (Estes, 1998). However, when mental rotation performance was measured in terms of increases in reaction time along with angular discrepancy, only 6-year-olds performed similar to adults, while 4-year-olds did not. Moreover, when a hand was used as a mental rotation stimulus this produced an increase in reaction times from about 3,100 ms to nearly 5,000 ms in 5- to 6-year-old children who did not yet attend school, and from about 2,000 ms to nearly 3,500 ms in 7-year-old first graders (Krüger & Krist, 2009).

Nevertheless, bodies instead of cube aggregates support women's mental rotation ability (Alexander & Evardone, 2008). Interestingly, a hybrid between cube aggregates and human heads, hands and feet also lowered the cognitive load for adults in comparison to the classic cube aggregates, but only when the body parts were orderly attached and not when they were randomly fixed onto the ends of the aggregates (Krüger, Amorim, & Ebersbach, 2014). Quaiser-Pohl, Neuburger, Heil, Jansen, and Schmelter (2014) found that measuring mental rotation ability with cube aggregates and time limits was too difficult for second graders (6- to 9-year-olds) but not for fourth graders (8- to 12-year-olds).

Our aim was to keep the 3D cubes similar to the original stimuli of Shepard and Metzler (1971), but to test children in the multiple choice test format used by Vandenberg and Kuse (1978). We designed the Rotated Colour Cube Test (RCCT) with one single multi-coloured three-dimensional cube and thus simplified the complexity of the geometric cube aggregates (Vandenberg & Kuse, 1978), but not their three-dimensional volume. Similar facilitations were effective in the Three-Mountains-Task that measures the ability to form spatial perspectives when three overlapping mountains (Piaget & Inhelder, 1956) were reduced to a single clearly visible mountain (Liben & Belknap, 1981).

First, we gradually increased task difficulty by varying the rotation of the model cube from an upright canonical position to balancing it on one of its corners without rotating the target and distracters. Thereafter, differences in rotation and colour between the model, target and distracters were gradually introduced. The initial two test Sections (A & B) investigated whether young children could identify test cube items from distracters by simple perceptual matching. Only thereafter were they asked to process rotated cubes in Sections (C &D) (see Fig. 1). We expected children to perform better on simple perceptual matching tasks than in the identification of rotated cubes, and both age and gender differences to appear with increasing task difficulty.

Second, we tested 7- to 10-year-old children as research suggests that differences in mental rotation emerge in this age range (Geiser, Lehmann, Corth, & Eid, 2008; Geiser et al., 2008; Johnson & Meade, 1987; Titze, Jansen, & Heil, 2010; Vederhus & Krekling, 1996). As both time limits (Glück & Fabrizii, 2010; Voyer et al., 1995) and response format (Glück & Fabrizii, 2010) influence mental rotation performance, we removed time

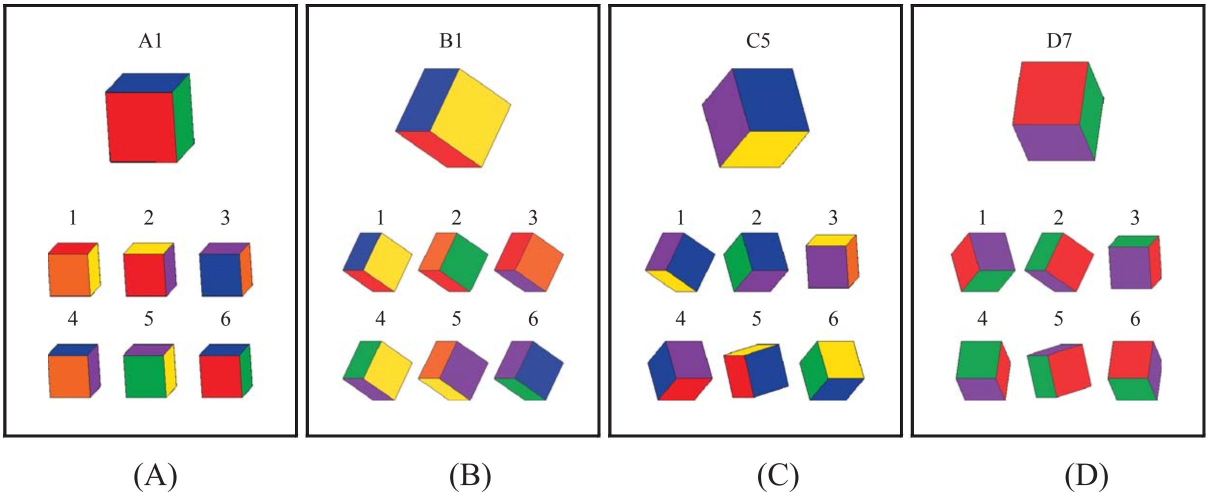


Fig. 1. Examples of Task Sheets. *RCCT A*: differently coloured cubes identical in orientation (the correct test cube is on lower row furthest to the right). *RCCT B:* differently coloured cubes identical in orientation, but in a non-canonical view (correct cube is in the upper row, furthest to the left). *RCCT C*: rotational variance between distracter cubes (the correct cube is in the upper row, furthest to the left). *RCCT D:* rotational variance between distracter cubes, but all cubes have the same colours (the correct cube is in the lower row in the middle).

restrictions and used the same response configuration as in the Raven Coloured Progressive Matrices Test (RCPM), which requires participants to identify one target from six to eight distracters.

Third, we also tested children with the RCPM as it is a standardized test used to measure non-verbal reasoning. For children, the RCPM is one of the purest measures of fluid intelligence. The RCPM first appeared in 1947 as a specialized form of the Raven's Standard Progressive Matrices Test, specifically created for testing 5- to 10-year old children. In a meta-analysis by Vijver (1997) of cross-cultural intelligence test scores, the RCPM was the second most used test after the Wechsler Intelligence Scales for children. The aim was to control children's fluid intelligence, but also to compare the two non-verbal tests with each other for shared variance.

The general assumption is that there are no gender differences in the RCPM scores. This inference was first made by Raven (1939, p. 30) who noted that in the standardization sample, there were no gender difference between boys and girls up to the age of 14 years, both in the mean and the variance of scores. Eysenck and Kamin (1981, p. 41) also noted equal scores between the two genders for children and adults. Jensen (1998, p. 541) concluded that there was no consistent discrepancy between female and male scores in the Raven's Standard or Coloured Progressive Matrices Tests. Court's (1983) literature review which summarized 118 studies confirmed that no gender differences in performance were found, and this was confirmed for children by Lynn and Irwing (2004). Hence, in the current study, the RCPM provided an important objective measurement instrument.

Method

Participants

Participants ($N = 100$) were 51 boys and 49 girls from a school in West London. The majority of the children were black British. Parental consent was obtained and children were informed that they were free to withdraw from the study at any time they wished. There were

Table 1
Participant Numbers, Mean and Standard Deviation of Age Groups

	Free School Meals (FSM)						
	Boys			*Girls*			Total SES
Age groups	n	*M*	*SD*	n	*M*	*SD*	
7-8 years	8	7;5	0;5	9	7;5	0;3	17
9 years	11	8;2	0;3	5	8;4	0;5	16
10 years	6	9;9	0;5	8	9;5	0;5	14
FSM by Gender	25			22			47
	Parent-Financed School Meals (PSM)						
7-8 years	7	7;5	0;3	5	7;5	0;4	13
9 years	8	8;5	0;3	13	8;5	0;4	21
10 years	11	10;0	0;5	9	9;8	0;6	20
PSM by Gender	26			27			53
Total Gender	51			49			100

Table 2
RCPM Scores (in %) by Socio-Economic Status, Age Group and Gender

Age groups Gender	Socio-economic Status					
	Free School Meal		Parent-financed School Meal			
	M	*SD*	*M*	*SD*	*t*	*P*
7-8 years	61.44	15.21	70.83	14.96	–1.649	0.111
Girls	62.04	14.16	77.78	16.55	–1.881	0.084
Boys	60.76	17.28	65.87	12.60	–0.645	0.530
9 years	**58.68**	**15.28**	**73.81**	**13.74**	**–3.162**	**0.003****
Girls	60.00	15.91	70.94	14.37	–1.407	0.178
Boys	**58.08**	**15.74**	**78.47**	**12.04**	**–3.062**	**0.007****
10 years	**71.03**	**13.02**	**81.39**	**13.09**	**–2.275**	**0.030***
Girls	70.49	14.08	74.38	12.71	–0.600	0.558
Boys	**71.76**	**12.72**	**87.12**	**10.78**	**–2.641**	**0.019***

Note. $^{*}p < 0.05$. $^{**}p < 0.01$. Statistical effects set in bold were significant.

$n = 47$ children on free school meals, and $n = 53$ children on parent financed school meals, with a total sample of $N = 100$ children, age means are listed in Table 1. This variable was used as a between-subjects variable of socio-economic status (SES) in addition to gender.

In order to test whether fluid intelligence was dependent on socio-economic status, we carried out *t*-tests on RCPM scores (see Table 2). Only boys in the two older age groups differed significantly in fluid intelligence, with better scores in the parent-financed school meal groups for the 9-year-old and the 10-year-old group. We therefore controlled the analysis of the mental rotation test by gender, age and whether school meals were free or paid for by parents (SES). We did not partial out the RCPM scores because fluid intelligence is an essential part of the mental rotation task. Instead, in a second step, we analysed the correlations between RCCT and RCPM in order to validate the new test on mental rotation.

Apparatus and Material

Rotated Colour Cube Test (RCCT). The RCCT is a non-verbal task with 3D images of coloured cubes which were digitally produced with Adobe Illustrator. Three cube faces are visible at all times with each face showing one of six distinct colours (i.e. yellow, orange, red, green, blue, and purple). In the following paragraphs, the rationale for including different types of sections is explained.

There were 32 pages with four sections and thus eight trials in each section. Task difficulty was gradually increased through improved distracter and target colour similarity (see Table A1 in the Appendix). The prediction was that increases in similarity between target and distracter cubes should add to task difficulty because this produces a loss of perceptual discriminability (Gerhardstein & Rovee-Collier, 2002; Treisman, 1988; Treisman & Gelade, 1980).

The RCCT is composed of a sequence of four Sections A, B, C, and D that increased in complexity (see Fig. 1). In **RCCT A**, target and distracter cubes are displayed in the canonical perspective, as if standing on a flat surface. In **RCCT B**, target and distracter cubes are displayed standing in a less familiar position on one corner. In **RCCT C**, target and distracter cubes are initially presented in identical orientation in Levels I and II, and thereafter in different orientations in Levels III and IV (see Table A1 in the Appendix, first column to the left). **RCCT D** is the same as **RCCT C**, but all distracter cubes are now identical in colour.

Each Section had four trials with two levels of distracter numbers, that is, first six, then eight distracters. Trials gradually increased in difficulty through colour congruency by having distracters with one, two or three colours in common with the target cube. Only Section D had distracters with all three colours identical with the target.

Gradually increasing task difficulty over the four RCCT Test Sections (A-D) provided the framework for testing object identification and object rotation. In Sections A and B, we changed target orientation from a canonical cube view (RCCT A) to that of a more unusual view of a cube balanced on a corner (RCCT B), because children prefer objects in a view that is functional (Davis, 1985). For instance, children draw a car from the side and a house from the front because this is where they enter. They would find a cube sitting flat on the ground more familiar than a cube balancing on one corner, and hence probably easier.

The following two test Sections (RCCT C-D) measure more complex perceptual matching ability where distracters no longer have a uniform orientation, that is, the target as well as the distracter cubes vary in orientation. In Section C, colour similarity of the distracters was gradually increased (see Table A1 in the Appendix), but in Section D the target and the distracter cubes were similar in colour in all trials. In these two sections the model and the target cube had different orientations in Levels III and IV.

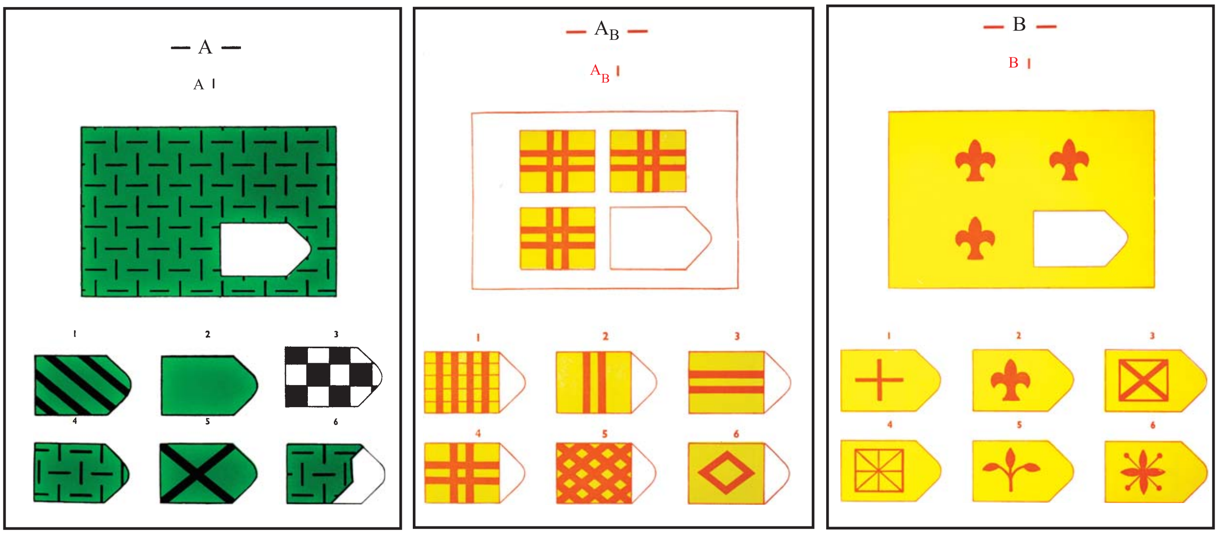
Task booklet. A booklet with 36 A4 sized pages that all followed the same layout was used for testing. Each page showed one enlarged model cube on the top and two rows of up to eight smaller cubes below (see Fig. 1). The first four pages of the booklet were for practice only, with one example from each category (A, B, C and D). The task was to identify verbally and/or through pointing which of the cubes was identical to the target cube on top of the page.

Procedure

Children were individually tested in a quiet, familiar setting at their school. They were allowed to choose a sticker as a reward after completing the task. Answers were recorded by the researcher on a test response sheet during the session. Scores were added up by two researchers independently. No disagreement was found.

Task instructions. In the warm-up phase children were asked, "Do you want to play a game?" and were then shown a physical model of a coloured cube and asked, "Do you know what this is?" All children responded positively with the answer 'This is a cube' or 'This is a dice'. Thereafter, children first solved four practice trials in which the experimenter pointed at the enlarged target cube and asked the participant, "Which cube is the same as this one?"

After the participant had correctly answered the first two practice questions identifying the same cube as the target cube, the child was then tested with two practice questions that involved mental rotation. At this point, the researcher showed a physical cube model, turned it slightly and said, "These sides are turned". The researcher then pointed towards the 3D cube illustrations on the cube panel. The practice questions were repeated until the child could identify the correct cube image. Children then proceeded to the task proper. Initially we considered adding a fold-out cube in the upper right corner of each page, but this proved to be too difficult. In a pilot study to the current investigation with another sample of 52 children (Lütke, 2009) we had decided to omit the illustration of the fold-out cube, because only one child asked the instructor what colours were one the hidden side of the cube and hence it was not a pertinent question, especially after our hands-on introduction.



(A) (AB) (B)

Fig. 2. Examples of Task Sheets. *A*: Identification of a patch in a continuous pattern (correct item is on lower row furthest to the left). *AB:* Identification of a patch of a discrete pattern (correct item is lower row furthest to the left). *B:* Identification of a patch in a continuous pattern with discrete items (correct item is upper row in the middle).

Raven's Coloured Progressive Matrices Test (RCPM). The nonverbal RCPM is designed to measure the ability to reason by analogy and to form perceptual relations similar as in Spearman's *g*. The RCPM is made up of a sequence of three Sections (i.e. A, AB, B; see the examples in Fig. 2). Pattern fragments require integration into a larger systematic context (Raven & Court, 1998). The RCPM consists of 36 such individual matching-to-sample tests. Each page depicts a task that offers a context with a fragment left blank in the bottom right corner of the pattern. A 2 by 3 matrix of fragment below shows one target and five distracter fragments. Participants are required to find the fragment from this set of six alternatives that best completes the pattern.

Results

Accurate performance was computed in per cent for each section of the Rotated Colour Cube Test (RCCT) and the Raven Coloured Progressive Matrices Test (RCPM). In cases where the Mauchley's test of Sphericity was violated, we adjusted the degrees of freedom with Greenhouse-Geisser. Statistically significant effects were followed up with *post-hoc* tests. In the first part of the Results section, we report individual and age differences in the RCCT, in the second part we report individual and age differences on the RCPM, and in the third part we report the comparison of the RCCT and the RCPM overall scores.

Rotated Colour Cube Test (RCCT). A 4 (Sections) by 3 (Age) by 2 (Gender) by 2 (School meal type, FSM) MANOVA was carried out, with repeated measurement for the RCCT Sections. Group means are listed in Table 3 and the statistical effects in Table 4. There was a significant main effect for the RCCT Sections, $F(2.23, 195.96) = 330.56$, $p < 0.001$, $\eta^2 = 0.79$, with a very large effect size. Pairwise *post-hoc* comparisons ($p_s < 0.001$, two-tailed) confirmed that simple perceptual matching in RCCT A ($M = 93.6\%$) and RCCT B ($M = 91.9\%$) differed significantly from identification of the more difficult rotated targets in RCCT C ($M = 83.5\%$) and RCCT D ($M = 48.7\%$), but not from each other. This seemed to show that the step from a canonical orientation in RCCT A to a more unusual position, balanced on

Table 3
RCCT Scores by Age Group and Gender (Accuracy in %)

Gender	7-8 years	9 years	10 years	Total
		Section A		
		Free School Meals		
Girls	88.89 (17.05)	95.00 (6.85)	93.75 (9.45)	92.05 (12.53)
Boys	85.94 (18.22)	89.77 (9.39)	93.75 (6.85)	89.50 (12.33)
		Parent-financed School Meals		
Girls	97.50 (5.59)	94.23 (8.25)	95.83 (6.25)	95.37 (7.06)
Boys	92.86 (9.83)	96.88 (5.79)	98.86 (3.77)	96.63 (6.67)
		Section B		
		Free School Meals		
Girls	81.94 (18.87)	95.00 (6.85)	89.06 (10.43)	87.50 (14.43)
Boys	92.19 (13.26)	87.50 (14.79)	93.75 (10.46)	90.50 (13.15)
		Parent-financed School Meals		
Girls	92.50 (6.85)	89.42 (10.01)	93.06 (6.59)	91.20 (8.36)
Boys	91.07 (6.10)	96.88 (5.79)	100.00 (0.00)	96.64 (5.65)
		Section C		
		Free School Meals		
Girls	79.17 (6.25)	80.00 (6.85)	82.81 (9.30)	80.67 (7.45)
Boys	78.13 (11.08)	82.95 (14.00)	87.50 (13.69)	82.50 (13.01)
		Parent-financed School Meals		
Girls	77.50 (5.59)	83.65 (15.63)	87.50 (00)	83.80 (11.40)
Boys	80.36 (9.84)	93.75 (6.68)	88.64 (8.76)	87.98 (9.67)
		Section D		
		Free School Meals		
Girls	44.44 (21.75)	57.50 (11.18)	45.31 (22.10)	47.73 (19.91)
Boys	39.06 (21.59)	40.91 (19.44)	41.67 (15.14)	40.50 (18.50)
		Parent-financed School Meals		
Girls	40.00 (16.30)	47.12 (15.44)	44.44 (12.67)	44.91 (14.40)
Boys	46.43 (15.67)	65.63 (19.76)	71.59 (19.44)	62.98 (20.76)

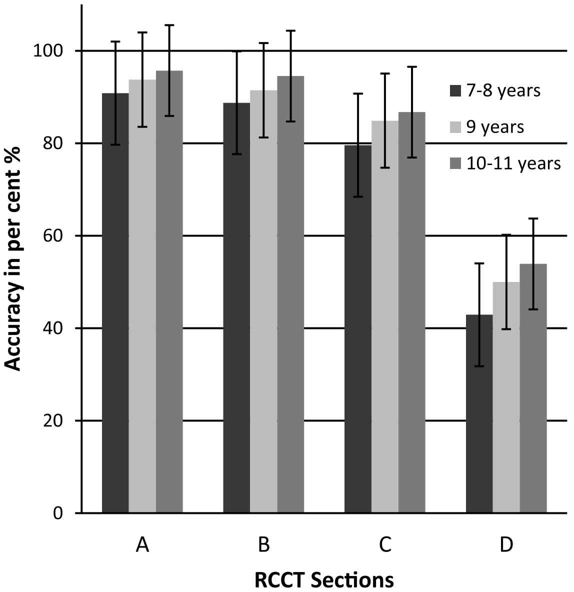


Fig. 3. Increases in performance across RCCT Sections per age group.

one corner in RCCT B did not increase task difficulty for children. In contrast, the introduction of individually rotated model and distracter cubes in the test panel in Section C led to a decrease in performance of about 10%, and the removal of distinctive and unique cube colours in Section D led to an even more pronounced drop from about 80% to 40% (see Fig. 3).

Furthermore, there were two significant main effects for FSM, $F(1, 88) = 8.01$, $p < 0.01$, $\eta^2 = 0.08$, and age groups, $F(2, 88) = 4.73$, $p < 0.05$, $\eta^2 = 0.10$. Children with free school meals ($M = 76.9\%$) performed overall significantly worse than children with parent financed school meals ($M = 81.9\%$). Multiple comparisons of age differences showed that 7- to 8-year-old children ($M = 75.5\%$), differed from 10-year-olds ($M = 81.7\%$), but no other comparison was significant.

There was also a significant two-way interaction of gender and FSM, $F(1,88) = 5.58$, $p < 0.05$, $\eta^2 = 0.06$, and these factors interacted significantly in a three-way interaction with the RCCT Sections, $F(2.23, 195.96) = 6.47$, $p < 0.01$, $\eta^2 = 0.07$. To investigate the three-way interaction between RCCT Sections, gender and FSM, the MANOVA was re-run with a split sample analysis for SES in order to consider how boys and girls from different SES differed in their performance on individual RCCT Sections.

In the state-funded free school meal group, there were neither gender differences, $p_s > 0.61$, nor age differences, $p_s > 0.34$ in performance. But when parents were able to pay for school meals, boys ($M = 85.2\%$) outperformed girls ($M = 78.9$ %) and this difference was highly significant, $F(1, 47) = 14.27$, $p < 0.001$,

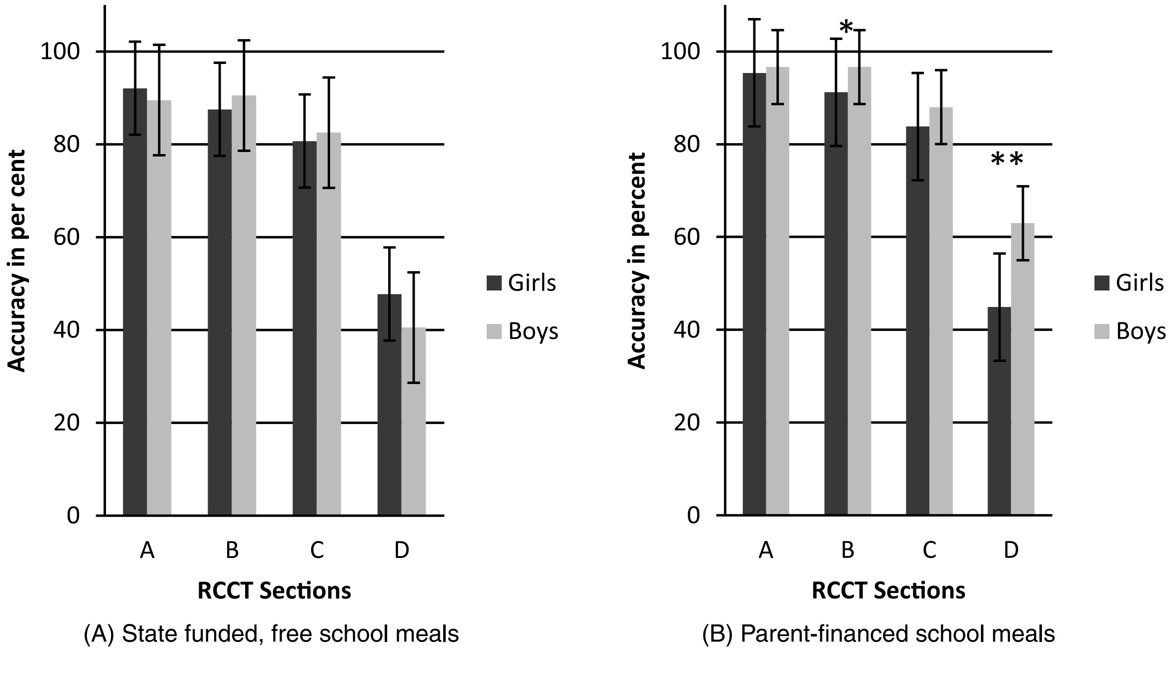


Fig. 4. Gender differences in RCCT Section performance for (A) children receiving state financed school meals versus (B) children whose parents financed their school meals. *Note* * = $p < 0.01$, ** = $p < 0.001$.

Table 4
Analysis of Variance for RCCT Performance with Age, Gender and School Meal Type as Between Subject Variables

Source	*SS*	*df*	*MS*	*F*	*p*	η^2
			Between-Subjects Effects			
Gender	582.73	1.000	582.73	2.040	0.157	0.023
Age	**2701.44**	**2.000**	**1350.72**	**4.729**	**0.011***	**0.097**
FSM	**2287.70**	**1.000**	**2287.70**	**8.010**	**0.006****	**0.083**
Gender*Age	429.21	2.000	214.61	0.751	0.475	0.017
Gender*FSM	**1595.04**	**1.000**	**1595.04**	**5.584**	**0.020***	**0.060**
Age*FSM	134.65	2.000	67.33	0.236	0.790	0.005
Gender*Age*FSM	922.05	2.000	461.02	1.614	0.205	0.035
			Within-Subject Effects			
RCCT	**121229.74**	**2.227**	**54441.98**	**330.56**	**0.000*****	**0.790**
RCCT*Gender	436.56	2.227	196.05	1.190	0.309	0.013
RCCT*Age	624.37	4.454	140.20	0.851	0.504	0.019
RCCT*FSM	251.22	2.227	112.82	0.685	0.520	0.008
RCCT*Gender*Age	586.10	4.454	131.60	0.799	0.539	0.018
RCCT*Gender*FSM	**2371.39**	**2.227**	**1064.95**	**6.466**	**0.001*****	**0.068**
RCCT*Age*FSM	841.18	4.454	188.88	1.147	0.337	0.025
RCCT*Gender*Age*FSM	506.37	4.454	113.70	0.690	0.615	0.015

Note. Degrees of Freedom were corrected with Greenhouse-Geisser. RCCT = Rotated Cube Sections; FSM = school meal type; Age = Age groups. *$p < 0.05$. **$p < 0.01$. ***$p < 0.001$. Statistical effects set in bold were significant.

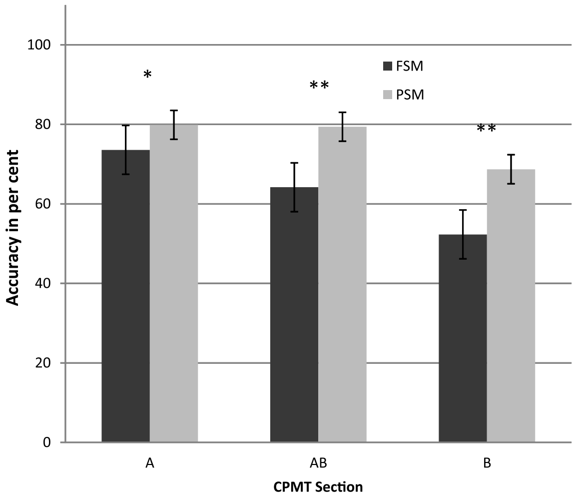


Fig. 5. Increasing effects of socio-economic status in the Sections of the Coloured Raven Progressive Matrices Test. *Note* * = $p < 0.05$, ** = $p < 0.001$.

$\eta^2 = 0.23$. Furthermore, only in this high SES group the age difference was significant, $F(2, 47) = 6.07, p < 0.01$, $\eta^2 = 0.21$.

Post-hoc t-tests for independent samples were run for boys and girls, per RCCT Section. In each of the two halves of the RCCT, always in the second, more difficult Section (RCCT B and D), a significant gender difference was found: In RCCT A, the mean performance of boys and girls did not differ significantly (boys $M = 96.6\%$; girls $M = 95.4\%$), $p > 0.51$, but in RCCT B where the cubes had a non-canonical orientation, boys performed significantly better ($M = 96.6\%$) than girls ($M = 91.2\%$), t (51) = –2.76, $p < 0.01$. Likewise, in the RCCT C, boys ($M = 87.98$) and girls ($M = 83.80$) did not differ significantly, $p > 0.16$, but in RCCT D where all rotated cubes had the same colour, boys ($M = 63.0\%$) performed significantly better than girls ($M = 44.9\%$), t (51) = –3.69, $p < 0.001$ (see Fig. 4, right). Thus, boys from a relatively higher socio-economic background excelled in the more challenging perceptual matching and mental rotation tasks. This confirmed that these two tasks measure related abilities.

Raven Coloured Progressive Matrices Test (RCPM). Accuracy was computed in per cent correct for each type of RCPM Section A, AB and B (see Table 5). As with the RCCT, we conducted a 3 (Section) by 3 (Age) by 2 (Gender) by 2 (School meal type) MANOVA with repeated measurement for each Section.

There was a significant main effect for the factor RCPM Section, $F(1.86, 163.93) = 43.11, p < 0.001$, $\eta^2 = 0.33$, with a large effect size (see Table 6). Pairwise *post-hoc* comparisons ($p_s < 0.001$) confirmed significant differences between RCPM A ($M = 76.44\%$), RCPM AB ($M = 72.30\%$), and RCPM B ($M = 61\%$). Sections became increasingly more difficult as the RCPM progressed.

Furthermore, there were two significant between-subjects effects. The effect for FSM, $F(1, 88) = 16.51$,

Table 5
RCPM Scores by Age Group and Gender (Accuracy in %)

Gender	7-8 years	9 years	10 years	Total
		Section A		
		Free School meals		
Girls	74.07 (8.78)	65.00 (10.87)	78.13 (13.32)	73.49 (11.68)
Boys	77.08 (13.91)	70.46 (14.61)	75.00 (11.79)	73.67 (13.54)
		Parent-Financed School Meals		
Girls	81.67(13.69)	78.21 (11.56)	81.48 (12.35)	79.94 (11.84)
Boys	73.81 (10.13)	76.04 (14.39)	86.36 (10.72)	79.80 (12.73)
		Section AB		
		Free School Meals		
Girls	62.03 (21.70)	65.00 (16.03)	75.00 (17.25)	67.42 (19.06)
Boys	58.33 (20.89)	57.58 (25.67)	72.22 (21.52)	61.33 (23.18)
		Parent-Financed School Meals		
Girls	81.67 (19.00)	70.51 (16.53)	81.48 (17.57)	76.23 (17.55)
Boys	67.86 (16.96)	86.46 (18.87)	89.39 (13.99)	82.69 (18.24)
		Section B		
		Free School Meals		
Girls	50.00 (17.68)	50.00 (22.82)	58.33 (23.57)	53.03 (20.50)
Boys	46.88 (23.54)	46.21 (19.14)	68.06 (23.22)	51.67 (22.69)
		Parent-Financed School Meals		
Girls	70.00 (24.00)	64.10 (19.95)	60.18 (16.55)	63.89 (19.20)
Boys	55.95 (15.00)	72.92 (7.39)	85.61 (13.99)	73.72 (17.27)

Table 6
Analysis of Variance for RCPM Performance with Age, Gender and Free School Meals

Source	*SS*	*df*	*MS*	*F*	*p*	η^2
			Between-Subjects Effects			
Gender	79.64	1.000	79.64	0.134	0.715	0.002
Age	**5330.51**	**2.000**	**2665.25**	**4.499**	**0.014***	**0.093**
FSM	**9780.36**	**1.000**	**9780.36**	**16.511**	**0.000****	**0.158**
Gender*Age	2134.50	2.000	1067.25	1.802	0.171	0.039
Gender*FSM	202.71	1.000	202.71	0.342	0.560	0.004
Age*FSM	515.22	2.000	257.61	0.435	0.649	0.010
Gender*Age*FSM	1628.43	2.000	814.21	1.375	0.258	0.030
			Within-Subject Effects			
RCPM	**12270.34**	**1.863**	**6586.99**	**43.109**	**0.000****	**0.329**
RCPM*Gender	267.71	1.863	143.71	0.941	0.387	0.011
RCPM*Age	799.40	3.726	214.57	1.404	0.237	0.031
RCPM*FSM	**1083.69**	**1.863**	**581.75**	**3.807**	**0.027***	**0.041**
RCPM*Gender*Age	1262.67	3.726	338.91	2.218	0.074	0.048
RCPM *Gender*FSM	426.85	1.863	229.14	1.500	0.227	0.017
RCPM*Age*FSM	271.72	3.726	72.93	0.477	0.739	0.011
RCPM *Gender*Age*FSM	593.38	3.726	159.27	1.042	0.384	0.023

Note. Degrees of Freedom were corrected with Greenhouse-Geisser. RCCT = Rotated Cube Sections; FSM = School meal type; Age = Age groups. *$p < 0.05$. ***$p < 0.001$. Statistical effects set in bold were significant.

$p < 0.001$, $\eta^2 = 0.16$, showed that children with free school meals ($M = 63.85\%$) performed overall significantly worse than children with parent financed school meals ($M = 75.76\%$). The *post-hoc* tests of the age effect, F(2, 88) = 4.50, $p < 0.05$, $\eta^2 = 0.09$, showed performance of both the 7-8 and 9-year-old children was worse than in 10-year-olds.

There was a significant two-way interaction of RCPM Sections and FSM, $F(1.86, 163.93) = 3.807$, $p < 0.05$, $\eta^2 = 0.04$, that interacted neither with age, $p > 0.74$, nor with gender, $p > 0.23$. *T*-tests for independent samples compared children with free school meals and parent financed school meals per RCPM Section. This revealed a significant difference in each Section (see Fig. 5), which increased the further children progressed in the Raven test, Section A: $t(98) = -2.5$, $p < 0.05$, Section AB: $t(98) = -3.83$, $p < 0.001$, Section B: $t(98) = -4.04$, $p < 0.001$.

Table 7
Analysis of Variance for RCCT vs. RCPM Performance with Age, Gender and Free School Meals

Source	*SS*	df	MS	F	*p*	η^2
			Between-Subjects Effects			
Gender	148.30	1.000	148.30	0.745	0.390	0.008
Age	**1874.83**	**2.000**	**937.41**	**4.710**	**0.011***	**0.097**
FSM	**3281.50**	**1.000**	**3281.51**	**16.489**	**0.000****	**0.158**
Gender*Age	644.28	2.000	322.14	1.619	0.204	0.035
Gender*FSM	397.31	1.000	397.31	1.996	0.161	0.022
Age*FSM	84.79	2.000	42.40	0.213	0.809	0.005
Gender*Age*FSM	666.78	2.000	333.39	1.675	0.193	0.037
			Within-Subject Effects			
Test	**4240.60**	**1.000**	**4240.60**	**60.712**	**0.000*****	**0.408**
Test*Gender	23.93	1.000	23.93	0.343	0.560	0.004
Test*Age	**577.37**	**2.000**	**288.68**	**4.133**	**0.019***	**0.086**
Test*FSM	**550.54**	**1.000**	**550.54**	**7.882**	**0.006****	**0.082**
Test*Gender*Age	174.53	2.000	87.26	1.249	0.292	0.028
Test*Gender*FSM	69.02	1.000	69.02	0.988	0.323	0.011
Test*Age*FSM	120.61	2.000	60.30	0.863	0.425	0.019
Test*Gender*Age*FSM	106.54	2.000	53.27	0.763	0.469	0.017

Note. Degrees of Freedom were corrected with Greenhouse-Geisser. Test = Test type (RCCT vs. RCPM); FSM = school meal type; Age = Age groups. *$p < 0.05$. **$p < 0.01$. ***$p < 0.001$. Statistical effects set in bold were significant.

Comparison of the RCCT and the RCPM

Because the RCCT was a new test development, we used the established RCPM for cross-validation. The RCCT and RCPM scores were significantly correlated in 7- to 8-year-old children $r(28) = 0.52$, $p = 0.004$, in 9-year-old children $r(35) = 0.60$, $p < 0.001$, and in 10-year-old children $r(32) = 0.72$, $p < 0.001$, and increased with age.

We conducted a more comprehensive MANOVA on the two *overall scores* of the RCCT and the RCPM, respectively, that allowed for a direct comparison. A 2 (RCCT vs. RCPM) by 3 (Age) by 2 (Gender) by 2 (School meal type) MANOVA revealed no significant gender differences, all $p_s > 0.16$ (see Table 7). This demonstrated that gender differences were limited to the more difficult RCCT Sections and did not appear when *overall scores* were used. Furthermore, a significant within-subject main effect, $F(1, 88) = 60.71$, $p < 0.001$, indicated that on average the RCPM ($M = 69.9\%$) was more difficult than the RCCT ($M = 79.5\%$). This difference showed a comparably large effect size of $\eta^2 = 0.41$, while all other significant effects sizes were smaller, $\eta^2 < 0.16$.

A significant main effect for age groups interacted in a two-way interaction between the two tests, $F(2, 88) = 4.13$, $p < 0.05$, $\eta^2 = 0.86$ (see Fig. 6), with an even larger effect size. RCCT scores increased with age by 7.3% (age 7-8 $M = 75.2\%$; age 9 $M = 80.2\%$; age 10 $M = 82.5\%$). Also RCPM scores increased with age, by 11.8% (age 7-8 $M = 65.3\%$; age 9 $M = 67.3\%$; age 10 $M = 77.1\%$). *Post-hoc t*-tests (paired samples) revealed a significant difference in the two test scores in all three age groups, with the RCCT scores always significantly higher than the RCPM scores, $p_s < 0.01$. However, Fig. 6 shows that the difference between the test performance reduced with increasing age, and vice versa, the correla-

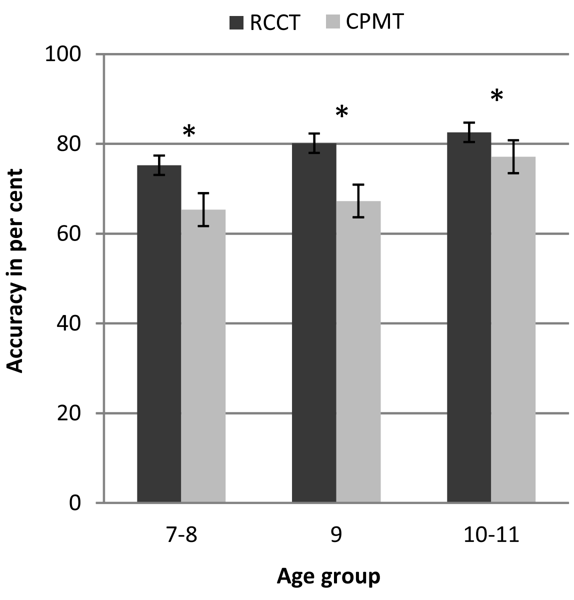


Fig. 6. Age group differences in RCCT and RCPM performance. *Note* * = $p < 0.01$.

tions between the two tests increased with age (see the first paragraph of this part of the report).

The significant between-subjects effect for FSM, $F(1, 88) = 17{,}15$ $p < 0.001$, showed that children receiving free school meals ($M = 70.4\%$) scored lower than children with parent financed school meals ($M = 78.6\%$), but importantly, a significant two-way interaction revealed that this varied depending on the test, $F(1, 88) = 7.88$, $p < 0.05$.

To test where the difference was located, the MANOVA was run again with a split sample for FSM. It showed that children with free school meals performed much better on the RCCT ($M = 76.9\%$) than on the RCPM ($M = 63.9\%$). However, a two-way interaction showed that this difference became smaller with age, $F(1, 47) = 3.56$, $p < 0.05$, 7- to 8-year-olds (RCCT: $M = 73.7\%$; RCPM: $M = 61.4\%$), to 9-year-olds (RCCT: $M = 78.6\%$; RCPM: $M = 59.0\%$), and 10-year-olds (RCCT: $M = 78.4\%$; RCPM: $M = 71.1\%$), as Raven scores were relatively improved in the older children on free school meals. No other statistical effects were significant, $p_s > 0.21$. Thus the RCCT was especially fair to younger low SES children.

In contrast, the sample of children with parent financed school meals showed the same disparity between tests, RCCT: $M = 81.9\%$; RCPM: $M = 75.8\%$, $F(1, 53) = 13.53$, $p < 0.001$, but no reduction of this difference with age, $F(1, 53) = 0.78$, ns. Instead, there was a main effect of age, $F(2, 53) = 3.66$, $p < 0.05$, which interacted with gender, $F(2, 53) = 3.93$, $p < 0.05$. Girls' test scores were similar at 7- to 8-years ($M = 77.3\%$); 9-years ($M = 74.8\%$); and 10-years ($M = 77.3\%$) and showed no improvement, whereas boys' performance increased with age 7- to 8-years ($M = 71.9\%$); 9-years ($M = 83.4\%$); 10-years ($M = 88.5\%$).

Discussion

This study introduces a new test, the Rotated Colour Cube Test (RCCT) as a measure of perceptual matching and mental rotation in children, using illustrations of a single multi-coloured three-dimensional (3D) cube as a model. We tested 7- to 10-year-old children. The new test is not a mental rotation experiment where angularity of the rotated stimulus and the corresponding reaction times are measured (Shepard & Metzler, 1971). Instead, it is a Mental Rotation test similar to those used with adults by Vandenberg and Kuse (1978) and Peters et al. (1995) that presented rotated models, a rotated target as well as several rotated cubes as distracters. However, while a single cube is a useful reduction of complexity for children in comparison to the cube aggregates of Shephard and Metzler (1971), it does not lend itself to spatial rotation in the same way as a cube aggregate because a single cube lacks a clear one-dimensional extension that points into space, comparable to a vector. Cube aggregates have extensions which have been compared to pictures of gymnasts with outstretched limbs (Alexander & Everdone, 2008). We are currently revising the current version of the test in which we will gradually introduce cube aggregates.

The first part of the test (Sections A, B) measured children's perceptual matching abilities, and the second part of the test (Sections C, D) more complex perceptual matching and mental rotation abilities. Children performed best in identifying a target cube amongst non-rotated distracters that was identical in colour and orientation to the model cube. Identifying a rotated target cube amongst rotated, similarly coloured distracters was the most difficult task. Additionally, we found gender differences in interaction with children's low vs. high SES background. Mental rotation performance significantly correlated with children's performance on the Raven's Coloured Progressive Matrices Test (RCPM).

We constructed the test format similarly to the RCPM, with a response panel of a target and several distracters, and by increasing task difficulty in each consecutive test section. We assessed a baseline for item identification of a model object in a canonical view (Section A) and in a rotated position (Section B) to make sure that children had an intact object concept. An object concept is not self-understanding because in cube drawings, children often draw just one side, or if they draw more than one side, these multiple cube faces are not integrated (e.g. Lange-Küttner & Ebersbach, 2012). We used colour to distinguish between distracters as it is such an important feature for children that for instance the Raven Test for children only exists in colour, whereas the version for adults is in black-and-white. In our test, children could identify the target by finding the correct spatial configuration of the coloured cube faces. Moreover, colour similarity of the cube distracters was increased during trials in each of the first three sections.

As expected, similar to the RCPM, the new RCCT became more difficult over the four test sections. There was no significant performance decrease in perceptual matching between the first two Sections A and B where the only difference was model cube orientation, except in the sub-sample of high SES boys who performed better in identifying a cube in a non-canonical position standing on a corner. The main difference in test performance arose between simple perceptual identification in RCCT Sections A and B, and the more challenging target cube identification amongst individually rotated distracter cubes in Sections C and D. In Section C, colour similarity was increased between targets and distracters, whereas in Section D colour was completely removed as a distinctive feature. Thus, performance in Sections C and D decreased due to an increase in the number of rotations of the distracters as well as due to a reduction of colour saliency. Indeed, the study showed that it is not just orientation of ONE object as such that is difficult for children, but differences in orientation and similarity between targets and distracters.

The increase in colour similarity between target and distracter cubes to a level where all colours were the same and cubes varied only in orientation occurred gradually over sections C to D (see Appendix, Column 'Colour Similarity'). But performance deteriorated particularly in section D where no unique object colour were available to distinguish between the distracter cubes. This is especially noteworthy because in *both* Section C and D, the model and the target could vary (see Appendix, Column 'Rotation', Levels III and IV). Hence, distinct unique colours between distracters were particularly helpful as a visual cue in narrowing down attention towards the rotated target. In conclusion, while *different orientations* of distracters made the RCCT more difficult, *different colours* of distracters had the opposite effect and made the RCCT easier because colour facilitated clearer discrimination between target and distracters.

Solving a three-dimensional mental rotation task involves the ability to maintain representations of relevant object attributes and their interrelation, while at the same time rotating mental images (Kaufman, 2007). Similar to adults, object colour can be more salient and important than object location (Hyun & Luck, 2007). Integration of the cube faces was easier when objects were different: Differences in the target cube's orientation and even individually rotated distracters were not especially difficult as long as the distracters' distinctive object colours were available as a cue. This may be somewhat counterintuitive as mental rotation is a spatial ability. However, colour of cube faces is a feature that defines the cube's internal structure, but it is not a spatial cue about the location of the cube. Because the cube had only changed orientation and not position, the object-place binding (Lange-Küttner, 2008, 2013) remains intact in mental rotation. In short, rotated objects stay in place. This in turn suggests that feature integration plays an important role in mental rotation.

As in previous studies on visual memory and spatial ability (Lange-Küttner, 2010a; Levine et al., 2005), a pronounced impact of gender and SES was already present in school children: Boys from a higher social-economic background performed better than girls from the same relatively advantaged background in Sections B (non-canonical cube orientation) and D (lack of unique distracter colour), while there was no difference between boys and girls from a low social-economic background. The 'gearing up' of the more privileged boys indicated that they were more likely to rise to a challenge (Lange-Küttner, 2012; Lange-Küttner & Green, 2007). This gender by task difficulty effect was particularly apparent when colour cues were not available in Section D, as only the upper middle class boys had a success rate of above 60% while everybody else was below 48%. It could well be that these boys developed more responsiveness and attention towards the less obvious cube features such as contour and line orientation (Enns & Rensink, 1991; Hystegge, Heim, Zettelmeyer, & Lange-Küttner, 2012; Lange-Küttner, Kerzmann, & Heckhausen, 2002; Treisman, 1986).

A limitation of the current test version is that it was given in booklet and not in a computerized form, so precise time measurement was not possible. Lack of a time constraint may have been the reason for the absence of a main effect of gender in mental rotation. Lange-Küttner and Ebersbach (2012) found that boys were comparably more efficient in mental rotation decision making, as they came to more correct conclusions within a given time. The efficient boys with shorter MRT reaction times were also more likely to draw two occluded cubes, whereas this was not the case for girls. Girls worked at their own steady pace independently of the task at hand, but in 6- to 9-year-old boys, mental rotation reaction times were already task-specific. Although we did not measure reaction times in the RCCT, we are currently developing a computerized version that will allow precise time measurements along with the introduction of simple cube aggregates.

Mental Rotation and Fluid Intelligence

Our results showed that in general, the Rotated Colour Cube Test (RCCT) was easier that the Raven's Coloured Progressive Matrices Test (RCPM), but this difference was more pronounced in 7- to 8-year-olds than in the 10- to 11-year-old children, especially when from families with a lower SES.

We suggest that the RCCT was easier than the Raven test since the spatial reasoning component was less complex. While single three-dimensional cubes were used in the RCCT, in the RCPM both continuous and discrete patterns had to be completed. That is, even if multiple coloured cube faces had to be perceptually integrated and distinguished against competing distracters, the RCCT Sections did not require the formation of a logical sequence of visual pattern fragments which may require executive attention (Jones, Rothbart, & Posner, 2003), or operational intelligence according to Piaget (Inhelder & Piaget, 1958). This might explain why younger children performed comparatively well in the RCCT, except in the last section where colour salience was removed. Therefore, this new test would lend itself to measuring object processing in even younger age groups.

However, besides these differences in the two tests, the significant correlations also suggested strong similarities. The Raven's Matrices test was identified as measuring both fluid intelligence and spatial ability (Guttman, 1974). Similarly, it was proposed that spatial ability tests load considerably on g (Ullstadius, Carlstedt, & Gustafsson, 2004). We suggest that the similar response format with a perceptual discrimination between target and multiple distracters in both tests may account for the significant correlations in each age group.

In agreement with previous research (Eysenck & Kamin, 1981; Raven, 1939) we found no gender differences on the RCPM, whereas gender differences in the RCCT only emerged in the more difficult Sections B (perceptual matching) and D (mental rotation). This may be due to the difference in dimensionality between the two tests. The RCPM only includes 2D items, whereas the RCCT only consists of 3D items. As the visual information system is sensitive to dimensionality and finds processing of three-dimensional information more difficult (Jansen et al., 2013), this may account for finding gender differences only in the three-dimensional RCCT and not in the RCPM. It is indeed important to have a distinct 3D mental rotation test designed specifically for children, for instance, in order to assess abilities in Math, Science and the Arts from an early age.

The unexpected result of a drop in the levels of performance for children from a low social-economic background on the RCPM supports findings of a study with children from a Pakistani background (Aziz & Farooqi, 1991). Raven's Progressive Matrices Tests is seen as a culture-fair test of intellectual functioning (Anderson, Kern, & Cook, 1968; Jensen, 1974; Kaplan & Saccuzzo, 1996; Valencia, 1984). However, in the current study this was not the case, which contradicts expectations (American Educational Research Association, American Psychological Association, & National Council on Measurement in Education, 1999, Standard 7.1). The disadvantageous influence of low socio-economic status on both the RCCT and RCPM highlights the need for developing further tests that may help to identify children who can benefit from early intervention strategies (Noble et al., 2015).

While our research sample was relatively large with $N = 100$, cells were unequal to some degree, though not dramatically so (Howell, 1992, section 13.9, pp. 409). There were 51 boys and 49 girls thus the sample was nearly perfectly gender-balanced. Likewise, for SES there were 47 children on free school meals and 53 children whose parents could afford to pay for school meals. But the smaller cells of the interactions (see Table 1) were unequal, with subsamples between n_s from 5 to 13. So there could have been an element of chance in the obtained significances of some interactions. However, we believe that because the interactions concerned mostly the more difficult sections B and D, that the interaction of task difficulty with individual differences was systematic and genuine. In fact, there was a political initiative insofar as free school meals for all were introduced in London's entry classes to primary schools (Burns, 2014) at the time when this manuscript was submitted for publication.

The newly developed RCCT distinguishes itself from other available tests for children by preserving and simplifying Shepard and Metzler's (1971) three dimensional geometric properties and by providing a 3D test specifically adapted for young children. Our research has shown that young children can solve tasks with three dimensional cube illustrations, but increasingly struggle when supportive colour information is reduced. The current study demonstrated that a reduction in task complexity without resorting to 2D images, and varying distracter similarity and colour salience were effective means of adjusting task difficulty. As the MRT is widely used with adults, it was important to create a simplified test for younger children that preserves three-dimensions as well as the use of geometric stimuli, with the aim to bridge the gap between the classic complex three-dimensional cube aggregates used for adults (Shepard & Metzler, 1971) and simplified two-dimensional versions for children.

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Bio Sketches

Nikolay Lütke, Bachelor of Science, doctoral student at the London Metropolitan University. Test development of 3D perception and mental rotation in children.

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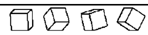
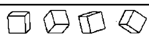
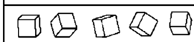
Appendix Table A1

Properties of the Target Cube, the Test Cube and Distracters

Level	Page	Cubes	Distracter Colour Similarity	Rotation
			Section RCCT A	
I	**A1**	6	100 % distracters with 1 colour identical to test cube	
	A2	8		
II	**A3**	6	100 % distracters with 2 colours identical to test cube	
	A4	8		
III	**A5**	6	50% distracters with 3 colours identical to test cube	
	A6	8		
IV	**A7**	6	100 % distracters with 3 colours identical to test cube	
	A8	8		
			Section RCCT B	
I	**B1**	6	100 % distracters with 1 colour identical to test cube	
	B2	8		
II	**B3**	6	100 % distracters with 2 colours identical to test cube	
	B4	8		
III	**B5**	6	50% distracters with 3 colours identical to test cube	
	B6	8		
IV	**B7**	6	100 % distracters with 3 colours identical to test cube	
	B8	8		
			Section RCCT C	
I	**C1**	6	100 % distracters with 1 colour identical to test cube	
	C2	8		
II	**C3**	6	100 % distracters with 2 colours identical to test cube	
	C4	8		
III*	**C5**	6	100% distracters with 2 colours identical to test cube	
	C6	8		
IV*	**C7**	6	50 % distracters with 3 colours identical to test cube	
	C8	8		
			Section RCCT D	
I	**D1**	6	100% distracters with 3 colours identical to test cube	
	D2	8		
II	**D3**	6	100% distracters with 3 colours identical to test cube	
	D4	8		
III*	**D5**	6	100% distracters with 3 colours identical to test cube	
	D6	8		
IV*	**D7**	6	100 % distracters with 3 colours identical to test cube	
	D8	8		

Note. * indicates mental rotation tasks