Visual perception, visual-spatial cognition and mathematics: Associations and predictions in children with cerebral palsy

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ABSTRACT

Background: Previous research suggests that children with cerebral palsy (CP) have impairments in visual-spatial and mathematics abilities, although we know very little about the association between these two domains.

Aims: To investigate the extent of visual-spatial and mathematical impairments in children with CP and the associations between these two domains.

Method and Procedure: Thirty-two children with predominantly quadriplegic spastic and/or athetoid (dyskinetic) CP (13 years 7 months) and a group of typically developing (TD) children (8 years 6 months) matched by receptive vocabulary were given a battery of visual-spatial and mathematics tasks. Visual-spatial assessments ranged from simple tests of perception to complex reasoning about these stimuli. A standardised test of mathematics ability was administered to both groups.

Outcomes and Results: The children with CP had significantly poorer mathematical and visual-spatial abilities than the TD group. For the TD group age was the best predictor of mathematical ability, in the CP group receptive vocabulary and visual perception abilities were the best predictors of mathematical ability.

Conclusion and Implications: The CP group had extensive difficulties with visual perception; visual short-term memory; visual reasoning; and mental rotation all of which were associated with their mathematical abilities. These findings have implications for the teaching of visual perception and visual memory skills in young children with CP as these may help the development of mathematical abilities.

What this paper adds

Results supported and extended previous research. Children with CP, in comparison with a TD group, were found to have impairments to visual-spatial perception including processing information in visual short-term memory, in mental rotation tasks and in matrices reasoning tasks. The CP group also had significantly poorer mathematical abilities than the TD group. We provide additional information about the presence of significant relationships between visual-spatial perceptual abilities and the mathematical abilities of both groups of children. We demonstrated that the CP group showed extensive, significant relationships between visual-spatial tests and their mathematical abilities. These findings suggest the potential importance of teaching and developing visual-spatial

abilities in children with CP, particularly those abilities that might have specific roles in the development of mathematics. Further research in the form of interventions, such as those described in a study of the impact of mental rotation training on arithmetic performance (Cheng & Mix, 2014), may greatly benefit children with CP and their progress in mathematical learning.

1. Introduction

Cerebral palsy (CP) is typically caused by brain lesion(s) that are usually diagnosed within the first two years of life. It is most often caused by brain trauma in the uterus; at birth; or by other causes in early infancy (Rosenbaum, Nigel, Leviton, Goldstein & Bax, 2007). The condition affects the contraction, tone and function of muscles, and hence motor development, with a prevalence of approximately 2–3 children in every thousand (Odding, Roebroeck, & Stam, 2006). Research into CP has identified that, along with the characteristic motor impairments, there often are cognitive impairments (Odding et al., 2006; Stadskleiv, Jahnsen, Andersen & von Tetzchner, 2017). Related to this, many children with CP have difficulties with developing mathematical concepts (Jenks, val Lieshout & de Moor, 2012; van Rooijen et al., 2012). Previous research into the mathematical abilities in CP have identified associations with mathematics and visual-spatial impairment such as visual short term memory (Jenks et al., 2009; Peeters, Verhoeven, & de Moor, 2009); non-verbal matrices tasks (van Rooijen et al., 2012; Jenks et al., 2007); and mental rotation abilities (Courbois, Coello, & Bouchart, 2004). Thus, our investigation builds on previous research by seeking to determine the precise profile of visual-spatial deficits in a group of children with CP, and by investigating whether the reported deficits in visual-spatial cognition and mathematics are associated.

1.1. Typical mathematical development and visual-spatial abilities

Mathematical skills develop on a 'learning trajectory' (Purpura & Ganley, 2014), that is, understanding basic knowledge and skills is necessary before more complex mathematical comprehension is achieved. There are a number of cognitive processes which contribute to mathematical development. Research concerning typically developing (TD) children, for example, has demonstrated that visual-spatial abilities are a strong predictor of mathematical competence (see Uttal et al., 2013; Verdine, Irwin, Golinkoff & Hirsh-Pasek, 2014). In addition, visual short-term memory (STM) as assessed by Corsi block recall has been linked to mathematical abilities (Fuchs et al., 2005; Kyttälä & Lehto, 2008). Furthermore, non-verbal intelligence is usually assessed by tasks that involve visual-spatial abilities (e.g. Raven's Progressive Matrices RPM, Raven, Raven, & Court, 2008) and has also been found to be related to mathematical ability (Deary, Strand, Smith, & Fernandes, 2007; Kyttälä & Lehto, 2008). These findings provide a rationale to investigate the relationship between visual-spatial perception and mathematical abilities in children with CP.

1.2. Mathematical abilities, visual-spatial abilities, and cerebral palsy

Researchers comment on the paucity of investigations into numerical and arithmetic abilities of children with CP particularly those involving aspects of visual-spatial perception (Schmetz, Magis, Detraux, Barisnikov, & Rousselle, 2018; van Rooijen et al., 2012). Available research has shown that children with CP are more likely to experience difficulties with mathematical learning than TD children (Frampton, Yude, & Goodman, 1998), and a small number of studies have highlighted that children with CP are often delayed in acquiring numerical skills such as: subitizing (quantifying sets); counting; and basic arithmetic problem-solving (Jenks, van Lieshout, & de Moor, 2012; van Rooijen et al., 2012). In a longitudinal study over two years, van Rooijen et al. (2014) found that those children with CP and higher non-verbal intelligence increased their mathematical skills on a trajectory similar to a comparison group of TD children; however, they did not catch up with their TD peers.

Many children with CP have visual-spatial perceptual impairments despite typical or near-typical visual acuity (Akhutina, Foreman, Krichevets, & Vahakuopus, 2003; Ego et al., 2015; Menken, Cermak, & Fisher, 1987; Reed & Drake, 1990; Ortibus, Lagae, Casteels, Demaerel, & Stiers, 2009; Stadskleiv, Jahnsen, Andersen, & von Tetzchner, 2017). Ego et al. (2015), in a systematic review of visual-perceptual impairments in children with CP, identified 15 studies which included one of five standardised tests that assessed visual perception. The review indicated that the proportion of children with visual-perception impairments ranged from 40% to 50%, with no study reporting a significant effect of CP subtype or IQ level, although the severity of neurological lesions appeared to be associated with visual perception abilities.

There has been discussion of whether visual-spatial impairments could directly be caused by neurological lesions and their sequalae (Menken et al., 1987), and it is also possible that an inability to explore space because of physical disabilities may limit the development of spatial functioning and visual-spatial skills in these children (see Clearfield, 2004; Stanton, Wilson, & Foreman, 2002). Because of the fine-motor difficulties of many children with CP (Ballester-Plané et al., 2016; Rosenbaum et al., 2007) we decided to focus on visual-spatial perception assessments which do not involve manipulation; the one that was chosen was the Test of Visual Perception ([TVPS-3]; Martin, 2006).

We also decided to use three other assessments which not only involve visual-spatial perception, but also additional cognitive processing of visual-spatial information. These were a short term visual-spatial memory task, a mental rotation task, and a matrices task. It has been reported that children with CP have impaired performance on these tasks. In the case of visual-spatial memory, Gagliardi, Tavano, Turconi, and Borgatti (2013) used a computerised version of the Corsi blocks task where children with CP were asked to remember the sequence in which a set of blocks were touched by the experimenter. The researchers found that the children with CP performed significantly worse than TD children of the same chronological age. Different, age-related, errors were observed across the CP group. For example, position errors, e.g. selecting blocks from the wrong place, were more common in the younger

children of the CP group, indicating visual spatial memory difficulties, whilst the older children in the CP group were more likely to have problems with sequencing skills (also see Schmetz et al., 2018). Corsi type tasks are of relevance to mathematical ability as the visual spatial sketchpad may be used as a 'mental blackboard' (Baddeley, 2007) when distinguishing between different mathematical forms and shape, as well as retaining previous visual information (see Hubber, Gilmore, & Cragg, 2014).

To date, there have been few studies on object-based mental rotation abilities in children with CP. In these tasks participants identify whether rotated and upright shapes have the same identity (see Fig. 1) (Schmetz et al., 2018). We included this task for three reasons. Firstly, it measures a relatively pure form of visual-spatial processing ability (Shepard & Metzler, 1971). Booth et al. (1999) have suggested that during this process, mentally rotated stimuli are temporally stored in working memory, and the visual-spatial sketchpad is implicated in the manipulation of the visual images (Gathercole, Pickering, Ambridge & Wearing, (2004); Hyun & Luck, 2007). Thus, reduced working memory capacity (i.e. limited cognitive resources) could be responsible for poor task performances on these rotation tasks. Secondly, children with CP have been reported to have impaired performance on this task (Courbois et al., 2004). Thirdly, mental rotation has consistently been found to be strongly associated with mathematical abilities in TD children and interventions involving mental rotation can help these children's mathematical performance on some types of problems (e.g. Cheng & Mix, 2014).

Matrices tasks are another assessment which have an important visual-spatial component in which children with CP often have significantly low scores. In these tasks, several visual arrangements of a pattern are presented, and the participant chooses an item to complete a sequence which has a different but related visual arrangement. Children with CP have lower scores on Raven's Progressive Matrices (RPM or Raven's Progressive Coloured Matrices [RCPM], Raven et al., 2008) than chronologically age matched TD children (Jenks et al., 2012; Peeters, Verhoeven, Van Balkom, & De Moor, 2008). This is usually interpreted as indicating that the children have lower non-verbal intelligence as the task involves non-verbal reasoning, but matrices tasks have an important visual-spatial component and notably Ego et al. (2015) in their systematic review included the RPM as a visual-perceptual assessment. Consequently, we were interested in investigating whether matrices tasks had similar relationships to mathematical abilities as other visual-spatial tasks.

As far as we can ascertain there are few studies that have investigated the relationship between matrices and mathematical abilities in children with CP (Jenks et al., 2009; Peeters et al., 2009). van Rooijen et al. (2012) reported that CP children's RCPM performance was significantly correlated ($r = 0.61$) with their arithmetic abilities at ages 6–8 years. In other studies, RCPM assessments have had a strong association with basic mathematical abilities in children with CP who attend mainstream schools as well as those who attend special schools (Jenks et al., 2007). Furthermore, this assessment has been found to correlate significantly with addition and subtraction tests in CP children aged between 6 and 11 years (van Rooijen, Verhoeven, & Steenbergen, 2011).

Given these previous findings, in the current study we investigated the extent to which visual-spatial cognition and mathematical ability are impaired in children with CP, and the extent to which these visual abilities predict mathematical ability. Thus, our investigation builds on previous research by determining the precise profile of visual-spatial deficits in a group of children with CP, and by investigating whether the reported deficits in visual-spatial cognition predicts mathematical ability.

1.3. Overview

Although visual-spatial abilities have been identified as relating to mathematical abilities in the typical population, there have been few studies which have focused on the role of a range of visual-spatial assessments and their relationship to the mathematical abilities of children with CP. Accordingly, it was decided to compare children with CP in relation to TD children who had similar receptive vocabulary. Our first question concerned whether there was a difference in the mathematical and visual-spatial abilities of the two groups and the size of any difference. We were also interested in whether visual-spatial impairments occurred when the assessments did not involve an important motor component (i.e. the primary impairment in CP) and whether tasks that involved the processing of additional visual-spatial information (e.g. memory, mental rotation, non-verbal reasoning) made the tasks more difficult for children with CP due to cognitive load, for example, switching attention (Henry, 2011).

The second question concerned whether visual-spatial abilities are related to mathematical abilities in CP, and how this compares to children with TD. Because mathematical abilities are affected by age and language (Butterworth, 2005; Fuchs & Fuchs, 2002), we also examined whether visual-spatial abilities still predicted mathematics scores when the effects of these potential confounds were removed.

2. Method

2.1. Design

This is a cross-sectional study in which we are interested in group comparisons on individual tasks between CP and TD children, and the relationships between visual-spatial cognitive abilities and mathematical abilities for both groups. We used IBM: SPSS Statistics software (version 21) and stepwise hierarchical regression analyses were conducted to further examine the data.

Given that individuals with CP are able to access assessments involving receptive language (Bishop, Byers Brown, & Robson, 1990; Dahlgren Sandberg, 2001), we decided to match a sample of children with CP to a TD sample using a measure of receptive vocabulary. Given the broad battery of experimental measures that we employed, which spanned across two domains, the choice of a matching measure was not straight forward. Thus, we chose receptive language as a proxy for general IQ. Whilst this does dictate that performance in the domains of interest is likely to be poor relative to the TD group, the use of a battery of tasks enables us to ask

questions regarding profiles of performance, i.e. which aspects of visual-spatial cognition are more vs. less impaired, and to detail how cross domain associations compare to those observed in the typical population.

2.2. Participants

Thirty-two children with a diagnosis of CP (18 males), aged between 7 years and 18 years; 2 months, were selected from two special schools for children with physical disabilities in the UK. The children were selected from special schools as they were an opportunistic sample and the first author was familiar to the children in both schools. Medical information was not available to the researchers, but observations made by experienced teaching staff and the first author indicated that all the children, bar one, had predominantly either quadriplegic spastic or athetoid CP or a mixture of both which had variable effects on their functionality. The remaining child had hypotonic muscle tone and poor posture, possibly ataxic CP (see Rosenbaum et al., 2006). Twenty-six of the children used a wheelchair to move around school, and seventeen of these children used a walking frame for part of the time. Six children moved around school with no aids.

Teacher rating of the children's mobility using the Movement Assessment Battery for Children Checklist (Henderson, Sugden, & Barnett, 2007) was undertaken and the results (higher scores up to a maximum of 90 indicated poorer mobility) were as follows: Mean: 56.94; SD: 16.32; Minimum: 15; Maximum: 87. Most of the children performed typically in the section of the checklist describing fine-motor abilities, e.g. manipulating small objects such as picking up beads and moving small cubes except for one child who used her big toe for pointing and keyboarding, and two others who found moving sheets of paper difficult. However, all the children were able to point.

The children were selected using the following criteria by the teaching staff:

- Sufficient communication and speech abilities to verbally answer questions in test situations;
- Typical visual acuity (with glasses if necessary);
- Typical hearing abilities (with a hearing aid if necessary);
- Sufficient dexterity to respond to the tasks.

Ethical approval was obtained from the relevant University Committee prior to the study (BERA, 2011). Parental written consent and the children's verbal consent were obtained prior to testing. Children were seen on an individual basis in quiet areas or rooms. To avoid fatigue, particularly in the CP group, sessions were kept to between 20 and 30 minutes, over 6–8 occasions.

Performance of the CP group was compared to that of 32 TD children (16 males) aged between 6 years 2 months and 11 years 7 months from three mainstream schools in the UK. The two groups of children were individually matched for raw scores on the British Picture Vocabulary Scale ([BPVS-III]; Dunn, Dunn, & NFER, 2009). As can be seen in Table 1, the mean percentile score of children with CP indicates they had poor receptive vocabularies.

2.3. Procedure and assessments

All assessments were administered and scored according to the relevant assessment manual by experienced researchers. The order of the assessments was determined by each researcher according to the length of time available for each session, and the length of time taken by each child to complete a task. Typically, the assessments for the children with CP were undertaken in the following order: BPVS-III, Mathematics Oral test, Matrices from the British Ability Scales 3rd edition ([BAS3] Elliot & Smith, 2011); Mathematics written paper, Mental Rotation Task, Working Memory Test Battery (WMTB-C) Block Recall; TVPS-3 (R). In order to reduce fatigue, a longer test such as the BPVS-3 was followed by a shorter test such as the Mathematics oral paper within one session. The children in the TD group were assessed in sessions that lasted up to an hour.

2.3.1. Receptive language

Participants completed the British Picture Vocabulary Scale (BPVS III; Dunn et al., 2009), a measure of receptive vocabulary involving the child selecting which of four pictures corresponds to a spoken word.

Table 1

Age (years: months) and Receptive Vocabulary in CP and TD Groups (standard deviations in parentheses). (For interpretation of the references to colour in the figure text, the reader is referred to the web version of this article).

	BPVS-III Receptive Vocabulary			
	Mean Age	Mean Raw Score	Standardised Scores	Mean Percentile Rank
CP Group	13:7	123.8	18.53	18.5
	(2:5)	(22.9)	(24.2)	(24.2)
TD Group	8:6	124.1	59.38	59.4
	(1:6)	(22.3)	(24.1)	(24.1)

2.3.2. Mathematical ability

Mathematics ability was measured using the Mathematics Computation test from the Wide Range Achievement Test ([WRAT-4]; Wilkinson & Robertson, 2006). This has two sections. Part 1 is an oral test comprising fifteen items starting with simple counting, identification of numbers and basic addition and subtraction calculations. Part 2 is a written paper with calculations involving the four rules of number, including fractions and decimals. It starts with simple sums and progresses to complex calculations and has to be completed within fifteen minutes. Scores from both papers are added together to give a total raw score.

2.3.3. Visual-spatial measures

Participants completed a battery of visual-spatial measures as detailed below.

2.3.3.1. The Test of Visual Perception Skills 3rd Edition (Revised), TVPS-3 (R), (Martin, 2006). This test was used to assess a range of visuospatial abilities. It consists of seven subtests which measure a different aspect of visual or spatial abilities. The test is not timed. A summary visuospatial perception score can be calculated from the results of the seven sub-tests.

Visual discrimination

Visual discrimination is the ability to distinguish between different shapes, patterns, forms or colours. The test requires the child to match a shape at the top of a page with one of the five shapes displayed at the bottom of the page

Visual memory

This is the ability to remember the exact shape, form, number of visual stimuli for a short space of time. The test consists of seeing a shape on one page for five seconds. On the next page, the child has to identify the same shape from a display of four shapes.

Visual spatial relationships

This is the ability to understand or recognise the positioning of shapes or objects. The test involves showing five shapes or drawings on a page of which four are identical and one is slightly different in some way.

Visual sequential memory

This is the ability to remember a sequence of visual information such as numbers or patterns. A child has to remember a specific shape or set of shapes which is presented on one page. After five seconds the child is presented with four sets of similar shapes on the next page, only one of which is identical to the first array.

Visual form constancy

This is the ability to recognise or name shapes, forms or objects by their specific attributes. A shape is displayed on the top half of a page. The bottom half displays five shapes one of which is the top shape transformed in some way, e.g. by rotating the image.

Visual figure ground

This is the ability to identify a shape which is inserted or placed against a background. The test requires a child to select which of four displays contains the identical shape to the one at the top of the page.

Visual figure closure

This test requires the ability to make sense of images which are not clear or finished in some way. An incomplete shape is shown at the top of a page, e.g. a rectangle with no corners, and four complete images are shown at the bottom of the page. Only one of these images can be drawn from the incomplete shape.

2.3.3.2. The Block Recall Test. This test from The Working Memory Test battery (WMTB-C) (Pickering & Gathercole, 2001) was included as a measure of visuospatial short-term memory (STM). This test is akin to a Corsi block test.

2.3.3.3. A Mental Rotation task. This test was included as a measure of the ability to process spatial information. In this task (from Broadbent, Farran, & Tolmie, 2014), participants view two mirror imaged monkeys on the top half of a computer screen (Fig. 1).

The children were asked to choose which of the two monkeys on the top half of the screen matched a monkey on the bottom half of the screen. Crucially, the monkey in the bottom half of the screen was displayed rotated at 0°, 45°, 90°, 135° or 180° (6 practice trials; 32 experimental trials). The percentage of correct responses was calculated for each participant. The task was completed on a laptop, but a large-keys keyboard was available for those children who found the laptop keys difficult to access. Two children in the CP group pointed to their chosen monkey and their choices were typed for them.

2.3.3.4. The Matrices subtest from the British Ability Scales 3rd edition (BAS3) (Elliot & Smith, 2011). This test was included as a visual-spatial assessment of non-verbal reasoning.

3. Results

3.1. Group differences in mathematics and visual-spatial cognition

The mean raw and standardised scores of the WRAT-4, TVPS-3 (R), Block Recall and BAS-3 matrices are given in Table 2. Independent *t*-tests revealed that, despite the CP group having a higher chronological age than the TD group, the CP group had significantly lower raw scores than the TD group on WRAT-4 Mathematics ($t[62] = -3.49$, $p < .001$, $d = -0.87$) and the four measures of visual-spatial cognition: the summary score for the TVPS-3 ($t[62] = -7.05$, $p < .001$, $d = 1.76$); WMTB-C Block Recall ($t[62] = -4.86$, $p < .001$, $d = 1.21$); the Mental Rotation task ($t[62] = -4.5$, $p < .001$, $d = 1.16$; and BAS-3 Matrices ($t[62] = -5.28$, $p < .001$, $d = 1.32$). All of these comparisons produced large to extremely large effect sizes (Cohen, 1992). A Bonferroni
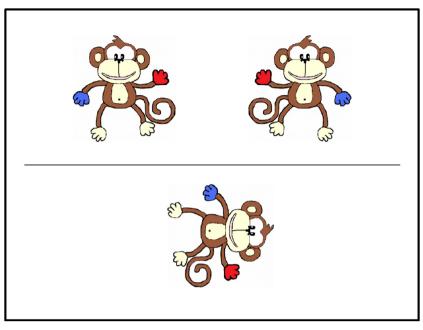
Fig. 1. Monkey rotation task.

Table 2
Mean raw scores of the CP and TD groups on the assessments of mathematical and visual-spatial abilities (standard deviation in parentheses; standardised scores are in italics).

	CP Group	TD Group	Cohen's *d*
WRAT-4 Mathematics	20.25 (7.55) *64.78*	26.41 (6.51) *99.69*	0.87
TVPS-3 (R) Summary Score	26.75 (17.20) *60.13*	58.22 (18.48) *95.81*	1.76
WMTB-C Block Recall	15.75 (7.14) *7.56*	23.53 (5.57) *39.88*	1.21
Mental Rotation Task (proportion correct)	0.63 (0.16)	0.84 (0.20)	1.16
BAS-3 Matrices	16.69 (11.35) *2.09*	31.06 (10.39) *42.53*	1.32

WRAT4: mathematics ability.
TVPS-3 (R): visual perception.
WMTB-C: visual short-term memory (STM).
BAS-3: non-verbal matrices.

correction gives the critical significance value for the five tests as $p < .003$, consequently, all differences can be considered significant. Thus, these comparisons suggest that the CP group had significantly poorer mathematical and visual-spatial abilities relative to the TD group.

Because there were group differences in the summary raw scores from the TVPS-3 it was decided to check whether these differences occurred across all of the sub-scales. Table 3 details the mean raw scores on the subtests. The children in the CP group scored lower than the control group and independent *t*-tests gave the following statistics: Visual Discrimination $t[62] = -4.74, p < .001, d = 1.2$; Visual Memory $t[62] = -6.46, p < .001, d = -1.6$; Visual Spatial Relations $t[62] = -6.45, p < .001, d = -1.6$; Visual Sequential Memory $t[62] = 4.93, p < .001, d = 1.25$; Form Constancy $t[49.53] = 4.62, p < .001, d = -1.31$; Figure Ground $t[53.65] = -5.74, p < .001, d = 1.57$ and Visual Closure $t[52.83] = 3.55, p < .010, d = 0.98$. These differences involved large to

Table 3
Mean TVPS-3 (R) visual perception raw scores (Max: 16) obtained for each group (standard deviation in parentheses).

	CP Group	TD Group	Cohen's *d*
Visual Discrimination	4.94 (6.82)	7.34 (3.08)	1.18
Visual Memory	4.31 (3.51)	9.66 (3.09)	1.62
Visual Spatial Relations	4.75 (3.92)	11.47 (4.41)	1.61
Visual Sequential Memory	4.81 (3.50)	9.06 (3.40)	1.25
Form Constancy	3.03 (2.35)	6.88 (4.08)	1.31
Figure Ground	3.22 (2.6)	8.03 (3.96)	1.57
Visual Closure	2.84 (2.53)	5.78 (3.94)	0.98

Table 4
Correlations between age, receptive vocabulary, maths, visual perception, visual STM, mental rotation and matrices for CP and TD groups (CP group above the diagonal and top right, RD below the diagonal and bottom left).

	Age	BPVS	WRAT-4	TVPS-R	WMTB	Rotation	BAS-3
Age	1	.475**	0.189	−0.018	0.015	0.184	0.267
BPVS Rec vocab	.852**	1	.748**	.488**	0.299	0.254	.746**
WRAT-4 Maths	.905**	.845**	1	.763**	.588**	.497**	.79**
TVPS-3 (R) Visual perception	.732**	.774**	.723**	1	.669**	.528**	.625**
WMTB-C V. STM	.617**	.464**	.584**	0.337	1	.595**	.482**
Mental rotation	.402*	0.096	0.243	.39*	0.336	1	.464**
BAS-3 Matrices	.699**	.584**	.604**	.683**	.351*	.432*	1

* $p < .05$.
** $p < .01$.

extremely large effect sizes. Form Constancy, Figure Ground and Visual Closure all had unequal homogeneity of variance according to Levene's test, these were checked with Mann-Whitney U tests ($U = 228.50$, $p < .001$; $U = 135.00$, $p < .001$; $U = 265.50$, $p < .01$ respectively). Applying a Bonferroni correction set the critical significance value for the seven tests to $p < .0008$, as a result we need to be cautious when interpreting these differences as significant, particularly the findings about Visual Closure.

3.2. Predictors of mathematical ability

To investigate the relationships between the four assessments involving visual-spatial abilities (i.e. visual perception; visual STM; rotation; matrices task) to mathematical abilities, stepwise hierarchical regressions were conducted separately for each independent variable. The correlations between these variables are shown in Table 4. For the TD group, the correlation between age, receptive vocabulary and mathematical ability was above r = 0.80 giving rise to concern about multi-collinearity. However, for both groups the relevant statistics for tolerance and VIF were satisfactory. Mahalanobis values were acceptable except for one TD participant for mental rotations and the removal of this case did not change the significance values, all Cook's distance measures were acceptable.

Table 5 provides information about the outcome of the regression analyses. For each multiple regression, age was entered at step 1 and receptive vocabulary was entered at step 2. In this way age and language ability were controlled. At step 3 the independent variable of interest (e.g. visual perception) was entered.

For the TD group, the adjusted R^2 at step 3 was 0.82. At step 1, the entry of age resulted in a R^2 change of 0.82 ($p < .001$), and at step 2 the entry of receptive vocabulary resulted in a R^2 change of 0.02 ($p < .070$). However, the entry of the visual variables at step 3, failed to produce a significant change in R^2. Examination of the standardised beta coefficients at step 3 revealed that age was the only significant predictor, although the beta coefficients for receptive vocabulary had p values between .05 and .10.

For the CP group, the regression equation accounted for slightly less of the variance, the R^2 at step 3 was 0.75. In contrast to the TD group, at step 1, the entry of age resulted in a non-significant R^2 change of 0.04 ($p < .001$), and at step 2 the entry of receptive

Table 5
Regression analyses to predict mathematical ability from age, receptive vocabulary and visual abilities.

	Adjusted R2	R^2 Change	STANDARDISED BETA COEFFICIENTS		
	at Step 3	Step 3	Step 3		
VARIABLES			Age	Receptive Vocabulary	Independent Variable (given in leftmost column)
TD Group					
TVPS-3 (R)	0.82	0.01	.66***	0.24	0.05
WMTB-C	0.83	0.00	.62**	0.28	0.07
Mental Rotation	0.83	0.01	.79***	0.19	−0.09
BAC-3 Matrices	0.82	0.00	.71***	0.27	−0.05
CP Group					
TVPS-R	0.75	.17***	−0.05	.53***	.51***
WMTB-C	0.69	.13**	−0.15	.71***	.38**
Mental Rotation	0.68	.11**	−.24*	.77***	.35**
BAS-3 Matrices	0.67	.11**	−0.16	.46*	.49**

TVPS-R: Visual perception.
WMTB-C: Visual STM.
BAS-3: Non-verbal matrices.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

Table 6

Correlations between the subtests of visual-spatial ability, (correlations of CP group in top right above the diagonal, TD in bottom left below the diagonal).

	Age	Receptive Voc.	Vis. Discrim.	Vis Memory	Spatial Relat.	Vis. Seq. Memory	Form Constancy	Figure Ground	Visual Closure
Age	1	.475**	0.017	−0.038	0.113	0.038	−0.161	−0.105	−0.038
Receptive Voc.	.852**	1	.461**	.408*	.526**	.533**	0.185	0.231	0.246
Vis. Discrim	.614**	.592**	1	.621**	.581**	.486**	.472**	.577**	.488**
Vis. Memory	.443*	.402*	.523**	1	.568**	.688**	.523**	.702**	.430*
Spatial Relat.	.588**	.655**	.702**	.337	1	.632**	.625**	.576**	.680**
Vis. Seq. Memory	.538**	.560**	0.307	.273	.362*	1	.649**	.559**	.496**
Form Constancy	.561**	.670**	.569**	.550**	.549**	0.306	1	.719**	.626**
Figure Ground	.488**	.573**	.653**	.404*	.490**	0.309	.393*	1	.655**
Visual Closure	.414*	.371*	.547**	.360*	0.335	0.199	0.241	.504**	1

* $p < .05$.
** $p < .01$.

vocabulary resulted in a significant R^2 change of 0.56 ($p < .001$). The entry of the visual cognition variable at step 3 always produced a significant increase in R^2 (range 0.11–0.17). The beta coefficients at step 3 show that only in one case did age have a significant coefficient (mental rotation), whereas the beta coefficient for both receptive vocabulary and for the visual-spatial variables always had values with $p < .05$. For some variables (visual discrimination, visual STM and mental rotation), there was a noticeably higher beta coefficient for receptive vocabulary than for the relevant visual ability.

Additionally, we investigated the relationship between the visual perception subtests and mathematics performance in each group. For the TD group, the correlation between age and receptive vocabulary was above 0.80 giving rise to concern about multi-collinearity (see Table 6). However, all the relevant statistics for tolerance and VIF were satisfactory, as were Mahalanobis values and Cook's distance.

In the regression analyses, as before, age was entered at step 1, and receptive vocabulary was entered at step 2, with the relevant visual perception subtest being entered at step 3. The findings from these analyses are given in Table 7. For the TD group, the adjusted R^2 was 0.83. The changes in R^2 at step 1 and 2 were as before (for age at step 1, $R^2 = 0.82$ ($p < .001$; for receptive vocabulary at step 2 $R^2 = 0.02$ ($p < .070$). However, at step 3 the entry of the visual perception subtests, failed to significantly increase this variance except for one variable (visual sequential memory). Examination of the standardised beta coefficients at step 3 revealed that age was a highly significant predictor, and that the beta coefficient for visual sequential memory indicated it was the only other significant predictor.

For the CP group, the adjusted R^2 value was 0.58 and there were similar statistics for step 1 and 2 (step 1, age, R^2 change = 0.04, $p < .001$; and at step 3, receptive vocabulary, R^2 change = 0.56, $p < .001$). The entry of the visual perception subtests at step 3

Table 7

Regression analyses to predict mathematical ability the TVPS-3 (R) subtests.

VARIABLES	Adjusted R2 Step 3	R^2 Change Step 3	STANDARDISED BETA COEFFICIENTS Step 3		
			Age	Receptive Vocabulary	Independent Variable
TD Group					
Visual Discrimination	0.83	0.00	.71***	0.29	−0.08
Visual Memory	0.82	0.00	.68***	0.27	−0.00
Spatial Relationships	0.82	0.00	.68***	0.28	−0.02
Visual Sequential	0.86	.03*	.63***	0.19	.21*
Form Constancy	0.82	0.00	.68***	0.26	0.01
Figure Ground	0.82	0.00	.68***	0.30	−0.5
Visual Closure	0.83	0.00	.65***	0.26	0.06
CP Group					
Visual Discrimination	0.58	0.02	−0.17	.75***	0.17
Visual Memory	0.77	.17***	−0.07	.59***	.47***
Spatial Relationships	0.74	.17***	−0.13	.55***	.50***
Visual Sequential	0.69	.13**	−0.09	.56***	.44**
Form Constancy	0.61	0.05	−0.14	.77***	0.24
Figure Ground	0.66	.10**	−0.12	.73***	.33**
Visual Closure	0.64	.08*	−0.16	.75***	.29*

* $p < .05$.
** $p < .01$.
*** $p < .001$.

always produced a significant increase in R^2 except for visual discrimination and form constancy. The beta coefficients at step 3 showed that age was never a significant predictor of mathematical ability, whereas receptive vocabulary was always a significant predictor, and five of the visual perception subtests were significant predictors (the exceptions being visual discrimination and form constancy).

4. Discussion

This study was carried out in order to determine whether the difficulties that children with CP have with developing mathematical skills are related to their visual and spatial perception impairments. The children in the CP and TD groups were matched on receptive vocabulary, an assessment commonly used with children with CP (Bishop et al., 1990; Dahlgren Sandberg, 2001). The children with CP were selected to have spoken language and manual dexterity which were sufficient to complete the tests, so the results of this study cannot be generalised to all children with CP. The group comparisons revealed that mathematics and visual-spatial abilities in the CP group were at a lower developmental level (based on standardised scores) than in the TD group and that their visual-spatial abilities were generally very poor.

The group comparisons showed that the test of visual perception (TVPS-3) was the most problematic of the four assessments for the CP group as shown by Cohen's *d* (Tables 2 and 3) and so we will discuss this assessment first. The analyses revealed that the CP group had lower raw scores on all the visual perception subtests than the TD group and for all assessments there was a large to extremely large difference. Given that we carried out analyses on all seven subtests it is possible that some of these findings were due to chance factors, however, all differences were in the same direction and the findings for the different subtests were similar. Across the seven subtests there was no clear evidence of less impaired performance on the subtests without notable memory demands (Visual Discrimination, Spatial Relationships, Form Constancy, Figure Ground, and Figure Closure) compared to those that had memory demand (Visual Memory, Visual Sequential Memory). Thus, our findings suggest that children with CP have impaired performance with all the visual perception subtests in the TVPS-3, irrespective of the form of the task. These figures are comparable to those produced in a study of children with CP who also used the TVPS-3 (Menken et al., 1987). The finding that children with CP had the lowest scores on the visual perception test, in comparison to the other three tests which also assessed cognitive processing (memory, executive functioning, general problem solving), suggests that visual perception impairments rather than more general cognitive impairments might be the primary disability; although there was evidence from the visual perception test that visual memory was both severely impaired and related to mathematical ability. Consequently, there is the possibility that performance on some cognitive and mathematical assessments is impeded by impairments in basic visual perception rather than the cognitive demands of the tasks.

We now turn to consider the other three visual-spatial assessments. A computer version of the WMTB-C visual STM task has been used by Gagliardi et al. (2013), who reported significantly lower performance of children with CP compared to a CA comparison group. The children with CP in our investigation also had significantly lower performance than the TD group on the visual STM task. One reason for the low raw scores of the CP group on this test might be because of poor fine motor skills as suggested by Gagliardi et al. (2013), however the children in our study were considered by their teachers to have sufficient manual dexterity to complete simple assessment tasks, and all of the children completed this test. Furthermore, Stadskleiv et al. (2017) found that the physical dexterity of their participants with CP made no difference to their abilities in a recall test (completed on a computer), and informal observations by the first author suggested that the responses on the visual STM task of children in our study were not dependent on precise motor movements other than pointing. All this supports the idea that the CP group's lower scores are more likely to be due to their difficulties with perceiving the shape and positions of the blocks or remembering the sequences of the blocks rather than their motor skills (see Gagliardi et al., 2013).

The Mental Rotation Task relies on the children's abilities to perceive and store visual information while attention is given to another picture and this process is likely to involve executive working memory processes (Henry, 2011). A previous study using mental rotation tasks which required children with CP to identify shapes that were similar or mirror images of each other, demonstrated that the CP group had significantly longer response times than the TD group, but a similar amount of errors (Courbois et al., 2004). In our study, the children needed to identify markers such as the position of the red and blue gloves on the hands of the monkeys or the position of the arms (see Fig. 1) and remember these orientations while looking at the monkey in the bottom of the picture. We found that the CP group had a significantly lower percentage of correct responses than the TD group, and Cohen's *d* indicated that their decrement of performance on mental rotation was similar to the TVPS-3 subtests of Visual Discrimination, Spatial Relationships and Form Constancy, all of which involve the ability to make comparisons between different visual stimuli that are presented on one page. Thus, for the CP children, the Mental Rotation task appeared to have a similar profile of scores as other comparable visual-spatial tasks and it did not appear to be markedly more difficult than other assessments of visual-spatial abilities.

The children with CP also had BAS-3 matrices scores that were significantly lower than those of the TD group. The identification of low matrices scores in children with CP is consistent with other studies which have used the RPM/RCPM (Jenks et al., 2012; Peeters et al., 2008). Our findings are also consistent with the evidence that children with CP have better receptive language than non-verbal ability as assessed by matrices tasks (Bishop et al., 1990; Dahlgren Sandberg, 2001). However, our findings differ from those of Ballester-Plané et al. (2016), whose study showed that participants with CP had better RCPM performance than receptive language. The reasons for this discrepancy between the findings from their and our investigation are not clear, although their participants were mainly adults and the types of CP may be different as our participants had mixed types of CP. Research comparing groups of children with CP suggest that children with dyskinetic CP may perform better on receptive language assessments, but results are not conclusive (Ballester-Plané et al., 2018). Further research is needed to understand the reason for any differences between adults and children with CP.

One explanation for the impaired visual-spatial abilities in children with CP is that there could be motor or even perceptual difficulties when executing relevant manual tasks that are used in the assessments (Abercrombie, 1964; Akhutina et al., 2003). In addition, van Rooijen et al. (2012) reported that fine and gross motor skills had significant correlations with arithmetic abilities in children with CP, and fine motor skills was a significant predictor in a structural equation model which contained assessments of decoding and non-verbal intelligence. As already mentioned the visual-spatial tasks we administered had minimal motor components which suggest that poorer visual-spatial performance was unlikely to have been directly due to motor impairments.

Regression analyses were conducted to investigate whether visual-spatial abilities were related to mathematics performance and whether the relationships were similar in the CP and TD groups. When interpreting these relationships, it is useful to bear in mind that having low scores on a visual-spatial assessment does not necessarily result in the assessments being significantly correlated with mathematical ability. In theory, children could have had low scores on visual-spatial assessments, but these scores might not be significantly related to mathematical ability, however, in their study, van Rooijen et al. (2012) report that the RCPM was significantly correlated with arithmetic ability in children with CP.

The first set of regression analyses involved age and receptive vocabulary as covariates, and each of the four visual-spatial perceptual abilities. In the TD group, only age was a significant predictor of mathematical ability. In contrast, in the CP group, receptive vocabulary and the four visual-spatial variables were significant predictors of mathematical ability. This suggests that for the TD group, age and by implication age-related general cognitive development, is more important than receptive vocabulary and visual-spatial perceptual abilities in the development of mathematical competence. Whereas, for children with CP, our findings suggest that receptive vocabulary and visual spatial abilities are more important than age in the development of mathematical competence.

We also investigated whether there were significant relationships between the visual perception subtests and mathematics ability (see Table 5). Regression analyses revealed for the TD group that at step 3, mathematical ability was significantly predicted by age, but not by receptive vocabulary and visual perception (except in the case of visual sequential memory). In contrast, for the CP group, receptive vocabulary was the most important predictor of mathematical ability, and all the visual subtests except for visual discrimination and form constancy were significant predictors of the mathematical ability at step 3.

These findings suggest that visual-spatial impairments in CP are wide reaching with cascading developmental effects on other abilities. In addition, the presence of the significant relationships between visual-spatial abilities and mathematics, even after accounting for age and receptive vocabulary, suggests that in the CP group impaired visual-spatial abilities limit the development of mathematical competence. However, given the number of regressions conducted caution is needed when interpreting the significance of the findings, although it is reassuring that the different analyses produced remarkably consistent findings.

4.1. Implications and summary

This study has confirmed that many children with CP have visual-spatial perception difficulties which are likely to have an effect on their ability to develop mathematical skills. An inability to perceive and identify shapes and patterns can affect how children learn to read and write numbers; learn to calculate sums such as on a number-line; read and understand written problems; and set out sums. These are all basic skills that young children develop before more complex tasks can be learnt. Teachers and clinicians need to be aware of these difficulties and modify their teaching approaches to include tasks and activities that can help to improve the children's visual and spatial capabilities. Our findings suggest that the largest impairments in these abilities involved visual memory, visual spatial relationships and figure ground, while the strongest predictors of mathematical ability involved visual memory, visual spatial relationships and visual sequential memory. Therefore, activities that target these processes might be of help to the education of children with CP.

To summarise, researchers have identified that many children with CP have difficulties with visual and spatial perception and have delayed development in mathematical skills. Our investigation supported and extended these findings. The analyses revealed that children with CP, in comparison to a group of receptive language matched TD children, had significant poorer performance on an assessment of mathematical ability and on a battery of visual-spatial assessments which only required responses involving basic motor abilities. Furthermore, we did not find that tasks which involved additional demands from the active processing of visual-spatial information resulted in markedly worse performance. Moreover, in the CP group virtually all of the visual-spatial assessments were significant predictors of mathematical ability even after controlling for the effects of age and receptive vocabulary; whereas in the TD group, virtually all the visual-spatial assessments had non-significant relationships with mathematical ability. These findings suggest that in children with CP, visual-spatial abilities may be important for carrying our mathematical tasks, and more important than for TD children. Further research, possibly based around experimental interventions, is needed to determine whether these associations involve a causal relationship.

Acknowledgements

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