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The relation between visual functions, functional vision, and bimanual function in children with unilateral cerebral palsy

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ABSTRACT

Background: Accurate visual information is needed to guide and perform efficient movements in daily life.
Aims: To investigate the relation between visual functions, functional vision, and bimanual function in children with unilateral cerebral palsy (uCP).
Methods and procedures: In 49 children with uCP (7-15 y), we investigated the relation between stereoacuity (Titmus Stereo Fly test), visual perception (Test of Visual Perceptual Skills), visuomotor integration (Beery Buktenica Test of Visual-Motor Integration) and functional vision (Flemish cerebral visual impairment questionnaire) with bimanual dexterity (Tyneside Pegboard Test), bimanual coordination (Kinarm exoskeleton robot, Box opening task), and functional hand use (Children's Hand-use Experience Questionnaire; Assisting Hand Assessment) using correlations (r_s) and elastic-net regularized regressions (d).
Outcomes and results: Visual perception correlated with bimanual coordination (r_s=0.407-0.436) and functional hand use (r_s=0.380-0.533). Stereoacuity (r_s=−0.404), visual perception (r_s=−0.391 to −0.620), and visuomotor integration (r_s=−0.377) correlated with bimanual dexterity. Functional vision correlated with functional hand use (r_s=−0.441 to −0.458). Visual perception predicted bimanual dexterity (d=0.001-0.315), bimanual coordination (d=0.004-0.176), and functional hand use (d=0.001-0.345), whereas functional vision mainly predicted functional hand use (d=0.001-0.201).

Abbreviations: AHA, Assisting Hand Assessment, Fifth Edition; Beery-VMI, Beery Buktenica Test of Visual-Motor Integration, Sixth Edition; CHEQ, Children's Hand-use Experience Questionnaire, Second Edition; CP, Cerebral palsy; CVI, Cerebral Visual Impairment; FCVIQ, Flemish cerebral visual impairment questionnaire; MACS, Manual Ability Classification System; TPT, Tyneside Pegboard Test; TVPS-4, Test of Visual Perceptual Skills, Fourth Edition; uCP, Unilateral cerebral palsy; VI, Visual impairment; VMI, Visuomotor integration.

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Conclusions and implications: Visual functions and functional vision are related to bimanual function in children with uCP highlighting the importance of performing extensive visual assessment to better understand children's difficulties in performing bimanual tasks.

What this paper adds: Previous findings showed that up to 62 % of children with unilateral cerebral palsy (uCP) present with visual impairment, which can further compromise their motor performance. However, the relation between visual and motor function has hardly been investigated in this population. This study makes a significant contribution to the literature by comprehensively investigating the multi-level relation between the heterogenous spectrum of visual abilities and bimanual function in children with uCP. We found that mainly decreased visual perception was related to decreased bimanual dexterity, bimanual coordination, and functional hand use while impairments in functional vision were only related to decreased functional hand use. Additionally, elastic-net regression models showed that visual assessments can predict bimanual function in children with uCP, however, effect sizes were only tiny to small. With our study, we demonstrated a relation between visual functions and bimanual function in children with uCP. These findings suggest the relevance of thoroughly examining visual functions in children with uCP to identify the presence of visual impairments that may further compromise their bimanual function.

Accurate visual information is needed to guide motor tasks efficiently, serving as input and feedback for executing and fine-tuning movements in daily life. The relation between visual and motor function is controlled by a complex neural network. Early brain lesions disrupting this neural network can severely impact visuomotor information processing (Jeannerod, 1986). This is particularly relevant for cerebral palsy (CP), a predominantly motor disorder often accompanied by additional disturbances (e.g., sensation, perception, cognition, communication and behaviour, epilepsy) (Graham et al., 2016; Rosenbaum et al., 2007), in which visual impairment (VI) is a well-recognized comorbidity (Duke et al., 2022; Ego et al., 2015). CP is a heterogeneous condition, with 44 % of the cases presenting with spastic unilateral CP (uCP), characterized by sensorimotor impairments predominantly on one side of the body (Himmelmann & Uvebrant, 2018). In children with uCP, motor difficulties are mainly present in the upper limb, resulting in impairments in bimanual dexterity (Basu et al., 2018; Decraene et al., 2021) and coordination (Decraene et al., 2023; Mailleux et al., 2023; Rudisch et al., 2016). Besides motor problems, up to 62 % of children with uCP show some degree of VI, covering a broad spectrum, including ocular (i.e., myopia, hypermetropia, and astigmatism), oculomotor (i.e., strabismus), geniculostriate (i.e., visual acuity, stereoacuity), and visual–perceptual impairments (Crotti et al., 2024) which can be measured through standardized tests as reported in the literature on children with CP (Ciner et al., 2018; Deramore Denver et al., 2016). Additionally, cerebral visual impairment (CVI), defined as VI which cannot be attributed to disorders of the anterior visual pathways or any potentially co-occurring ocular impairment, is frequently reported as a comorbidity in CP (9 %−70 %) (Heydarian et al., 2022; Schenk-Rootlieb et al., 1994). Impairments in such visual functions may further compromise the motor task performances of children with CP (Bakke et al., 2019), especially those involving complex movements, such as bimanual dexterity (Wiesendanger & Serrien, 2001) and coordination (Swinnen & Gooijers, 2015). Previous findings showed that children with uCP with more impaired motor skills, measured according to the Gross Motor Function Classification System and the Bimanual Fine Motor Function, presented with more severe VI (Rauchenzauner et al., 2021). Additional studies highlighted that decreased visual-perceptual functions were related to worse writing skills (Bumin & Kavak, 2008) and to reduced motor skills during activities of daily living in children with uCP (James et al., 2015). Furthermore, VI can affect the quality of life of children with CP hindering their self-esteem, emotional and social well-being (Colenbrander, 2005; Mitry et al., 2016; Tessier et al., 2014). Altogether, these findings underline the importance of investigating the use of vision (i.e., functional vision) (Bennett et al., 2019) in relation to motor function in everyday life (i.e., functional hand use). Nevertheless, although previous studies indicated that VI may be related to motor performance in children with uCP (Bumin & Kavak, 2008; James et al., 2015; Rauchenzauner et al., 2021), these studies only included a limited assessment of visual and bimanual function, no investigation of functional vision (James et al., 2015; Rauchenzauner et al., 2021), or a relatively small sample size ($n < 30$) (Bumin & Kavak, 2008).

Therefore, due to the limited existing research, we performed an exploratory study (1) to comprehensively map the associations between visual functions, functional vision, and bimanual function in children with uCP using a comprehensive assessment; and (2) to explore the extent to which assessments of visual functions and functional vision predict bimanual function in children with uCP.

1. Material and methods

1.1. Participants

Between 2021 and 2022, children diagnosed with spastic uCP were recruited via the CP care program of University Hospitals Leuven (Belgium). The recruitment was performed by two trained child physiotherapists (L.D. and L.K.), during which participants were included if they were aged between 7 to 15, if they could understand the test instructions based on available cognitive information in the medical records and in consultation with the treating child neurologist, and if they were able to actively grasp an object (e.g. a small block 3 cm × 3 cm × 1 cm and/or a pencil) with their non-dominant hand (i.e., House Functional Classification Score ≥ 4) (House et al., 1981).

Non-inclusion criteria were upper limb botulinum neurotoxin-A injections six months before testing or upper limb surgery two years before the assessments. For each participant, we further collected the following descriptive characteristics: lesion timing, classified according to the Magnetic Resonance Imaging Classification Scale (MRICS) (Himmelmann et al., 2017), and binocular far visual acuity, measured with the Freiburg Visual Acuity Test (FrACT) (Bach, 1996). Additionally, the level of manual ability, categorized according to the Manual Ability Classification System (MACS) (Eliasson et al., 2006), and the diagnosis of CVI were retrieved from medical records. This study was approved by the Ethics Committee Research UZ/KU Leuven (S62906).

1.2. Measures

Based on previous studies, standardized and age-appropriate tests showing established psychometric properties in children with CP were selected to assess visual functions (Berelowitz & Franzsen, 2021; Crotti et al., 2024; Ego et al., 2015; Ghasia et al., 2011), functional vision (Ben Itzhak et al., 2021), and bimanual function (Amer et al., 2016; Basu et al., 2018; Decraene et al., 2021, 2023; Holmefur & Krumlinde-Sundholm, 2016; Krumlinde-Sundholm & Eliasson, 2009; Rudisch et al., 2016; Sköld et al., 2011). Each participant performed the assessments either on the same day (approximately for eight hours) or divided across two days, each lasting four hours, depending on the family's preference. To accommodate the extensive battery of tests, breaks were interspersed between assessments to provide children with opportunities for sufficient rest. A graphical overview of the assessments is provided in Figure A.1.

1.3. Visual functions

Binocular stereoacuity, defined as the perception of depth and three-dimensional structure through binocular vision (Howard & Rogers, 1996), was investigated wearing 3D glasses using the fly and the circle subtests of the Titmus Stereo Fly (Stereo Optical Corporation, 2018). In the fly subtest, the child must pinch the wings of a fly displayed in a three-dimensional perspective. The circle subtest includes nine trials with a disparity ranging from 800 to 40″ where the participant has to look at four circles and choose the one that seems to come out closer. Stereoacuity was scored as the last correctly identified circle, with ordinal values ranging between 1 and 9. Information from the fly subtest was retrieved if the child failed to identify the first circle and scored as 0 if failed and 0.5 if successful (Crotti et al., 2024; Stereo Optical Corporation, 2018).

Motor-free visual-perceptual skills, defined as the abilities responsible for the reception and cognition of visual stimuli (Schneck, 2013) were assessed using five subtests of the Test of Visual Perceptual Skills, Fourth Edition (TVPS-4) in which the participant had to identify a targeted black-and-white image among four or five options presented on a booklet (Martin, 2017). The visual memory and sequential memory subtests were not administered in our study since our aim was not to assess memory-related impairments (Crotti et al., 2024). For each subtest, namely visual discrimination (i.e., finding the exact targeted image among similar images), spatial relationships (i.e., finding the one image that is different from the rest), form constancy (i.e., finding the matching image that can be larger, smaller, rotated), visual figure-ground (i.e., finding a target image embedded in a complex design), and visual closure (i.e., matching an incomplete target image), the participant's answers were recorded as raw scores (ranging from 0 to 18). According to the manual, TVPS-4 raw scores were translated into the age-equivalent scaled scores (mean=10, SD=3).

Motor-dependent visual-perceptual skills, were investigated using the visuomotor integration (VMI) subtest of the Beery Buktenica Test of Visual-Motor Integration, Sixth Edition (Beery- VMI) (Beery et al., 2010), which measures the integration of visual-perceptual and motor skills as the participant is asked to copy increasingly more difficult geometric figures. The visual perception and motor coordination subtests of the Beery-VMI were not included in the analysis since the former assesses motor-free visual perception which is already fully screened with the TVPS-4 while the latter assesses fine motor control, which is not the focus of our study. According to the manual, raw scores of the VMI were calculated as the number of figures copied correctly (ranging between 0 to 30) and translated into the age-equivalent standard scores (mean=100, SD=15). The scaled scores of the TVPS-4 subtests and the standard scores of VMI were transformed into standardized z-scores (mean = 0, SD = 1).

1.4. Functional vision

Functional vision was assessed using the Flemish cerebral visual impairment questionnaire (FCVIQ) (Ortibus et al., 2011), a 46-item binary-response screening tool filled by the caregivers. Responses can be calculated as total score according to the sum of the 'yes' items (1, the child presents the characteristic described in the item; 0, characteristic not present) and/or grouped into five factors: object and face processing impairments; visual (dis)interest; clutter and distance viewing impairments; moving in space impairments; and anxiety-related behaviours (Ben Itzhak et al., 2020). In our previous study (Crotti et al., 2024), we reported that in our sample of children with uCP, only six children (12 %) with data on the FCVIQ have cerebral visual impairment (CVI). Additionally, we showed that children with uCP do not show large variability between and within factors on the FCVIQ data when grouped into the five factors (Ben Itzhak et al., 2020). Furthermore, no significant difference was found between the five FCVIQ factors between children with uCP with MACS-level I, II, and III. For this reason and to reduce the number of parameters included in our analysis, the results of the FCVIQ were calculated as a total score only.

1.5. Bimanual function

1.5.1. Bimanual dexterity and coordination

Bimanual dexterity, namely the ability to perform fast coordinated movements (Poirier, 2012), was assessed using the bimanual task of the Tyneside Pegboard Test (TPT), which measures the ability of the participant to pick up nine pegs, one at a time, from a board with one hand, move the peg through a central opening of a screen to the other hand, and place the peg in the adjacent board (Basu et al., 2018). The task was performed in two directions: from the non-dominant hand to the dominant hand and from the dominant hand to the non-dominant hand. For both directions separately, results were recorded in seconds (*sec*) as the time to complete the task, where higher scores indicate poorer bimanual performance (Basu et al., 2018; Decraene et al., 2021). According to the literature, we implemented a maximum time of completion (i.e., 120 *sec* for the non-dominant to dominant hand condition and 150 *sec* viceversa) for each child unable to perform a task or who performed slower than this proposed threshold (Decraene et al., 2021).

Bimanual coordination, defined as the integration of the left and right limb movements into a functional control entity (Swinnen & Gooijers, 2015), was measured with the Box opening task (Rudisch et al., 2016) and the Kinarm exoskeleton robot (Kinarm, 2021). In the Box opening task, the participant has to open a box with one hand and push the button inside the box with the other hand at a self-selected pace. Three-dimensional electromagnetic motion sensors from Polhemus G4 (Polhemus, Colchester, Vermont, USA) were placed on the dorsal hand side, over the third metacarpal bone, to measure spatiotemporal parameters of each hand at a frequency of 120 Hz. The task entails 10 trials, including two conditions, namely dominant hand and non-dominant hand, which are repeated in a standardized sequence. In the dominant hand condition, the participant opens the box with the dominant hand and pushes the button with the non-dominant hand, while in the non-dominant hand condition, the non-dominant hand is used to open the box and the dominant hand to push the button. According to previous findings, the dominant hand condition is the condition that is more discriminative and related to the level of motor impairments (Mailleux et al., 2023; Rudisch et al., 2016). For this reason, in our analysis, we only included the dominant hand condition, for which two bimanual parameters, namely total movement time and goal synchronization, were calculated with the use of MATLAB R2022a (The Mathworks Inc., Natick, MA, USA). Total movement time indicates the average time in seconds (*sec*) needed to complete the task while goal synchronization represents the spatial coupling between both hands at the end of the movement normalized across total movement time (*sec /sec*) (Mailleux et al., 2023; Rudisch et al., 2016). Higher scores on total movement time and goal synchronization indicate poorer bimanual performance. Bimanual coordination was additionally investigated with the ball-on-bar task (level 2) and the circuit task of the Kinarm exoskeleton robot. In level 2 of the ball-on-bar task, the participant has to balance a moving ball on a bar while reaching for targets. Task parameters were automatically calculated from the Kinarm software (Kinarm, 2021). Based on the study of Decraene et al. (Decraene et al., 2023), three bimanual task parameters, namely bar tilt standard deviation (i.e., variability of the bar angle across the task in *Radius*), hand speed difference (i.e., disparity between absolute hand speeds normalized by the mean hand speed in *%*), and difference in hand path length bias (i.e., difference in hand path length between hands in *cm/cm*) were included in the analysis. Lower scores on the bar tilt standard deviation, hand speed difference, and difference in hand path length bias indicate better bimanual performance.

In the circuit task, the participant has to move both hands simultaneously in different directions (right hand horizontally and left hand vertically) to move a cursor through a 45°-tilted circuit. Synchronization between movements of both hands was calculated with a bimanual coordination factor (range 0 to 0.7), with higher values indicating better bimanual coordination (Yeganeh Doost et al., 2017).

1.5.2. Functional hand use

Bimanual performance, namely the spontaneous use of the non-dominant hand during bimanual tasks, was measured using the Assisting Hand Assessment (AHA 5.0), a video-recorded semi-structured board game, including 20 items. The sum of each item, scored on a 4-point scale, resulted in a total raw score. The total raw score was converted to a logit-based scale (range 0 to 100) where higher scores indicate better bimanual performance (Krumlinde-Sundholm & Eliasson, 2009).

Perceived quality, that is parent observed use of the non-dominant hand during bimanual tasks of daily life, was assessed with the Children's Hand-use Experience Questionnaire (CHEQ 2.0) (Sköld et al., 2011). The CHEQ is a 27-item web-based questionnaire (http://www.cheq.se/) filled by the caregivers. Each item is scored according to three subscales namely, (1) the effectiveness of the use of the non-dominant hand during the bimanual task described (CHEQ-grip), (2) the time needed to complete the bimanual task described (CHEQ-time), and (3) the level of distress experienced by the child when using the non-dominant hand during the bimanual task described (CHEQ-feeling). For each subscale, the raw score was converted to a logit-based scale (range 0 to 100), with higher scores indicating better subjective experience (Sköld et al., 2011).

1.6. Statistical analysis

Frequencies were reported for descriptive characteristics, including sex, side of CP, lesion timing (MRICS), visual acuity, and MACS. Normality of data was assessed with the Shapiro-Wilk test. Results showed that the data of visual functions, functional vision, and bimanual function assessments were not normally distributed. Therefore, medians and interquartile ranges were calculated. First, to investigate univariate associations between visual functions, functional vision, and bimanual function, non-parametric pairwise partial Spearman's Rank correlations were performed. The pairwise method was chosen to maximize the use of available data and the 'partial' analysis was selected to include age as a covariate. Additionally, we performed false discovery rate (*adjusted p-value* $\leq$0.05) for multiple testing correction (Benjamini & Hochberg, 1995). Correlation coefficients (r_s) were interpreted as no or negligible (<0.30), low (0.30-0.49), moderate (0.50-0.69), high (0.70-0.89), or very high ($\geq$0.90) (Mukaka, 2012).

Secondly, elastic-net regularized regression prediction models were built to investigate to which extent assessments of visual functions and functional vision predict bimanual function in children with uCP. The models were fit and evaluated with a nested cross-validation approach. For the outer loop, leave-one-out cross-validation was used, which iteratively selects the data of one participant as a test set, and then trains the model on the data of the remaining participants. This process is repeated for every participant in the dataset. For the inner loop, an elastic-net regularized regression model was built on the training data. This model combines ridge

Table 1
Descriptive characteristics of children with unilateral cerebral palsy included in the analysis.

Characteristics	Category	uCP (*N* = 49), *n* (%)
Mean age (SD)		11 y 11mo (2 y 10mo)
Sex	Male	26 (53)
	Female	23 (47)
Side of cerebral palsy	Right-sided	24 (49)
	Left-sided	25 (51)
[a]MRICS	A	2 (5)
	B	28 (68)
	C	8 (20)
	D	1 (2)
	E	2 (5)
[b]Far visual acuity (VA)	Normal (VA ≤ 0.3 LogMAR)	43 (88)
	Mild (0.3 < VA < 0.5 LogMAR)	5 (10)
	Moderate (0.5 ≤ VA ≤ 1 LogMAR)	0 (0)
	Severe (VA > 1 LogMAR)	1 (2)
[c]Cerebral visual impairment (CVI)	No	37 (76)
	Yes	4 (8)
	[d]Suspected	3 (6)
	[e]Unknown	5 (10)
[c]MACS	I	27 (55)
	II	16 (33)
	III	6 (12)

Percentages are calculated out of the total sample of children with uCP included in the analysis (N = 49).
uCP: unilateral cerebral palsy. SD: standard deviation. y: years. mo: months. [a]Results available only in 41 children. MRICS: Magnetic Resonance Imaging Classification Scale. A: Maldevelopments; B: Predominant white matter injury; C: Predominant grey matter injury; D: Miscellaneous; E: Normal (Himmelmann et al., 2017). [b]Results calculated in LogMAR. LogMAR: logarithm of the minimum angle of resolution= −log10(decimal acuity) (Bach, 1996). VA: Visual acuity. CVI: Cerebral visual impairment. MACS: Manual Ability Classification System (Eliasson et al., 2006). [c]Results retrieved from medical records. [d]Suspected reflects screened for cerebral visual impairment with clear signs but no diagnosis. Caregivers of one child in this group did not fill in the FCVIQ. [e]Unknown reflects no reported data or missing data, which exists because of the retrospective data retrieval.

regression (L2) which shrinks the magnitude of the coefficients, and LASSO regression (L1) which excludes predictors that do not add variance to the model (Zou & Hastie, 2005). The balance between L2 and L1 is determined by the alpha parameter ranging between 0 (exclusively ridge regression) and 1 (exclusively LASSO regression). An additional variable, namely lambda, is computed to define the strength of the regularization with higher values indicating more shrinkage of the coefficients. A grid search with 10 alphas and 100 lambdas was conducted using 10-fold cross-validation to identify the combination of alpha and lambda that yielded the lowest cross-validation error (DeWitt & Bennett, 2019). The age of the participants and the results from the visual assessments (Titmus Stereo Fly, TVPS-4 subtests, VMI, FCVIQ total score) were standardized and used as predictors. Bimanual function parameters that showed significant partial Spearman' rank correlations were standardized and included as outcomes of the model. We used elastic-net regularized regression since it has the advantage of handling a larger number of predictors compared to a relatively small sample size (eight predictors for 45 participants in our study) and can select a subset of variables to reduce the impact of multicollinearity on the model's performance (Zou & Hastie, 2005). The power of each model (one for each outcome) was evaluated using the root-mean-square error (RMSE) and the out-of-sample R^2. The out-of-sample R^2 compares the variance of the test data explained by the machine learning model with the variance of the test data explained by the mean of the training data. The lower the value of the RMSE (0-∞), the better the model is while the R^2 was interpreted as weak (0.02-0.12), moderate (0.13-0.25), and large (>0.26) (Cohen, 1999). The effect size of each predictor was interpreted according to Cohen's$|d|$as tiny (<0.10), very small (0.10-0.19), small (0.20-0.49), moderate (0.50-0.79), large (0.80-1.19), very large (1.20-1.99), and huge (≥2.00) (Sawilowsky, 2009). Data were analysed using R (version 4.3.2). The script used for the elastic-net regularized regression is available at https://data.mendeley.com/datasets/9bccmf76sb/1.

2. Results

2.1. Participants

Fifty children with uCP were recruited for this study. One child was excluded from the analysis since none of the visual assessments were completed due to underlying comorbidities. Hence, 49 children with uCP (mean age 11y11mo, SD 2y10mo, range 7-15 y; 26 males; 25 left-sided uCP) were included in the analysis. Based on our previous study, 39 % of children in our sample showed impaired stereoacuity, up to 44 % of children have some degree of impairment in motor-free visual-perception, and 62 % in visuomotor integration (Crotti et al., 2024). Descriptives characteristics of the participants and medians and interquartile ranges for visual and bimanual function assessments are presented in Table 1 and Table A.1, respectively. In the correlation analysis, children with missing data were excluded from the statistical analysis of that specific test but included for assessments where data was present. In the elastic-net regression analysis, only children with complete data were selected ($N = 45$). A detailed overview of missing data and related reasons is presented in Figure A.2.

2.2. Relation between visual functions, functional vision, and bimanual function

Fig. 1. shows the significant Spearman's rank correlations between visual functions, functional vision, and bimanual function in children with uCP after applying false discovery rate correction. A full overview of the Spearman's rank correlations is presented in Table A.2.

In children with uCP, lower level of motor-free visual perception (TVPS-4) showed low to moderate correlations with lower level of bimanual dexterity (TPT: r_s=−0.391 to −0.620, p = 0.033-0.0003), bimanual coordination (Kinarm circuit task: r_s=0.407-0.436, p = 0.028-0.022), and functional hand use (AHA: r_s=0.409, p = 0.028; CHEQ: r_s=0.380-0.533, p = 0.042-0.006). Children with uCP with lower levels of stereoacuity (Titmus Stereo Fly; r_s=−0.404, p = 0.028) and visuomotor integration (VMI; r_s=−0.377, p = 0.042) needed more time to perform fast dexterous movements on the TPT. Lastly, children with uCP presenting with more VI characteristics in daily life (FCVIQ), experienced more time and distress when using the non-dominant hand during bimanual tasks (CHEQ-time; r_s=−0.441, p = 0.021; CHEQ-feeling; r_s=−0.458; p = 0.019).

2.3. Predicting bimanual function with visual functions and functional vision assessments

In the elastic-net regression analysis, 45 children with uCP were included. For each model, a graphical representation of the estimates of the visual assessments is shown in Fig. 2. Overall, visual functions and functional vision predicted bimanual function outcomes with tiny to small effect sizes. In the sections below, we present only the main predictors for each bimanual function model with at least a small effect size. Additionally, a detailed overview of the R^2 and the estimates of the individual predictors (including tiny to small effect sizes) is presented in Table A.3.

2.3.1. Bimanual dexterity and coordination

For bimanual dexterity, in both conditions of the TPT the prediction models had a weak performance (R^2=0.063-0.115; RMSE=0.957-0.930), with the TVPS-4 subtest spatial relationships showing small negative effect sizes (d=−0.315; d=−0.261). Additionally, the TVPS-4 subtest visual figure-ground had a small negative effect (d=−0.282) for the dominant to non-dominant hand condition. These results indicate that in children with uCP, lower motor-free visual-perceptual abilities predicted longer time to perform fast dexterous movements.

For bimanual coordination, the prediction model of the Kinarm circuit task had a large performance (R^2 =0.356; RMSE=0.794). However, this result was mainly driven by age showing a moderate effect size (d=0.606).

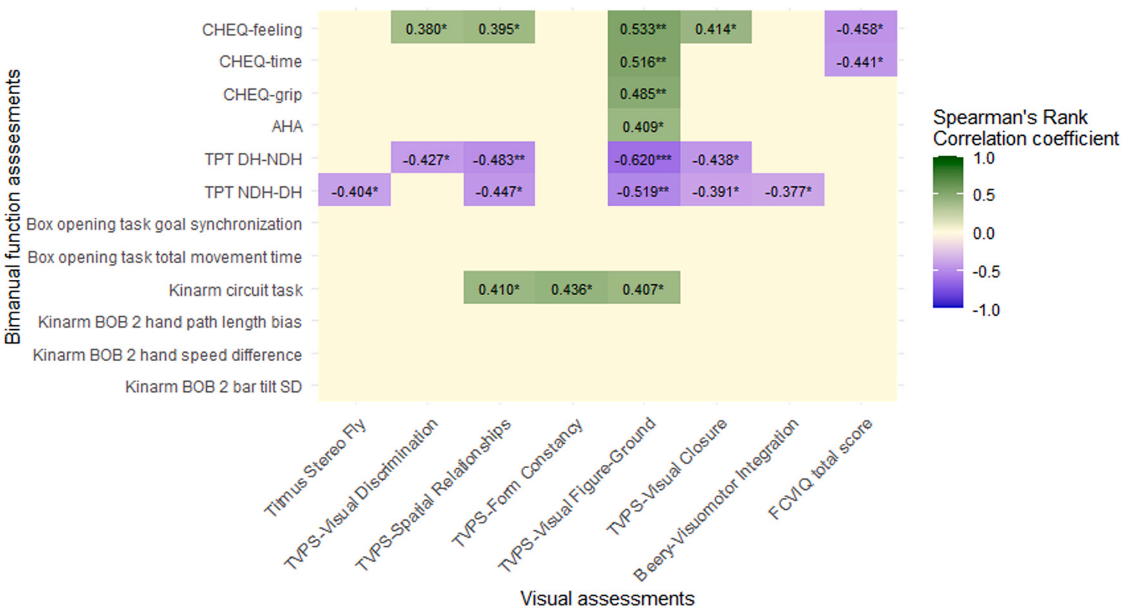

Fig. 1. Partial Spearman's rank correlation matrix showing the significant correlations between visual assessments and bimanual function assessments. TVPS: Test of Visual Perceptual Skills, Fourth edition; Beery: Beery-Buktenica Test of Visual-Motor Integration; FCVIQ: Flemish cerebral visual impairment questionnaire; BOB: Ball-on-bar task of the Kinarm exoskeleton robot; SD: standard deviation; TPT: Tyneside Pegboard Test; NDH: non-dominant hand; DH: dominant hand; AHA: Assisting Hand Assessment; CHEQ: Children's Hand-use Experience Questionnaire. Significant Spearman's rank correlation: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. Spearman rank's correlation coefficient, interpreted as no or negligible (<0.30), low (0.30-0.49), moderate (0.50-0.69), high (0.70-0.89), or very high (≥0.90) (Mukaka, 2012).

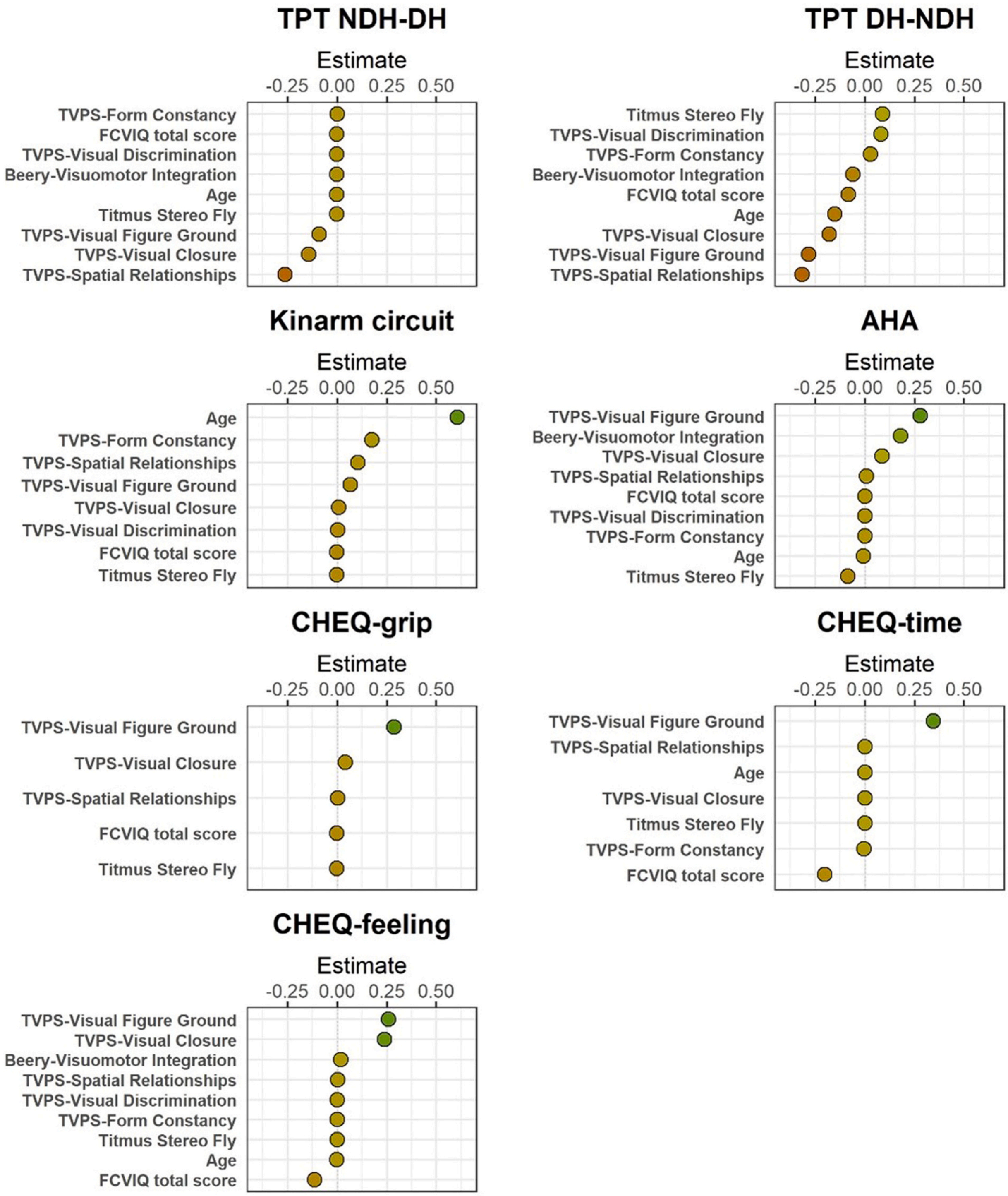

Fig. 2. The visual assessment predictors of the elastic-net regularized regression models for the Kinarm circuit task, the non-dominant hand to dominant hand and dominant hand to non-dominant-hand conditions of the Tyneside Pegboard Test, the Assisting Hand Assessment, and the subscales of the Children's Hand-use Experience Questionnaire, namely grip, time, and feeling. The average estimate is displayed for only the predictors that were included in at least one fold of the leave-one-out-cross-validation. TVPS: Test of Visual Perceptual Skills, Fourth edition; Beery: Beery Buktenica Test of Visual-Motor Integration; FCVIQ: Flemish cerebral visual impairment questionnaire; TPT: Tyneside Pegboard Test; NDH: non-dominant hand; DH: dominant hand; AHA: Assisting Hand Assessment; CHEQ: Children's Hand-use Experience Questionnaire (CHEQ).

2.3.2. Functional hand use

For bimanual performance, the prediction model of the AHA had a weak performance (R^2=0.035; RMSE=0.971) with the TVPS-4 subtest visual figure-ground showing a small positive effect size (d=0.279).

For the perceived quality of bimanual function (i.e., CHEQ), the prediction model had a weak performance for grip effectiveness of the non-dominant hand (R^2=0.104; RMSE=0.936) and a moderate performance for perceived time (R^2=0.210; RMSE=0.879) and for perceived feeling (R^2=0.171; RMSE=0.900). The TVPS-4 subtest visual figure-ground was the most significant predictor for all three subscales, showing small positive effect sizes (d=0.260-0.345). CHEQ-feeling was additionally positively predicted by the TVPS-4 subtest visual closure (d=0.239). Additionally, the FCVIQ total score predicted the subtest CHEQ-time, with a small effect size (d=−0.201).

3. Discussion

In this study, we comprehensively assessed visual functions, functional vision, and bimanual function in children with uCP to achieve a better understanding of their relation. We found low to moderate correlations between stereoacuity, visual perception, functional vision and bimanual function. Additionally, among visual assessments, visual perception (TVPS-4) was the main predictor of bimanual coordination, bimanual dexterity, and functional hand use with tiny to small effect sizes.

Our results suggest that different aspects of visual functions are related to bimanual function in children with uCP. Notably, our analyses (i.e., correlation and regression) did not report strong correlation coefficients or effect sizes.

Bimanual function was mostly correlated with visual perception. This is in line with a previous study in children with uCP (James et al., 2015) reporting that impaired visual perception, assessed with the TVPS-3, was related to reduced quality of motor and processing abilities in daily living, measured with the Assessment of Motor and Process Skills. We additionally showed, for the first time, that lower scores on almost all the TVPS-4 subtests were correlated with longer time to perform a bimanual dexterity task (TPT) and with reduced bimanual coordination (Kinarm circuit task). No correlation was found with the other bimanual coordination assessments (Kinarm ball-on-bar level 2 and Box opening task). A possible explanation is that the Kinarm circuit task requires more cognitive demand and the finest and more complex integration of visual stimuli (i.e., recognition and stabilization of the cursor position and keep the ball within the circuit borders) (Decraene et al., 2023), which is not crucial for less complex bimanual coordination tasks such as opening a box and pushing a button (Box opening task) or moving a ball to a fixed target position (Kinarm ball-on-bar level 2). Additionally, our results might suggest that the Box opening task and the Kinarm ball-on-bar level 2 could be more appropriate assessments than the Kinarm circuit and the TPT for evaluating purely bimanual coordination in children with uCP. Furthermore, lower bimanual performance (AHA) was correlated with a lower score on the TVPS-4 subtest visual figure-ground, which was the only subtest that also correlated with all the subscales of perceived quality of bimanual function (CHEQ).

Interestingly, our study highlighted that visual figure-ground was the visual perception subtest most strongly related to bimanual function. This is in line with one previous study in adults with hemiplegia due to stroke reporting that figure-ground discrimination was the visual perception subtest mostly correlated with an activity of daily living such as putting on and front-fastening a shirt (Mitcham, 1982). In our study, this relation was further confirmed by the elastic-net regression analysis, in which visual figure-ground was the most predictive variable of bimanual function in children with uCP. Our findings could be explained by the organization of the visual system in the brain, involving the ventral and dorsal stream. The dorsal pathway is considered to be responsible for figure-ground processes (Appelbaum et al., 2008) and the processing of visual information for movement control, also known as vision for action, while the ventral pathway is responsible for object recognition, namely vision for perception (Hesse et al., 2012). Hence, visual figure-ground and bimanual function might be controlled by overlapping neural areas, whose damage might impair both visual and bimanual functions in children with uCP. Our results should be considered with caution since estimated effect sizes of the regression models were small. Nevertheless, they might indicate that visual figure-ground could be the visual perception skill to prioritize during assessment of visual function in children with uCP.

Notably, our results showed limited to no relation between bimanual function and stereoacuity and VMI in children with uCP. This is in line with a previous study showing that differences in fine motor skill performance were not predicted by the level of stereoacuity in children with amblyopia (Webber et al., 2008). Additionally, since VMI assesses the integration of visual and motor function, we would expect more and stronger relations between this subtest and bimanual function. Nevertheless, it is important to notice that the VMI subtest of the Beery-VMI assesses the ability to copy and draw figures with the dominant hand. Hence, this subtest does not take into account the motor impairments of the non-dominant hand, which largely determines bimanual function in children with uCP (Klingels et al., 2012), potentially explaining the weak associations found in our results.

Functional vision (FCVIQ) was mainly correlated to perceived quality of bimanual performance (CHEQ-time and feeling), which was confirmed by the results of the elastic-net analysis. The relation between the FCVIQ and the CHEQ could be explained by the fact that both are parent-rated questionnaires. Based on previous research, we need to take into account that caregivers often report worse outcomes on questionnaires compared to their children (Robertson et al., 2021; White-Koning et al., 2007). We could hypothesize that parents of children with uCP have the tendency to underestimate the presence of VI of their children due to the diagnosis of the motor impairments which are more prominent and visible in daily life. Nevertheless, no information on the direction (worse or better visual function reported by parents) can be inferred from our analysis and further research is warranted to further understand the specificity of the FCVIQ in detecting VI in children with uCP (Crotti et al., 2024).

Interestingly, bimanual dexterity was the only bimanual function significantly correlated with all visual functions (stereoacuity, visual perception, and visuomotor integration). Our results suggest that bimanual dexterity is the bimanual function for which visual functions are more crucial. Indeed, the TPT assessment entails putting the peg accurately in the hole as fast as possible which requires the highest level of visuomotor integration and eye-hand coordination. Additionally, previous findings suggest that due to impaired stereognosis (Schermann & Tadi, 2024), children with uCP may have to rely more on visual feedback during bimanual dexterity tasks (Decraene et al., 2021). Hence, additional impairments in visual functions might negatively affect visual feedback, resulting in slower performance on bimanual dexterity tasks.

Overall in the regression models, we need to acknowledge that the visual assessments only showed tiny to small effect sizes in predicting bimanual dexterity, bimanual coordination, and functional hand use. Our results are not totally unexpected since other factors (e.g., motor and sensorimotor impairments), which were not assessed by the predictors of our models (i.e., visual assessments) have a large impact on bimanual function in children with uCP. Furthermore, additional visual functions (e.g., visual feedback, visual spatial attention), which were not included in our models, could have a potential role in impacting bimanual function and therefore, they should be addressed in future studies in children with uCP (Hawe et al., 2020). Differences in the magnitude of the results (i.e., moderate univariate correlations and tiny to small effect sizes of the regression models) between the correlation and regression analyses can be explained by the calculation of the out-of-sample R^2 which differs from the correlation coefficient of the Spearman's Rank analysis. The former compares the variance of the test data explained by the machine model to the variance of the test data explained by the mean of the training data, while the latter explains the strength and direction of the monotonic relation between two variables by comparing their ranks. Additionally, discrepancies in the results might arise due to the number of children included in the two analyses. Spearman Rank correlations were performed with a pairwise method, including different numbers of children based on available data for each pair of associations, whereas elastic net regression only included children with complete data ($N = 45$). Lastly, elastic net regression accounts for multicollinearity, potentially reducing the effect of the individual associations. Although we found differences between the strength of the findings of the correlation and regression analyses, in both methods, our results supported the presence of a relation between visual and bimanual function in children with uCP.

Nevertheless, some limitations of our study should be noted. First, the relatively small sample size could lead to imprecise parameter estimates of the regression models. To overcome the risk of overfitting, we performed an elastic-net regularized regression which allows to handle more predictors compared to the sample size (Zou & Hastie, 2005). Additionally, technical issues with the Box opening task resulted in more missing data for this assessment, which might have accounted for the non-significant correlations with the visual functions and functional vision assessments. Lastly, the low variance explained by the visual function assessments supports the need for clinicians to consider additional factors (e.g., stereognosis, cognitive function, visuospatial attention) that may impact bimanual function in children with uCP (Decraene et al., 2021; Swinnen & Gooijers, 2015). As a strength, we are the first study to include a comprehensive assessment of both visual and bimanual function in children with uCP. Despite the exploratory nature of our research, our results suggest the relevance of thoroughly examining visual functions in relation to bimanual function in children with uCP.

4. Conclusion

In conclusion, although visual comorbidities are well-recognized in children with uCP, their negative impact on bimanual function has only been examined in a limited manner. Through a comprehensive assessment, we demonstrated that several aspects of visual functions relate to bimanual function in children with uCP. Stereoacuity and visuomotor integration appear to be less associated with bimanual function while visual perception was the visual function most strongly related to bimanual function (i.e., bimanual dexterity, bimanual coordination, and functional hand use) in children with uCP. Interestingly, only bimanual dexterity was related to all visual functions. Lastly, we demonstrated that in children with uCP, visual assessments can predict bimanual function outcomes with tiny to small effect sizes. Our results provide a first insight into the complex relation between visual and bimanual function, highlighting the need to extensively map visual functions in children with uCP. Furthermore, our study could serve as the starting point to raise awareness about the need for more research on the relation between visual functions and motor outcomes, not only in children with uCP, but also in other clinical populations in which visual comorbidities are common.

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Declaration of Competing Interest

We have no Conflict of Interest.

Data availability

Data can be available upon reasonable request and the code is available online. Elastic-net regularized regression - R script: https://data.mendeley.com/datasets/9bccmf76sb/1.

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Appendices

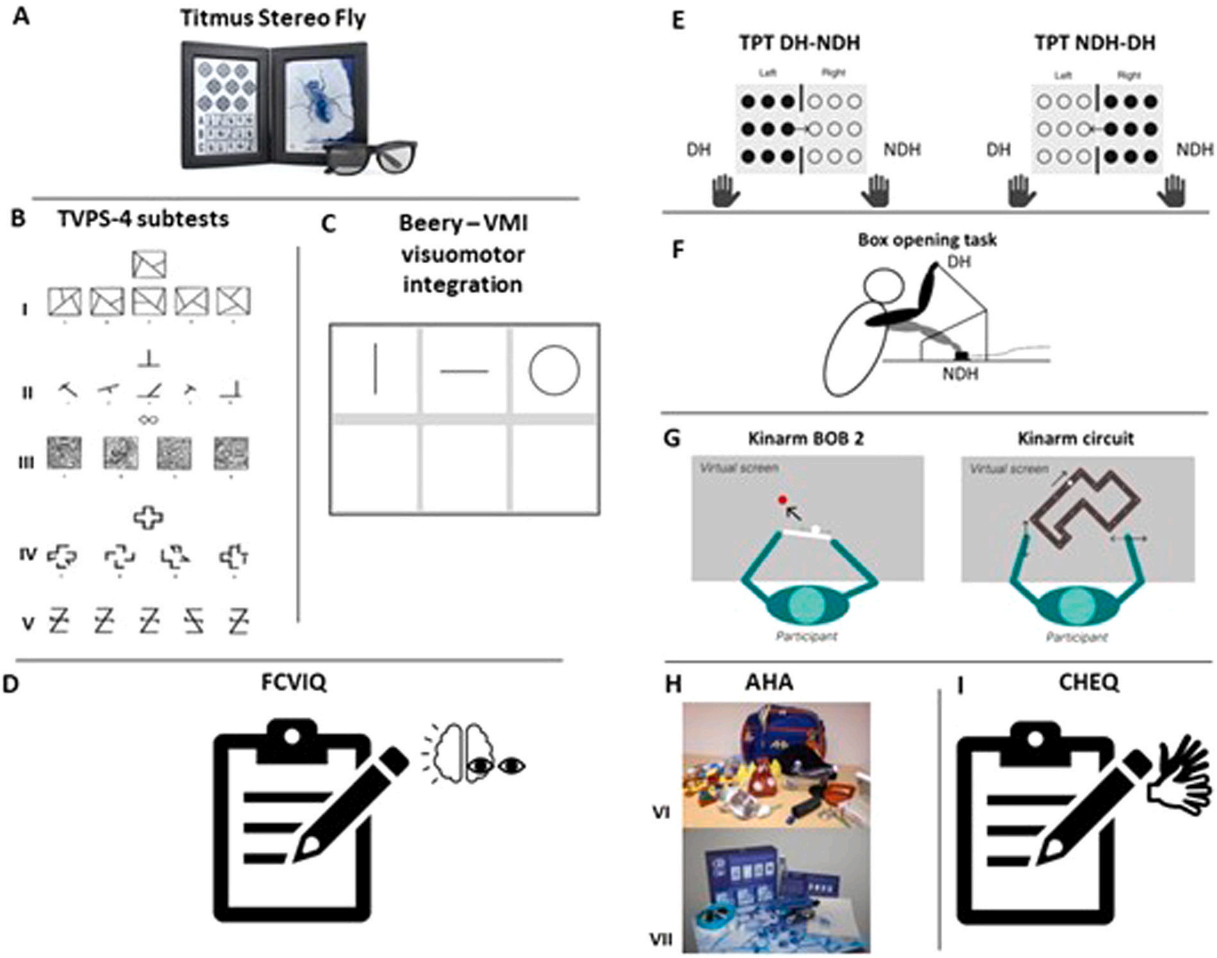

Figure A.1. Overview of the visual functions, functional vision, and bimanual function (bimanual dexterity, bimanual coordination, and functional hand use) assessments included in the present study. Visual functions assessments: A. Titmus Stereo Fly booklet and 3D glasses. B. Examples of the five subtests of the Test of Visual Perceptual Skills, Fourth edition (TVPS-4), namely visual discrimination (I), form constancy (II), visual figure-ground (III), visual closure (IV), and spatial relationships (V). C. The three first items of the visuomotor integration (VMI) subtest of the Beery-Buktenica Test of Visual-Motor Integration (Beery-VMI). Functional vision assessment: D. Flemish cerebral visual impairment questionnaire (FCVIQ). Bimanual dexterity assessment: E. Tyneside Pegboard Test (TPT); DH-NDH: dominant hand to non-dominant hand condition; NDH-DH: non-dominant hand to dominant hand condition. Bimanual coordination assessments: F. Dominant hand condition of the Box opening task; dominant hand (DH); non-dominant hand (NDH). G. Second level (2) of the Ball-on-bar task (BOB) and circuit task of the Kinarm exoskeleton robot. Functional hand use assessments: H. The test kit (VI) for children aged 6–12 years and the Go with the Floe board game (VII) (children>12 years) of the Assisting Hand Assessment (AHA). I. Children's Hand-use Experience Questionnaire (CHEQ). Adapted with permission (Decraene et al., 2021, 2023; Gerth et al., 2016; Ripley & Politzer, 2010; Rudisch et al., 2016; Stereo Optical Corporation, 2018).

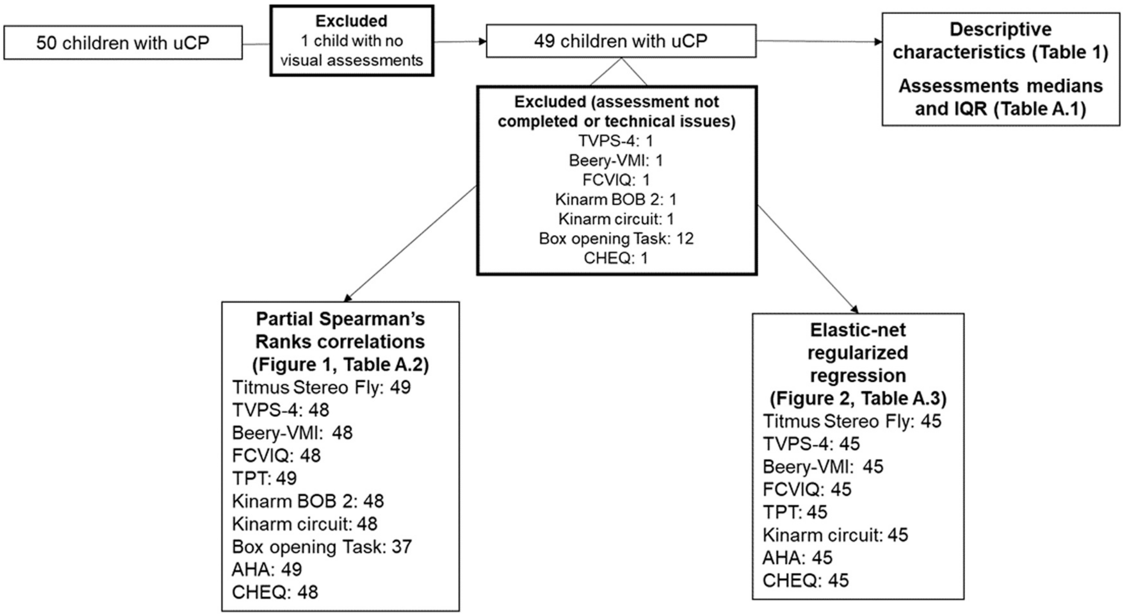

Figure A.2. Flow chart describing the study cohort. TVPS-4: Test of Visual Perceptual Skills, Fourth edition; Beery: Beery Buktenica Test of Visual-Motor Integration; VMI: Visuomotor integration; BOB: Ball-on-bar; FCVIQ: Flemish cerebral visual impairment questionnaire; TPT: Tyneside Pegboard Test; AHA: Assisting Hand Assessment; CHEQ: Children's Hand-use Experience Questionnaire.

Table A.1
Median and interquartile ranges of the visual functions, functional vision, and bimanual function assessments.

	Assessment	Median (IQR)		*uCP (N = 49), n* (%)	
Visual assessments	[a]Titmus Stereo Fly ↑	8.00	(3.00-9.00)	49	(100)
	[b]TVPS-Visual Discrimination ↑	-0.33	(−1.50-0.33)	48	(98)
	[b]TVPS-Spatial Relationships ↑	0.00	(−1.00-0.67)	48	(98)
	[b]TVPS-Form Constancy ↑	-0.33	(−1.00-0.67)	48	(98)
	[b]TVPS-Visual Figure-Ground ↑	-0.50	(−1.33-0.17)	48	(98)
	[b]TVPS-Visual Closure ↑	-0.67	(−1.33-0.17)	48	(98)
	[b]Beery-Visuomotor Integration ↑	-1.17	(−2.20-(−0.67))	48	(98)
	[c]FCVIQ total score ↓	4.00	(1.00-7.50)	48	(98)
Bimanual function assessments	[d]TPT NDH-DH ↓	22.42	(17.45-31.35)	49	(100)
	[d]TPT DH-NDH ↓	27.81	(19.10-41.17)	49	(100)
	[e]Kinarm circuit task ↑	0.26	(0.24-0.29)	48	(98)
	[f]Kinarm BOB 2 bar tilt SD ↓	0.07	(0.06-0.09)	48	(98)
	[g]Kinarm BOB 2 hand speed difference ↓	46.41	(39.76-58.97)	48	(98)
	[h]Kinarm BOB 2 hand path length bias ↓	0.02	(−0.02-0.04)	48	(98)
	[i]Box opening task goal synchronization ↓	0.10	(0.06-0.16)	37	(76)
	[d]Box opening task total movement time ↓	1.72	(1.55-2.33)	37	(76)
	[l]AHA ↑	75.00	(57.00-84.00)	49	(100)
	[l]CHEQ-grip ↑	52.50	(39.00-66.50)	48	(98)
	[l]CHEQ-time ↑	50.50	(42.50-61.50)	48	(98)
	[l]CHEQ-feeling ↑	52.50	(42.50-63.50)	48	(98)

Percentages are calculated out of the total sample of children with uCP included in the analysis (N = 49).
[a]Results report the last circle identified or the fly test. [b]Results are reported in *z*-scores. [c]Results calculated as the sum of the 'yes' items (1: the child presents the characteristic described in the item). [d]Results calculated in *sec*. [e]Results calculated according to the formula $\frac{\min(|V_x|,|V_y|)}{\sqrt{(V^2{}_x + V^2{}_y)}}$ with $V_{x/y}$ = absolute value of the horizontal/vertical hand velocity (Yeganeh Doost et al., 2017). [f]Results calculated in *Radius*. [g]Results calculated in *%*. [h]Results calculated in *cm/cm*. [i]Results calculated in *sec /sec*. [l]Results calculated in logit [0–100] (Krumlinde-Sundholm & Eliasson, 2009; Sköld et al., 2011). ↑: higher values indicate a better performance. ↓: lower values indicate a better performance. IQR: interquartile ranges calculated with Tukey's Hinges; *n*: number of children; TVPS: Test of Visual Perceptual Skills, Fourth edition; Beery: Beery Buktenica Test of Visual-Motor Integration; FCVIQ: Flemish cerebral visual impairment questionnaire; BOB: Ball-on-bar; SD: standard deviation; TPT: Tyneside Pegboard Test; NDH: non-dominant hand; DH: dominant hand; AHA: Assisting Hand Assessment; CHEQ: Children's Hand-use Experience Questionnaire.

Table A.2
Results of the partial Spearman's rank correlations after false discovery rate correction between visual and bimanual function assessments in children with unilateral cerebral palsy.

		Tyneside Pegboard Test		Kinarm exoskeleton robot				Box opening task		AHA		CHEQ	
		NDH-DH	**DH-NDH**	**BOB 2 bar tilt SD**	**BOB 2 hand speed difference**	**BOB 2 hand path length bias**	**Kinarm circuit task**	**Total movement time**	**Goal synchronization**	**AHA**	**CHEQ-grip**	**CHEQ-time**	**CHEQ-feeling**
Titmus Stereo Fly	r_s	**-0.404**	-0.236	-0.283	-0.211	-0.108	0.204	-0.049	-0.031	0.117	0.082	0.278	0.253
	p	0.028	0.195	0.133	0.256	0.509	0.265	0.803	0.876	0.482	0.609	0.137	0.176
TVPS-Visual Discrimination	r_s	-0.347	**-0.427** *	-0.155	-0.289	-0.108	0.331	-0.223	-0.175	0.275	0.329	0.313	**0.380** *
	p	0.07	0.022	0.373	0.133	0.509	0.087	0.281	0.373	0.141	0.087	0.104	0.042
TVPS-Spatial Relationships	r_s	**-0.447** *	**-0.483** *	-0.201	-0.215	-0.205	**0.410** *	-0.303	-0.216	0.245	0.312	0.341	**0.395** *
	p	0.02	0.01	0.27	0.253	0.265	0.028	0.155	0.287	0.185	0.104	0.081	0.033
TVPS-Form Constancy	r_s	-0.333	-0.331	-0.153	-0.108	-0.159	**0.436** *	-0.205	-0.221	0.19	0.191	0.156	0.284
	p	0.085	0.085	0.373	0.509	0.373	0.022	0.315	0.285	0.287	0.287	0.373	0.133
TVPS-Visual Figure-Ground	r_s	**-0.519** * *	**-0.620** * **	-0.323	-0.309	-0.204	**0.407** *	-0.129	-0.143	**0.409** *	**0.485** * *	**0.516** * *	**0.533** * *
	p	0.006	0.0003	0.094	0.104	0.265	0.028	0.506	0.465	0.028	0.01	0.006	0.006
TVPS-Visual Closure	r_s	**-0.391** *	**-0.438** *	-0.205	-0.145	-0.313	0.352	-0.258	-0.124	0.306	0.271	0.269	**0.414** *
	p	0.033	0.021	0.265	0.399	0.104	0.07	0.22	0.509	0.104	0.153	0.153	0.028
Beery-Visuomotor Integration	r_s	**-0.377** *	-0.249	-0.285	-0.173	-0.017	0.178	-0.166	-0.177	0.257	0.089	0.125	0.243
	p	0.042	0.178	0.133	0.327	0.91	0.317	0.399	0.373	0.17	0.588	0.465	0.195
FCVIQ total score	r_s	0.228	0.231	0.212	0.3	0.166	-0.178	0.291	0.02	-0.229	-0.306	**-0.441** *	**-0.458** *
	p	0.214	0.214	0.256	0.113	0.351	0.317	0.178	0.91	0.214	0.106	0.021	0.019

TVPS: Test of Visual Perceptual Skills, Fourth edition; Beery: Beery-Buktenica Test of Visual-Motor Integration; FCVIQ: Flemish cerebral visual impairment questionnaire; BOB: Ball-on-bar task of the Kinarm exoskeleton robot; SD: standard deviation; TPT: Tyneside Pegboard Test; NDH: non-dominant hand; DH: dominant hand; AHA: Assisting Hand Assessment; CHEQ: Children's Hand-use Experience Questionnaire. Significant Spearman's rank correlation in bold: *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$. Spearman rank's correlation coefficient, interpreted as no or negligible (<0.30), low (0.30-0.49), moderate (0.50-0.69), high (0.70-0.89), or very high (≥0.90) (Mukaka, 2012).

Table A.3
Results of the elastic-net regularized regression with the effect sizes (Cohen's *d*) of each predictor.

Bimanual function outcomes		Age	Titmus Stereo Fly	TVPS					Beery	FCVIQ	R^2
				Visual Discrimination	Spatial Relationships	Form Constancy	Visual Figure-Ground	Visual Closure	Visuomotor Integration	Total score	
TPT	**NDH-DH**	-0.002	-0.002	-0.001	-0.261	0.000[a]	-0.089	-0.142	-0.001	0.000[a]	0.115
	DH-NDH	-0.150	0.090	0.082	-0.315	0.030	-0.282	-0.178	-0.060	-0.083	0.063
KINARM	**Circuit task**	0.606	-0.002	0.004	0.104	0.176	0.066	0.009	0.000	0.000[a]	**0.356**
AHA	**AHA**	-0.006	-0.084	0.001	0.009	0.000[a]	0.279	0.088	0.182	0.001	0.035
CHEQ	**grip**	0.000	-0.002	0.000	0.004	0.000	0.288	0.041	0.000	-0.001	0.104
	time	0.002	0.000[a]	0.000	0.002	-0.004	0.345	0.001	0.000	-0.201	*0.210*
	feeling	0.000[a]	0.000[a]	0.001	0.003	0.001	0.260	0.239	0.018	-0.113	*0.171*

[a]The average estimate is less than 0.001. TVPS: Test of Visual Perceptual Skills, Fourth edition; Beery: Beery Buktenica Test of Visuo-Motor Integration; FCVIQ: Flemish cerebral visual impairment questionnaire; TPT: Tyneside Pegboard Test; NDH: non-dominant hand; DH: dominant hand; AHA: Assisting Hand Assessment; CHEQ: Children's Hand-use Experience Questionnaire (CHEQ). R^2: *R*-squared indicating the power of the model, interpreted as weak (0.02-0.12), moderate (0.13-0.25) in italics, and large (>0.26) in bold (Cohen, 1999). The estimate of each individual predictors was used as effect sizes (Cohen's d) and interpreted as tiny (<0.10) in white, very small (0.10-0.19) in light yellow, small (0.20-0.49) in dark yellow, moderate (0.50-0.79) in orange, large (0.80-1.19), very large (1.20-1.99) and huge (≥2.00) (Sawilowsky, 2009).

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