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

Monica Crotti

monica.crotti@kuleuven.be

KU Leuven, Department of Development and Regeneration, Locomotor and Neurological Disorders group, B-3000, Leuven, Belgium https://orcid.org/0000-0003-3206-2006

Els Ortibus

KU Leuven, Department of Development and Regeneration, Locomotor and Neurological Disorders group, B-3000, Leuven, Belgium https://orcid.org/0000-0002-1020-4408

Nofar Ben Itzhak

KU Leuven, Department of Development and Regeneration, Locomotor and Neurological Disorders group, B-3000, Leuven, Belgium https://orcid.org/0000-0002-5796-034X

Lize Kleeren

KU Leuven, Department of Rehabilitation Sciences, B-3001, Leuven, Belgium https://orcid.org/0000-0002-4649-4662

Lisa Decraene

KU Leuven, Department of Rehabilitation Sciences, B-3001, Leuven, Belgium https://orcid.org/0000-0002-9604-7027

Nicolas Leenaerts

KU Leuven, Leuven Brain Institute, Department of Neurosciences, Research Group Psychiatry, B-3000, Leuven, Belgium

Hilde Feys

KU Leuven, Department of Rehabilitation Sciences, B-3001, Leuven, Belgium

Lisa Mailleux

KU Leuven, Department of Rehabilitation Sciences, B-3001, Leuven, Belgium https://orcid.org/0000-0002-9955-098X

Research Article

Keywords: Visual function, Functional vision, Bimanual function, Upper extremity, Unilateral cerebral palsy

Posted Date: April 17th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-4045564/v1

Additional Declarations: The authors declare no competing interests.

Abstract

Background: Visual information is crucial for performing goal-directed 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 (7-15y), 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-(-0.620)), and visuomotor integration (r_s=-0.377) correlated with bimanual dexterity. Functional vision correlated with functional hand use (r_s=-0.441-(-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).

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

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 deficits 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 decreased visual perception was related to decreased bimanual dexterity, bimanual coordination, and functional hand use while decreased stereoacuity and visuomotor integration were related only to decreased bimanual dexterity. Lastly, we demonstrated that impairments in vision in daily life (functional vision) are related to decreased perceived quality of bimanual performance (functional hand use). Additionally, for the first time, elastic-net regression models were used to investigate if assessments of visual functions and functional vision could predict bimanual function in children with uCP. Results showed that visual assessments can predict bimanual function with tiny to small effect sizes, confirming that decreased visual impairment is related to lower motor performance in children with uCP. However, extensive visual function assessment is still currently not routinely implemented in the standard care of children with CP, leading to an underestimation of visual impairments which may further compromise their bimanual function. With our study, we highlighted the importance to thoroughly map visual impairments in children with uCP to achieve a better understanding of the complex clinical presentation of this neurodevelopmental condition.

1. INTRODUCTION

Visual information is crucial for performing goal-directed movements, 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 predominant motor disorder (Graham et al., 2016), 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 in the geniculostriate and/or visual-perceptual functions (Crotti et al., 2024). Impairments in visual functions may further compromise their motor performances (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 (Mitry et al., 2016), underlining 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). Hence, 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, the present study aims (1) to map the relation between visual functions, functional vision, and bimanual function in children with uCP using a comprehensive assessment; and (2) to explore to what extent assessments of visual functions and functional vision predict bimanual function in children with uCP.

2. MATERIAL AND METHODS

2.1. Participants

Between 2021 and 2022, children diagnosed with spastic uCP were recruited via the CP care program of the University Hospitals Leuven (Belgium). Participants were included if they were aged between 7 to 15, if they could understand the test instructions, and if they were able to actively grasp an object with their non-dominant hand (House Functional Classification Score ≥ 4) (House et al., 1981). Exclusion 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), binocular far visual acuity measured with the Freiburg Visual Acuity Test (FrACT) (Bach, 1996), and the level of manual ability categorized according to the Manual Ability Classification System (MACS) (Eliasson et al., 2006). This study was approved by the Ethics Committee Research UZ/KU Leuven (S62906).

2.2. Measures

In the following sections, we provide a description of the assessments of visual functions (stereoacuity, visual perception, and visuomotor integration), functional vision, and bimanual function (bimanual dexterity, bimanual coordination, and functional hand use) included in the present study. A graphical overview of the assessments is provided in Fig. 1.

2.2.1. Visual functions

Full details on the visual functions assessments can be found in (Crotti et al., 2024).

Binocular stereoacuity was investigated using the fly and the circle subtests of the Titmus Stereo Fly (Stereo Optical Corporation, 2018). 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).

Motor-free visual-perceptual skills were assessed using five subtests of the Test of Visual Perceptual Skills, Fourth Edition (TVPS-4) (Martin, 2017), namely visual discrimination, spatial relationships, form constancy, visual figure-ground, and visual closure. 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). According to the manual, TVPS-4 raw scores were translated into the age-equivalent scaled scores (mean = 10, SD = 3). Results were converted into standardized *z*-scores (mean = 0, SD = 1).

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). According to the manual, VMI raw scores were translated into the age-equivalent standard scores (mean = 100, SD = 15). Results were converted into standardized *z*-scores (mean = 0, SD = 1).

2.2.2. 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. Our previous findings (Crotti et al., 2024) showed that children with uCP do not show large variability on the FCVIQ data when grouped into the five factors described in the literature (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, results of the FCVIQ were calculated as a total score only, given by the sum of the characteristics indicated as present (1: the child presents the characteristic described in the item; 0: characteristic not present).

2.2.3. Bimanual function

2.2.3.1. Bimanual dexterity and coordination

Bimanual dexterity was assessed using the bimanual task of the Tyneside Pegboard Test (TPT), which measures the ability of the participant to pick up a peg from a board with one hand, move it 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 (Decraene et al., 2021), where higher scores indicate poorer bimanual performance.

Bimanual coordination was measured with the Box opening task (Rudisch et al., 2016) and the Kinarm exoskeleton robot (*Kinarm. Dexterit-E 3.9 User Guide. Kingston*, 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. 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 according to the literature (Mailleux et al., 2023; Rudisch et al., 2016). 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). 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. Dexterit-E 3.9 User Guide. Kingston*, 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).

2.2.3.2. 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, namely the subjective experience of the participant's hand use during bimanual tasks, 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).

2.3. 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 the relation between visual functions, functional vision, and bimanual function, pairwise partial Spearman's Rank correlations were performed with age as a covariate and using a false discovery rate (*adjusted p-value* ≤ 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 (≥ 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 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. The power of each model (one for each outcome) was evaluated using the root-mean-square error (RMSE) and the R^2. 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.

3. RESULTS

3.1. 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 7-15y; 26 males; 25 left-sided uCP) were included in the analysis. Descriptive 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.1**.

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

Figure 2 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**.

Low to moderate correlations were found between motor-free visual perception (TVPS-4) and (1) bimanual dexterity assessed with the TPT (p=0.033-0.0003, r_s=-0.391 to -0.620), (2) bimanual coordination assessed with the Kinarm circuit task (p=0.028-0.022, r_s=0.407-0.436), and (3) functional hand use assessed with the AHA (p=0.028, r_s=0.409) and (4) the CHEQ (p=0.042-0.006, r_s=0.380-0.533). These results indicate that children with uCP with a reduced level of motor-free visual-perceptual functions present with (1) worse bimanual dexterity, (2) worse motor coordination, (3) worse bimanual performance, and (4) reduced perceived quality when using the non-dominant hand during bimanual movements.

Additionally, stereoacuity (Titmus Stereo Fly; p=0.028, r_s=-0.404) and visuomotor integration (VMI; p=0.042, r_s=-0.377) showed low to moderate negative correlations with bimanual dexterity assessed with the TPT, suggesting that children with uCP with reduced stereoacuity and visual-perceptual functions need more time to perform fast dexterous movements. Lastly, low negative correlations were found between functional vision (FCVIQ total score) and the time and feeling of using the non-dominant hand (CHEQ-time; p=0.021, r_s=-0.441; CHEQ-feeling; p=0.019, r_s=-0.458), indicating that children with uCP presenting with more VI characteristics in daily life, experience more time and distress when using the non-dominant hand during bimanual tasks. No correlations were found between visual assessments and the Box opening task or the level 2 of the ball-on-bar task of the Kinarm.

3.3. 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 **Figure 3.** Additionally, a detailed overview of the R^2 and the estimates of the individual predictors is presented in **Table A.3**.

3.3.1. Bimanual dexterity and coordination

For *bimanual dexterity*, assessed with the TPT, the prediction model had a weak performance with an out-of-sample R^2 of 0.115 (RMSE=0.930) for the non-dominant to dominant hand condition and an out-of-sample R^2 of

0.063 (RMSE=0.957) for the dominant to non-dominant hand condition. For both conditions, the TVPS-4 subtest spatial relationships had small negative effect sizes (*d*=-0.261; *d*=-0.315, respectively) and the TVPS-4 subtest visual closure showed very small effect sizes (*d*=-0.142; *d*=-0.178, respectively). 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. Lastly, age had a very small negative effect (*d*=0.150) while other retained variables only showed a tiny ($|d|$<0.1) effect size.

For *bimanual coordination,* measured with the Kinarm circuit task, the prediction model had a large performance with an out-of-sample R^2 of 0.356 (RMSE=0.794). Age was the strongest predictor with a moderate effect size (*d*=0.606). Additionally, the TVPS-4 subtests spatial relationships (*d*=0.104) and form constancy (*d*=0.176) had very small positive effect sizes, indicating that in children with uCP, better motor-free visual-perceptual abilities predicted better bimanual coordination. The other retained predictors showed a tiny ($|d|$<0.1) effect size.

3.3.2. Functional hand use

For *bimanual performance*, assessed with the AHA, the prediction model had a weak performance with an out-of-sample R^2 of 0.035 (RMSE=0.971). The TVPS-4 subtest visual figure-ground was the strongest predictor, showing a small positive effect size (*d*=0.279), followed by the Beery-VMI contributing to the model with a very small positive effect size (*d*=0.182).

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 negatively predicted the subtest CHEQ-time, with a small effect size (*d*=-0.201) and the subtest CHEQ-feeling, with a very small effect size (*d*=-0.113). For both bimanual performance and perceived quality, other retained predictors only showed a tiny ($|d|$<0.1) effect size.

4. 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 VI play a role in bimanual function. Overall, we found no relation between *stereoacuity* and bimanual function, except for one weak correlation with bimanual dexterity (TPT). Also in the regression models, stereoacuity only showed null to tiny effect sizes. 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). Hence, our study demonstrates for the first time that also in children with uCP, stereoacuity plays a subordinate role in bimanual function.

Visual perception was mostly correlated with bimanual function. Lower scores on the TVPS-4 subtests were related to lower bimanual coordination, bimanual dexterity, and functional hand use (Kinarm circuit task, TPT, AHA, and CHEQ). 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. In our study, we showed for the first time that visual perception was also correlated with bimanual dexterity and bimanual coordination tasks. Longer time to perform a bimanual dexterity task (TPT) and worse bimanual coordination (Kinarm circuit task) were correlated with lower scores on almost all the TVPS-4 subtests. 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). Our results support the findings of a previous study, showing that lower scores on the subtests of the Motor-Free Visual Perception Test were related to impaired activities of daily living in children with developmental disabilities (Elbasan et al., 2011).

Overall, our study highlighted that visual figure-ground was the visual perception subtest mostly 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 variable showing the most and strongest effect sizes in predicting 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 objects' 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.

Remarkably, *visuomotor integration*, measured with the subtest of the Beery-VMI, showed a weak association with bimanual function. Lower scores on the VMI subtest were only correlated with longer time taken to perform dexterous bimanual movements (TPT). Additionally, in the regression models, the strongest contribution of the subtest VMI was a very small effect size in predicting the outcomes of the AHA. 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.

Interestingly, bimanual dexterity was the only bimanual function significantly correlated with all visual functions (stereoacuity, visual perception, and visuomotor integration). Our results show 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, impairments in visual functions might negatively affect visual feedback, resulting in slower performance on bimanual dexterity tasks.

Functional vision (FCVIQ) was mainly related to perceived quality of bimanual performance (CHEQ-time and feeling). Due to VI in daily life, children with uCP need more time and experience more distress in performing bimanual tasks. This relation was confirmed by the elastic-net regression analysis, in which the FCVIQ total score showed the strongest contribution to the model of the CHEQ-time and CHEQ-feeling. Notably, no relation was found between parent's reporting on VI in daily life (i.e., FCVIQ) and bimanual dexterity (i.e., TPT), bimanual coordination (i.e., Kinarm and Box opening task), and bimanual performance (i.e., AHA). 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) while more than 40% of children have some degree of impairment in visual perception. The FCVIQ is a screening questionnaire specifically designed for CVI. Hence, the lack of correlation between the FCVIQ and the bimanual function assessments might be explained by the low variability of our data, since our study included a low number of children with a diagnosis of CVI. On the other hand, the relation between the FCVIQ and the CHEQ could be explained by the fact that both are parent-rated questionnaires. Previous research showed 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).

Overall regression models did not show a strong performance of visual functions and functional vision in predicting bimanual function. The Kinarm circuit task was the only model showing a large predictive performance. Nevertheless, this result was mainly driven by age, which was the strongest predictor. 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. Although showing a weak predicting performance, regression models were significant, with visual assessments reporting tiny to small effect sizes in predicting bimanual dexterity, bimanual coordination, and functional hand use. Hence, our results highlight the presence of a relation between visual and 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).

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 influence the absence of significant correlations with the visual functions and functional vision assessments. Lastly, the low variance explained by VI 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).

5. CONCLUSIONS

In conclusion, although visual comorbidities are well-recognized in children with uCP, their negative impact on bimanual function was only examined in a limited manner. Through a comprehensive assessment, we demonstrated that several aspects of VI 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 mostly 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 VI in children with uCP to achieve a complete picture of the complex clinical presentation of this neurodevelopmental disability. Furthermore, our study could serve as the starting point to raise awareness about the influence of VI on motor outcomes, not only in children with uCP, but also in other clinical populations in which visual comorbidities are common.

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

Declarations

We have no Conflict of Interest.

ACKNOWLEDGMENTS

We would like to express our gratitude to all the participating families and children. Additionally, we would like to thank the master students who assisted with data collection.

FUNDING

The Flemish Research Foundation (FWO project, G0C4919N) provided financial support for this study. This work was additionally supported by the project: “PARENT” funded by the European Union’s Horizon 2020 Project MSCA-ITN-2020 – Innovative Training Networks Grant No. 956394.

References

1. Appelbaum, L. G., Wade, A. R., Pettet, M. W., Vildavski, V. Y., & Norcia, A. M. (2008). Figure-ground interaction in the human visual cortex. *Journal of Vision*, *8*(9), 8–8. https://doi.org/10.1167/8.9.8
2. Bach, M. (1996). The Freiburg Visual Acuity Test—Automatic measurement of visual acuity. *Optometry and Vision Science*, *73*(1). https://journals.lww.com/optvissci/Fulltext/1996/01000/The_Freiburg_Visual_Acuity_Test_Automatic.8.aspx
3. Bakke, H. A., Cavalcante, W. A., Oliveira, I. S. de, Sarinho, S. W., & Cattuzzo, M. T. (2019). Assessment of motor skills in children with visual Impairment: A systematic and integrative review. *Clinical Medicine Insights: Pediatrics*, *13*, 117955651983828. https://doi.org/10.1177/1179556519838287
4. Basu, A. P., Kirkpatrick, E. V., Wright, B., Pearse, J. E., Best, K. E., & Eyre, J. A. (2018). The Tyneside Pegboard Test: Development, validation, and observations in unilateral cerebral palsy. *Developmental Medicine and Child Neurology*, *60*(3), 314–321. https://doi.org/10.1111/dmcn.13645
5. Beery, K. E., Buktenica, N. A., & Beery, N. A. (2010). *Developmental Test of Visual-Motor Integration, Sixth Edition, Revised (VMI)*.
6. Ben Itzhak, N., Vancleef, K., Franki, I., Laenen, A., Wagemans, J., & Ortibus, E. (2020). Visuoperceptual profiles of children using the Flemish cerebral visual impairment questionnaire. *Developmental Medicine & Child Neurology*, *62*(8), 969–976. https://doi.org/10.1111/dmcn.14448
7. Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series B (Methodological)*, *57*(1), 289–300.
8. Bennett, C. R., Bex, P. J., Bauer, C. M., & Merabet, L. B. (2019). The assessment of visual function and functional vision. *Seminars in Pediatric Neurology*, *31*, 30–40. https://doi.org/10.1016/j.spen.2019.05.006
9. Bumin, G., & Kavak, S. T. (2008). An investigation of the factors affecting handwriting performance in children with hemiplegic cerebral palsy. *Disability and Rehabilitation*, *30*(18), 1374–1385. https://doi.org/10.1080/09638280701673609
10. Cohen, H. S. (1999). *Neuroscience for rehabilitation*. Lippincott Williams & Wilkins.

11. Crotti, M., Ortibus, E., Mailleux, L., Decraene, L., Kleeren, L., & Ben Itzhak, N. (2024). Visual, perceptual functions, and functional vision in children with unilateral cerebral palsy compared to children with neurotypical development. *Developmental Medicine & Child Neurology*. https://doi.org/10.1111/dmcn.15842
12. Decraene, L., Feys, H., Klingels, K., Basu, A., Ortibus, E., Simon-Martinez, C., & Mailleux, L. (2021). Tyneside Pegboard Test for unimanual and bimanual dexterity in unilateral cerebral palsy: Association with sensorimotor impairment. *Developmental Medicine & Child Neurology*, *63*(7), 874–882. https://doi.org/10.1111/dmcn.14858
13. Decraene, L., Orban de Xivry, J.-J., Kleeren, L., Crotti, M., Verheyden, G., Ortibus, E., Feys, H., Mailleux, L., & Klingels, K. (2023). In-depth quantification of bimanual coordination using the Kinarm exoskeleton robot in children with unilateral cerebral palsy. *Journal of Neuroengineering and Rehabilitation*, *20*(1), 154. https://doi.org/10.1186/s12984-023-01278-6
14. DeWitt, P. E., & Bennett, T. D. (2019). *ensr: R package for simultaneous selection of elastic net tuning parameters* (arXiv:1907.00914). arXiv. http://arxiv.org/abs/1907.00914
15. Duke, R. E., Nwachukuw, J., Torty, C., Okorie, U., Kim, M. J., Burton, K., Gilbert, C., & Bowman, R. (2022). Visual impairment and perceptual visual disorders in children with cerebral palsy in Nigeria. *British Journal of Ophthalmology*, *106*(3), 427–434. https://doi.org/10.1136/bjophthalmol-2020-317768
16. Ego, A., Lidzba, K., Brovedani, P., Belmonti, V., Gonzalez-Monge, S., Boudia, B., Ritz, A., & Cans, C. (2015). Visual-perceptual impairment in children with cerebral palsy: A systematic review. *Developmental Medicine & Child Neurology*, *57*, 46–51. https://doi.org/10.1111/dmcn.12687
17. Elbasan, B., Atasavun, S., & Düger, T. (2011). *Effects of visual perception and motor function on the activities of daily living in children with disabilities*.
18. Eliasson, A.-C., Krumlinde-Sundholm, L., Rösblad, B., Beckung, E., Arner, M., Ohrvall, A.-M., & Rosenbaum, P. (2006). The Manual Ability Classification System (MACS) for children with cerebral palsy: Scale development and evidence of validity and reliability. *Developmental Medicine and Child Neurology*, *48*(7), 549–554. https://doi.org/10.1017/S0012162206001162
19. Gerth, S., Klassert, A., Dolk, T., Fliesser, M., Fischer, M. H., Nottbusch, G., & Festman, J. (2016). Is Handwriting Performance Affected by the Writing Surface? Comparing Preschoolers', Second Graders', and Adults' Writing Performance on a Tablet vs. Paper. *Frontiers in Psychology*, *7*. https://www.frontiersin.org/journals/psychology/articles/10.3389/fpsyg.2016.01308
20. Graham, H. K., Rosenbaum, P., Paneth, N., Dan, B., Lin, J.-P., Damiano, D. L., Becher, J. G., Gaebler-Spira, D., Colver, A., Reddihough, D. S., Crompton, K. E., & Lieber, R. L. (2016). Cerebral palsy. *Nature Reviews. Disease Primers*, *2*, 15082. https://doi.org/10.1038/nrdp.2015.82
21. Hawe, R. L., Kuczynski, A. M., Kirton, A., & Dukelow, S. P. (2020). Assessment of bilateral motor skills and visuospatial attention in children with perinatal stroke using a robotic object hitting task. *Journal of NeuroEngineering and Rehabilitation*, *17*(1), 18. https://doi.org/10.1186/s12984-020-0654-1
22. Hesse, C., Ball, K., & Schenk, T. (2012). Visuomotor performance based on peripheral vision is impaired in the visual form agnostic patient DF. *Neuropsychologia*, *50*(1), 90–97. https://doi.org/10.1016/j.neuropsychologia.2011.11.002
23. Himmelmann, K., Horber, V., De La Cruz, J., Horridge, K., Mejaski-Bosnjak, V., Hollody, K., Krägeloh-Mann, I., & SCPE Working Group. (2017). MRI classification system (MRICS) for children with cerebral palsy:

Development, reliability, and recommendations. *Developmental Medicine and Child Neurology*, *59*(1), 57–64. https://doi.org/10.1111/dmcn.13166

24. Himmelmann, K., & Uvebrant, P. (2018). The panorama of cerebral palsy in Sweden part XII shows that patterns changed in the birth years 2007–2010. *Acta Paediatrica*, *107*(3), 462–468. https://doi.org/10.1111/apa.14147
25. House, J. H., Gwathmey, F. W., & Fidler, M. O. (1981). A dynamic approach to the thumb-in palm deformity in cerebral palsy. *The Journal of Bone and Joint Surgery. American Volume*, *63*(2), 216–225.
26. James, S., Ziviani, J., Ware, R. S., & Boyd, R. N. (2015). Relationships between activities of daily living, upper limb function, and visual perception in children and adolescents with unilateral cerebral palsy. *Developmental Medicine & Child Neurology*, *57*(9), 852–857. https://doi.org/10.1111/dmcn.12715
27. Jeannerod, M. (1986). Mechanisms of visuomotor coordination: A study in normal and brain-damaged subjects. *Neuropsychologia*, *24*(1), 41–78. https://doi.org/10.1016/0028-3932(86)90042-4
28. *Kinarm. Dexterit-E 3.9 User Guide. Kingston*. (2021).
29. Klingels, K., Demeyere, I., Jaspers, E., De Cock, P., Molenaers, G., Boyd, R., & Feys, H. (2012). Upper limb impairments and their impact on activity measures in children with unilateral cerebral palsy. *European Journal of Paediatric Neurology: EJPN: Official Journal of the European Paediatric Neurology Society*, *16*(5), 475–484. https://doi.org/10.1016/j.ejpn.2011.12.008
30. Krumlinde-Sundholm, L., & Eliasson, A.-C. (2009). Development of the Assisting Hand Assessment: A Rasch-built Measure intended for Children with Unilateral Upper Limb Impairments. *Scand. J. Occup. Ther.*, *10*, 16–26. https://doi.org/10.1080/11038120310004529
31. Mailleux, L., Decraene, L., Kalkantzi, A., Kleeren, L., Crotti, M., Campenhout, A. V., Verheyden, G., Ortibus, E., Green, D., Klingels, K., & Feys, H. (2023). *Spatiotemporal coordination in children with unilateral cerebral palsy: Insights from a bimanual goal-directed task* [Preprint]. In Review. https://doi.org/10.21203/rs.3.rs-3503178/v1
32. Martin, N. (2017). *Test of Visual Perceptual Skills 4th Edition (TVPS-4)*.
33. Mitcham, M. (1982). Visual perception and its relationship to an activity of daily living. *The Occupational Therapy Journal of Research*, *2*(4), 245–246. https://doi.org/10.1177/153944928200200404
34. Mitry, D., Williams, C., Northstone, K., Akter, A., Jewel, J., Khan, N., Muhit, M., Gilbert, C. E., & Bowman, R. (2016). Perceptual visual dysfunction, physical impairment and quality of life in Bangladeshi children with cerebral palsy. *British Journal of Ophthalmology*, *100*(9), 1245–1250. https://doi.org/10.1136/bjophthalmol-2015-307296
35. Mukaka, M. M. (2012). Statistics corner: A guide to appropriate use of correlation coefficient in medical research. *Malawi Medical Journal: The Journal of Medical Association of Malawi*, *24*(3), 69–71.
36. Ortibus, E., Laenen, A., Verhoeven, J., De Cock, P., Casteels, I., Schoolmeesters, B., Buyck, A., & Lagae, L. (2011). Screening for Cerebral Visual Impairment: Value of a CVI questionnaire. *Neuropediatrics*, *42*(04), 138–147. https://doi.org/10.1055/s-0031-1285908
37. Rauchenzauner, M., Schiller, K., Honold, M., Baldissera, I., Biedermann, R., Tschiderer, B., Albrecht, U., Arnold, C., & Rostasy, K. (2021). Visual impairment and functional classification in children with cerebral palsy. *Neuropediatrics*, *52*(05), 383–389. https://doi.org/10.1055/s-0040-1722679
38. Ripley, D., & Politzer, T. (2010). Vision disturbance after TBI. *NeuroRehabilitation*, *27*, 215–216. https://doi.org/10.3233/NRE-2010-0599

39. Robertson, A. O., Tadić, V., Horvat-Gitsels, L. A., Cortina-Borja, M., & Rahi, J. S. (2021). Differences in self-rated versus parent proxy–rated vision-related quality of life and functional vision of visually impaired children. *American Journal of Ophthalmology*, *230*, 167–177. https://doi.org/10.1016/j.ajo.2021.05.017
40. Rudisch, J., Butler, J., Izadi, H., Zielinski, I. M., Aarts, P., Birtles, D., & Green, D. (2016). Kinematic parameters of hand movement during a disparate bimanual movement task in children with unilateral Cerebral Palsy. *Human Movement Science*, *46*, 239–250. https://doi.org/10.1016/j.humov.2016.01.010
41. Sawilowsky, S. S. (2009). New effect size rules of thumb. *Journal of Modern Applied Statistical Methods*, *8*(2), 597–599. https://doi.org/10.22237/jmasm/1257035100
42. Schermann, T., & Tadi, P. (2024). Stereognosis. In *StatPearls*. StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK556003/
43. Sköld, A., Hermansson, L. N., Krumlinde-Sundholm, L., & Eliasson, A.-C. (2011). Development and evidence of validity for the Children's Hand-use Experience Questionnaire (CHEQ). *Developmental Medicine and Child Neurology*, *53*(5), 436–442. https://doi.org/10.1111/j.1469-8749.2010.03896.x
44. Stereo Optical Corporation. (2018). *Stereo Fly Test*. https://www.stereooptical.com/products/stereotests-color-tests/original-stereo-fly/#1529520225990-6a35365b-d00f
45. Swinnen, S., & Gooijers, J. (2015). Bimanual Coordination. *Brain Mapping: An Encyclopedic Reference*, *2*, 475–482. https://doi.org/10.1016/B978-0-12-397025-1.00030-0
46. Webber, A. L., Wood, J. M., Gole, G. A., & Brown, B. (2008). The effect of amblyopia on fine motor skills in children. *Investigative Ophthalmology & Visual Science*, *49*(2), 594–603. https://doi.org/10.1167/iovs.07-0869
47. White-Koning, M., Arnaud, C., Dickinson, H. O., Thyen, U., Beckung, E., Fauconnier, J., McManus, V., Michelsen, S. I., Parkes, J., Parkinson, K., Schirripa, G., & Colver, A. (2007). Determinants of child-parent agreement in quality-of-life reports: A European study of children with cerebral palsy. *Pediatrics*, *120*(4), e804–e814. https://doi.org/10.1542/peds.2006-3272
48. Wiesendanger, M., & Serrien, D. J. (2001). Toward a physiological understanding of human dexterity. *Physiology*, *16*(5), 228–233. https://doi.org/10.1152/physiologyonline.2001.16.5.228
49. Yeganeh Doost, M., Orban de Xivry, J.-J., Bihin, B., & Vandermeeren, Y. (2017). Two processes in early bimanual motor skill learning. *Frontiers in Human Neuroscience*, *11*, 618. https://doi.org/10.3389/fnhum.2017.00618
50. Zou, H., & Hastie, T. (2005). Regularization and variable selection via the elastic net. *Journal of the Royal Statistical Society. Series B (Statistical Methodology)*, *67*(2), 301–320.

Table

Table 1 is available in the Supplementary Files section

Figures

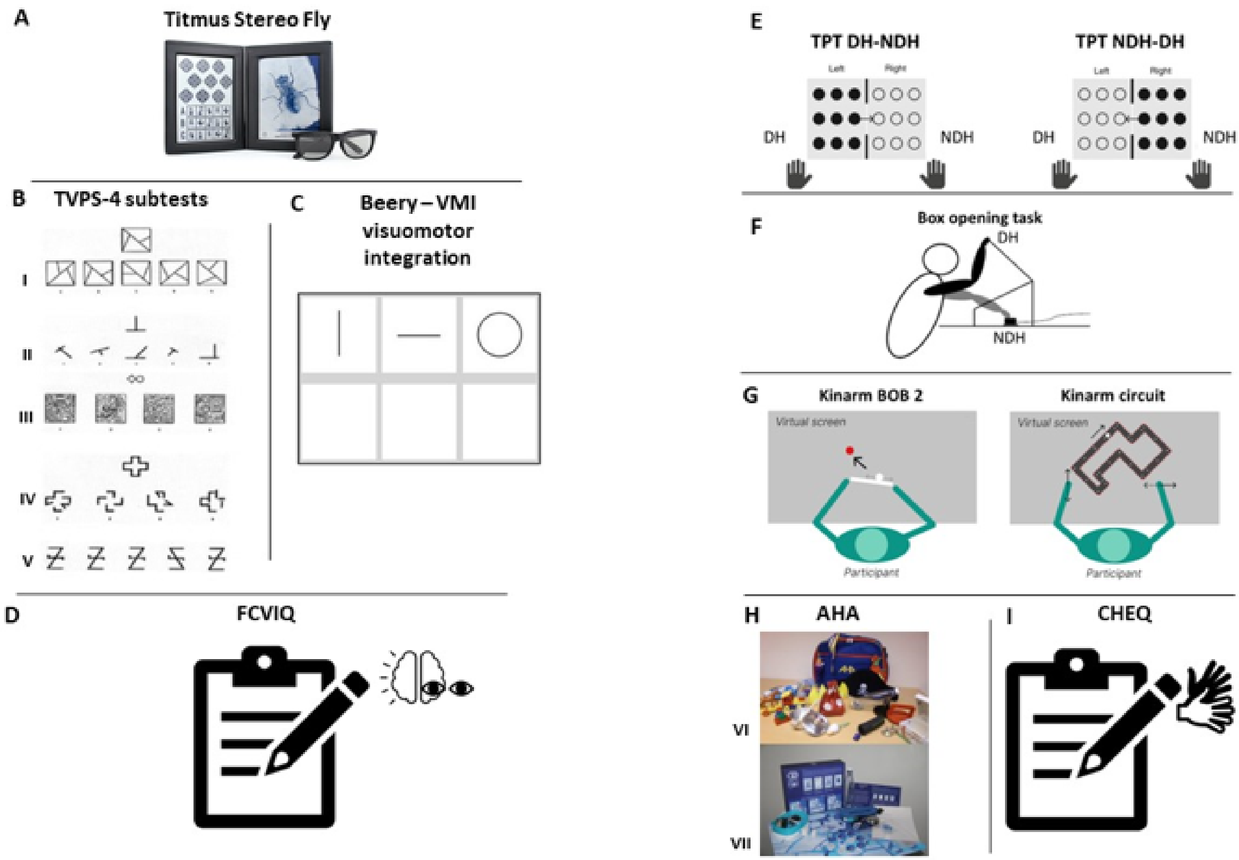

Figure 1

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 subtest of the Beery-Buktenica Test of Visual-Motor Integration (Beery). **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; DH-NDH: dominant hand to non-dominant hand condition; dominant hand (DH); non-dominant hand (NDH). **Bimanual coordination assessments: F.** Dominant hand condition of the Box opening task. **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).

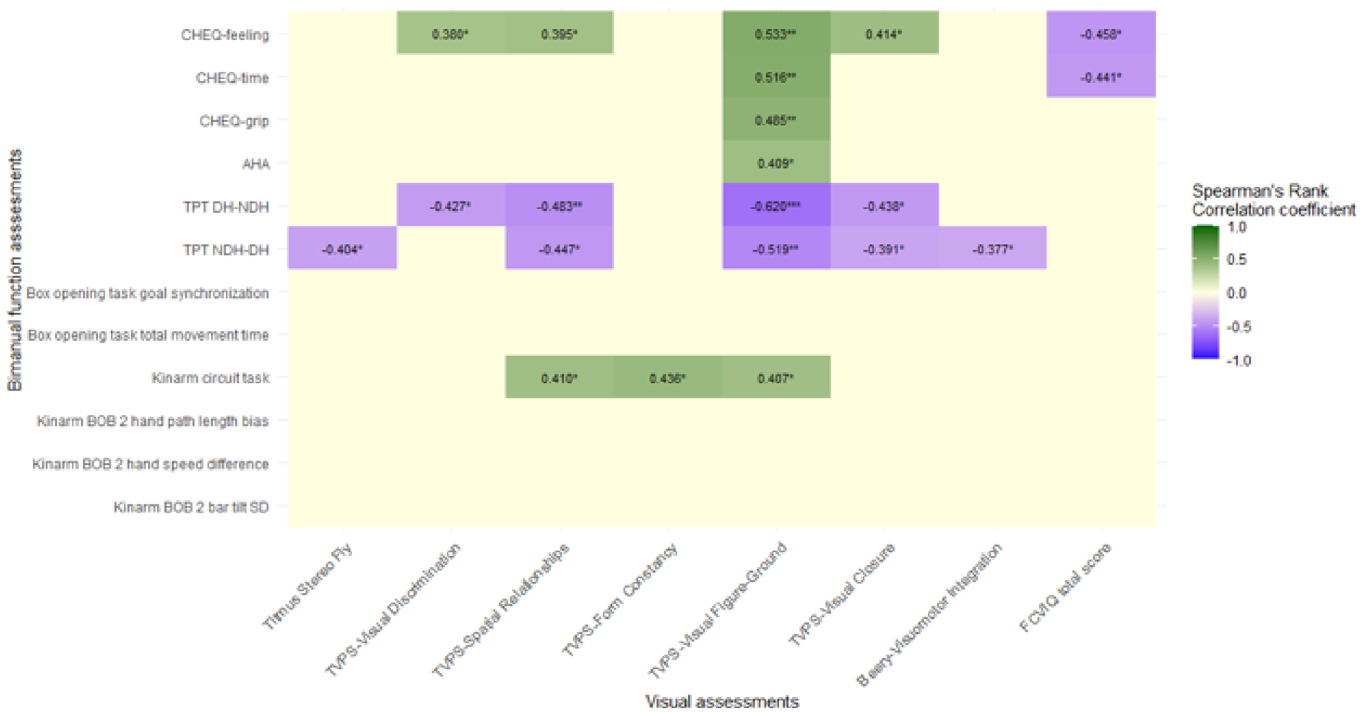

Figure 2

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).

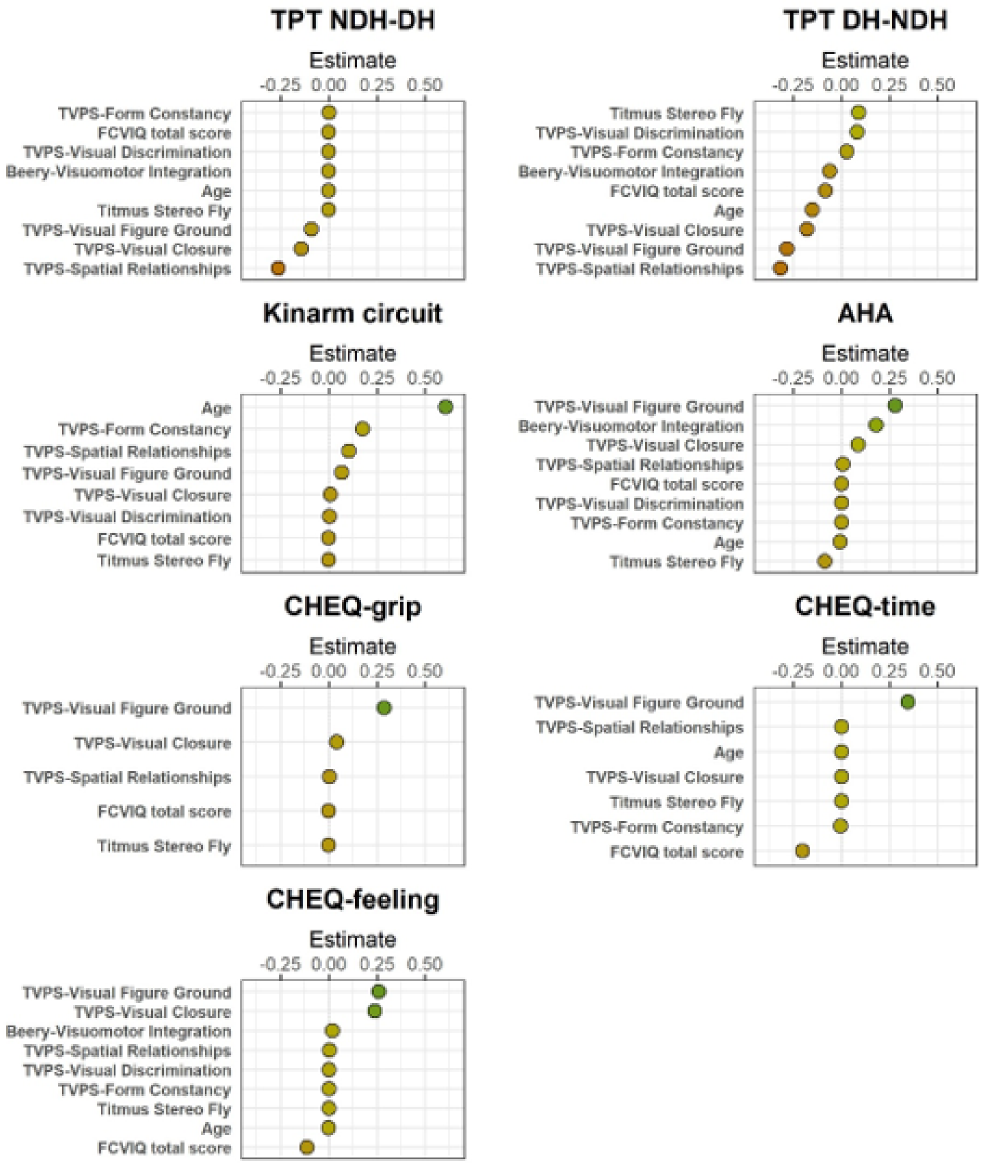

Figure 3

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).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table1.docx
- APPENDICES.docx