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Original article

Spatiotemporal coordination in children with unilateral cerebral palsy: Insights from a bimanual goal-directed task

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ABSTRACT

Background: In children with unilateral cerebral palsy (uCP), bimanual assessments mostly focus on qualitative assessments of the impaired upper limb during bimanual tasks, which do not capture the spatiotemporal coordination between both hands. Hence, we aimed to advance our understandings in spatiotemporal coordination in children with uCP compared to typically developing children (TDC) using a bimanual, asymmetrical, goal-directed task.

Participants and methodology: In this observational study, thirty-seven children with uCP (11y8m±2y10m, 20 males, 16 right-sided uCP, Manual Ability Classification System level I = 23, II = 11, III = 3) and 37 age and sex-matched TDC opened a box with one hand and pressed a button inside using the opposite hand. Spatiotemporal bimanual (movement time, temporal coupling, movement overlap, goal synchronisation) and unimanual (movement time, path length and smoothness) parameters were extracted. Between groups comparisons were investigated using a two-way mixed ANCOVA with age as covariate ($\alpha < 0.05$). Additionally, correlation coefficients between unimanual and bimanual parameters were calculated.

Results: Compared to TDC, children with uCP were slower ($p = 0.01$, $\eta_p^2 = 0.13$) and presented unimanual spatiotemporal deficits in both upper limbs ($p < 0.03$, $\eta_p^2 > 0.10$), which worsened in children with lower manual abilities ($p < 0.04$, $\eta_p^2 > 0.19$). However, they did not differ in bimanual coupling ($p > 0.31$, $\eta_p^2 < 0.03$). Furthermore, slower movement time was related with increased unimanual spatiotemporal deficits bilaterally ($r = 0.34$–0.80, $p = 0.001$–0.04), suggesting that reduced performance at both upper limbs contributes to bimanual difficulties in children with uCP.

Conclusions: The bilateral reduced spatiotemporal performance, related to longer bimanual movement time, stresses the importance to assess and treat both upper limbs in children with uCP.

1. Introduction

The vast majority of activities in daily life are highly dependent on bimanual coordination, in which both hands move independently while acting as one single unit through mutual coupling. In daily life, bimanual tasks are rarely symmetrical and often require disparate actions of both hands that need to be spatiotemporally tuned. Brain activity underlying bimanual coordination entails a widely distributed neural network [1,

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2]. Hence, brain damage can disturb the fine-grained synchronisation between both hands, as for example in children with unilateral cerebral palsy (uCP). UCP is caused by a non-progressive brain injury that occurs during the foetal period or early infancy, leading to sensorimotor impairments predominantly on one side of the body [3]. These lateralized impairments may in turn result in increased difficulties with performing bimanual tasks [4,5]. Strikingly, most studies have thus far used clinical measures of bimanual function that fail to capture the precise coordination between both hands [6]. Using more quantitative measures could aid in further improving our understanding of bimanual deficits in children with uCP.

However, studies have mostly used symmetrical bimanual tasks or tasks that are less relevant for daily life performance to examine bimanual coordination. Only two studies have used an asymmetrical goal-directed task to quantify bimanual coordination in children with uCP and typically developing children (TDC) using three-dimensional motion analysis. First, Hung et al. [7] used a drawer-opening task where participants had to open a drawer with one hand and activate a switch inside the drawer with the other hand. These authors found a worse bimanual coordination in children with uCP compared to TDC as shown by the decreased amount of time both hands are moving together (i.e. movement overlap) and the increased amount of time needed to synchronize both hands at the end of the task (i.e. goal synchronisation) [7]. However, this study included a small sample size of only 10 children with uCP. Rudisch et al. [8,9] also studied bimanual coordination during a box-opening task, where participants were instructed to open a box with one hand and press a button inside the box with the other hand. In 37 children with uCP, they found that bimanual coordination was more impaired in children with lower levels of manual ability as indicated by a longer task duration and reduced spatial accuracy [8]. However, bimanual coordination was not directly compared between children with uCP and TDC as results of the latter group were published in a separate study to study developmental characteristics of bimanual coordination [8,9]. Moreover, each hand has its distinct role during the performance of such bimanual tasks. Yet, these previous studies did not investigate the relation between unimanual and bimanual parameters. Investigation of this relationship could further improve our understanding of bimanual coordination deficits in children with uCP.

Hence, the overall aim of this study is to investigate spatiotemporal coordination using a bimanual, asymmetrical, goal-directed task in children with uCP compared to age- and sex-matched TDC. First, we will investigate (1) if bimanual and unimanual spatiotemporal coordination differs between children with uCP and TDC and (2) whether this differs depending on manual ability level in children with uCP. We hypothesize that children with uCP exhibit impaired bimanual and unimanual spatiotemporal coordination compared to their typically developing peers, which is more pronounced in children with lower manual abilities. Additionally, we will examine (3) the relation between unimanual and bimanual spatiotemporal parameters. We hypothesize that bimanual parameters will be related with unimanual parameters of both hands.

2. Methods

2.1. Design and participants

This observational study includes a cross-sectional study design and is reported according to the STROBE guidelines (Appendix A1). Children diagnosed with predominant spastic uCP and age- and sex-matched TDC participated in this study. Participants with uCP were recruited via the CP reference centre of the University Hospitals Leuven (Belgium), while TDC were contacted through schools, youth organisations or colleagues between April 2021 and August 2022. The inclusion criteria for children with uCP comprised: (1) age between 7 and 15 years, (2) ability to cooperate and comprehend instructions, and (3) the ability to hold an object independently with the non-dominant hand (House Functional Classification System [10] score four or higher). Children who underwent upper limb surgery during the preceding two years or had botulinum toxin injections in the upper limb within the previous six months were excluded from the study. The Manual Ability Classification System (MACS) was used to classify children with uCP based on their manual abilities, with higher levels indicating poorer manual ability [11]. Age- and sex-matched TDC were included if they did not have a history of neurological, musculoskeletal or uncorrected visual impairments. Parents of each participant gave written informed consent to participate in the study. Children from 12 years onwards additionally gave their written assent to participate. This study was ethically approved by the Ethics Committee Research UZ/KU Leuven (S62906) and performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

2.2. Bimanual box-opening task

We assessed the bimanual box-opening task (Oxford Brookes University, Oxford, UK) as developed and described by Rudisch et al. [8,9] Participants were instructed to open the lid of a transparent box with one hand (box hand) and press a button inside the box using their contralateral hand (trigger hand) after a demonstration as depicted in Fig. 1. It was instructed to perform the task at a self-selected pace, and not as fast as possible. Participants were seated on a chair in front of a table on which a transparent box was positioned 25 cm from the table's border. To establish a standardized starting position, both hands were placed with the palms facing the table on a red line that was positioned 15 cm in front of the box. Two conditions were performed: (1) opening the box with the dominant hand (dominant hand condition, DHC) and (2) opening the box with the non-dominant hand (non-dominant hand condition, NDHC). First, two practice trials for each condition were conducted to ensure task comprehension. Subsequently, a total of 10 trials were recorded for each participant, with each hand performing five trials in a standardized order: 3xDHC, 3xNDHC, 2xDHC, 2xNDHC. Each trial started with an indication of the starting hand and an auditory start-command. 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 120Hz.

2.3. Data processing

Data processing and quality screening was conducted with the use of MATLAB R2022a (The Mathworks Inc., Natick, MA, USA) as in line with Rudisch et al. [8,9] Position, velocity and acceleration profiles for each trial were calculated. In each trial, the movement of the box hand was separated into two phases: the first phase involves reaching to the box, and the second phase involves opening the box. In contrast, the movement of the trigger hand only involved one step to reach and contact the trigger. To calculate the parameters, five spatiotemporal events were calculated based on the displacement and velocity signal of each hand (Fig. 2): start of the box hand (e1), start of the second phase of the box hand (e2), end of the box hand (e3), start of the trigger hand (e4) and trigger press (e5). More detailed information about these steps can be found in the studies of Rudisch et al. [8,9] Based on these events, the following bimanual parameters were calculated for both conditions: total movement time, temporal coupling, movement overlap and goal synchronisation (Fig. 2). First, total movement time refers to the overall task duration, which is calculated by taking the difference between the end of the trigger hand and the beginning of the box hand (e5-e1). Second, temporal coupling is the time difference between the start of the trigger hand and the start of the second phase of the box-opening hand (e4-e2). A lower value indicates shorter time between the start of both hands and better synchronisation. Third, movement overlap is the time when both hands are simultaneously active and calculated by the difference between the end of the box hand and the start of the trigger hand

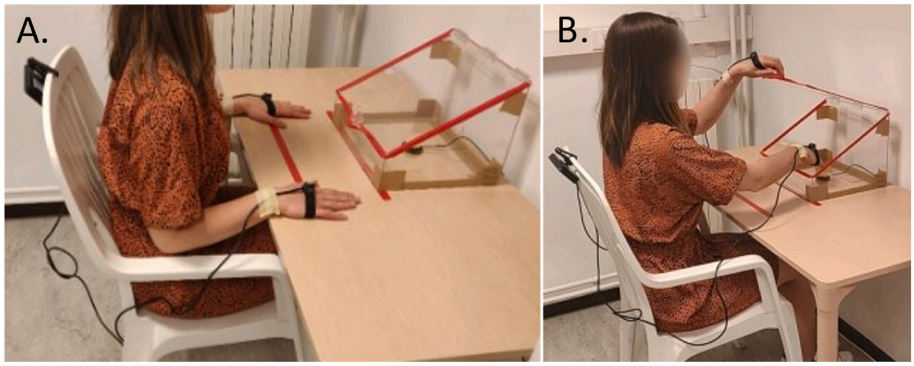

Fig. 1. Set-up of the box-opening task. In (A) the starting position is shown, while (B) shows a single trial with the left hand as the box hand and the right hand as the trigger hand.

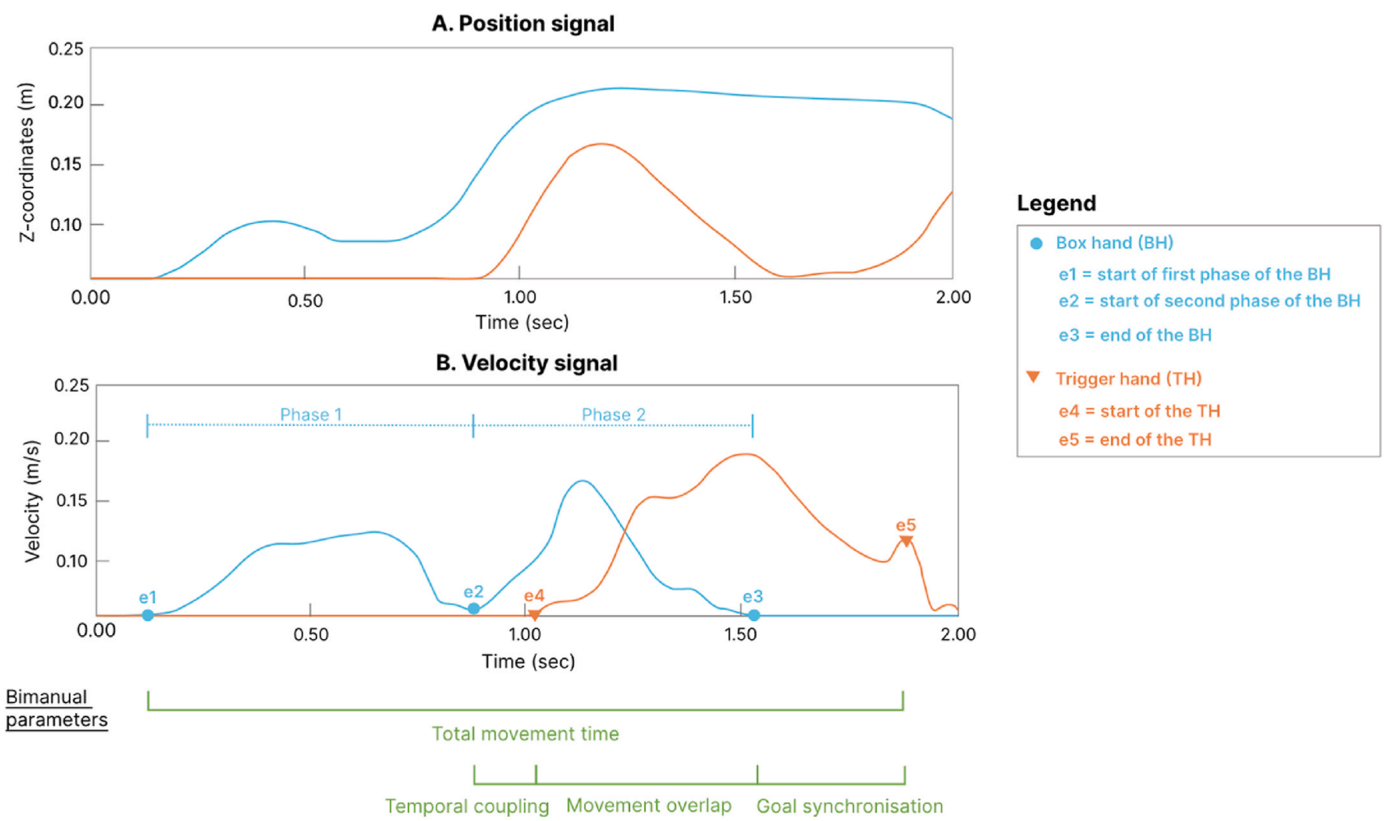

Fig. 2. The presented data represents a single trial of a typically developing child, demonstrating the position signal of vertical displacement (A) and velocity signal (B) over time in seconds for both the box hand (BH, blue) and trigger hand (TH, orange). In the velocity signal, five spatiotemporal events are highlighted. Bimanual parameters are depicted below the graphs in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(e3-e4). Lastly, goal synchronisation assesses how well the hands reach their end or respective goal at the same time, by subtracting the end of the box hand from the end of the trigger hand (e5-e3), where again a lower value indicates more synchronisation between both hands. Temporal coupling, movement overlap and goal synchronisation were normalised across total movement time. Furthermore, unimanual parameters were calculated for each hand separately: for the box hand (i.e., total time, (e3-e1); first phase, (e2-e1) and second phase, (e3-e2)) and the trigger hand (e5-e4). These unimanual parameters were also normalised across total movement time. Lastly, the position signal was used to calculate the path length of both hands (box hand, box hand phase 1, box hand phase 2 and trigger hand) and the velocity profile to define a proxy measure of smoothness of each hand [9]. The latter was calculated by the sum of the amount of local (highest and lowest) velocity peaks of each hand where a higher score represented a less smooth performance [9]. For every participant, the mean of each parameter was calculated of all valid trials in each condition, resulting in four bimanual and 10 unimanual parameters for each condition. Trials of bad quality due to technical problems (e.g., artefacts resulting from presence of metal components close to the device) were excluded. These artefacts included giant spikes in the velocity and acceleration profiles, resulting in an inability to calculate the events and therefore the outcome parameters. An example of a trial with bad quality can be found in appendix (A3). Only participants with at least three out of five valid trials for each condition were included in the statistical analysis [8,9].

2.4. Statistical analysis

Descriptive statistics were used to document the demographic and clinical characteristics of all participants. Differences in the box-opening task outcomes between children with uCP and TDC were investigated taking the two different conditions into account. A two-way mixed analysis of covariance (ANCOVA) was performed with group (uCP – TDC) as between-subjects variable, condition (DHC – NDHC) as repeated-measures variable and age as covariate. The assumption of homogeneity of the regression slopes was checked with the interaction of the between-subjects variable and covariate. If this interaction was not found to be statistically significant, it was removed from the two-way mixed ANCOVA analysis. In addition, if residuals were not normally distributed according to the Shapiro-Wilk test, or if there was unequal variance according to the Levene's test, transformation of the parameters was performed. An overview of the used transformations can be found in appendix (See A2). To ensure clinical interpretation, results of the statistical analysis were first back-transformed for the transformed variables before being further used in tables and figures [12]. When a statistically significant interaction effect was observed between the group and condition, Bonferroni-corrected post hoc comparisons were calculated to investigate the differences between the groups for each condition and between the condition within each group, using a corrected p-value for multiple comparisons ($\alpha = 0.05$). Partial eta squared (η_p^2) was used to compute effect sizes, which were classified as small (0.01–0.059), medium (0.06–0.13), or large (≥0.14) [13]. Lastly, due to the large amount of multiple comparisons [14], a false discovery rate was implemented to account for multiple testing, to ensure that only 5 % of the significant tests will result in false positive outcomes [15,16]. The similar model, i.e. two-way mixed analysis of covariance, was used to investigate differences between the levels of manual ability (i.e., MACS) in children with uCP. Lastly, we investigated the relation between unimanual and bimanual parameters in children with uCP with Pearson's (r) or Spearman's rho correlation coefficient (r_s), based on the normality of the data distribution measured with the Shapiro-Wilk test. Correlation coefficients were interpreted as no or little (<0.30), low (0.30–0.49), moderate (0.50–0.69), high (0.70–0.89) and very high (≥0.90) [17]. All statistical analyses were performed with SPSS version 28.0 (IBM Corp, Armonk, New York, USA).

3. Results

3.1. Participants

Out of 50 children with uCP and 50 TDC, 37 children with uCP (11y8m±2y10m, 20 males, 16 right-sided hemiplegia) and 37 individually matched TDC (mean age 11y8m±2y10m, 20 males, 34 right-handed) with a full dataset were eligible for further analysis. A flow chart displays the data collection process (Fig. 3). The descriptive characteristics of the excluded participants can be found in appendix (A4). Twenty-three children were classified as MACS level I, 11 children MACS level II and three children MACS level III. Lastly, the appendices include an example of the position and velocity signal of one trial during the DHC and NDHC for a child with uCP and a typically developing child (A5).

3.2. Differences between children with uCP and TDC

We examined how the box-opening task outcomes differed between children with uCP and TDC, while considering both conditions. There were no observed interaction effects between group and covariate age across all variables, leading to the removal of this interaction model from the analysis. A visual representation of the effect sizes can be found in Fig. 4, with an overview of the outcomes in Table 1 (see post-hoc analyses in appendix, A6).

First, for the bimanual parameters, only a significant main group effect was found for total movement time with a moderate effect size ($p = 0.01$, $\eta_p^2 = 0.13$), indicating that children with uCP have a higher total movement time for both conditions compared to TDC. The other bimanual parameters showed no significant interaction and also not a significant main group effect with only low effect sizes ($p = 0.28$–0.33, $\eta_p^2 = 0.01$–0.03).

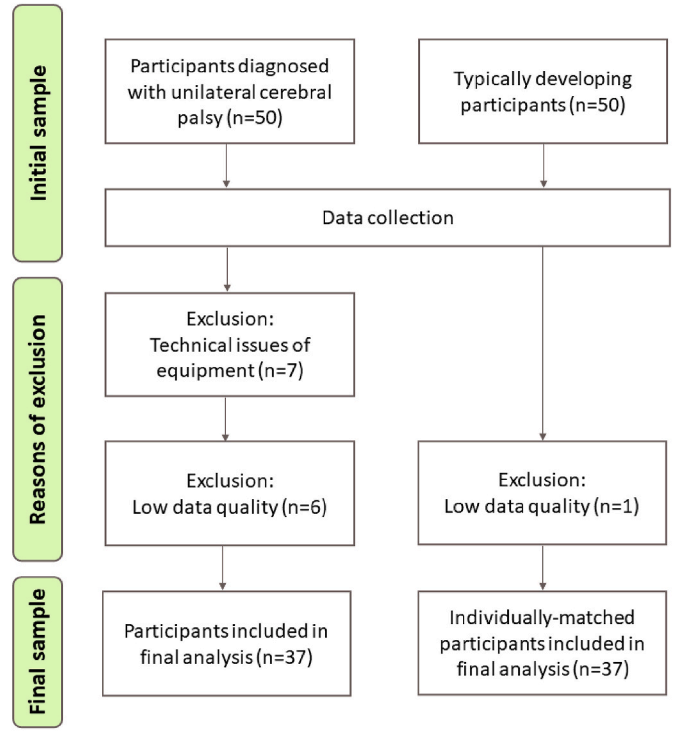

Fig. 3. Flow chart of the data collection process.

Second, for the unimanual parameters, significant two-way interactions with moderate effect sizes were found for movement time of the first phase of the box hand ($p = 0.03$, $\eta_p^2 = 0.10$) and trigger hand ($p = 0.01$, $\eta_p^2 = 0.11$). Post-hoc comparison showed that children with uCP exhibited a shorter movement time of the first phase of the box hand, but longer movement time of the trigger hand in the DHC compared to the NDHC ($p < 0.001$, $p = 0.001$) and compared to the DHC in TDC ($p < 0.001$, $p = 0.001$). Also for box hand smoothness, a large effect size and a significant two-way interaction was found ($p = 0.001$, $\eta_p^2 = 0.19$), suggesting that children with uCP exhibited poorer box hand smoothness in the NDHC compared to the DHC ($p < 0.01$) as well as compared to the NDHC of TDC ($p < 0.001$). For path length of the first phase of the box hand ($p = 0.01$, $\eta_p^2 = 0.11$), path length of the trigger hand ($p = 0.002$, $\eta_p^2 = 0.17$) and smoothness of the trigger hand ($p = 0.002$, $\eta_p^2 = 0.16$), only significant main group effects were found, indicating that children with uCP had longer path lengths and worse smoothness compared to TDC in both conditions. All other unimanual parameters showed low effect sizes with non-significant interactions and no significant main effects ($p = 0.11$–0.99, $\eta_p^2 = 0.00$–0.06).

3.3. Differences between MACS levels

Due to the low number of children with MACS level III (N = 3), comparison was done between MACS level I and II only. A visual representation of the effect sizes can be found in Fig. 5, with an overview of the means and 95 % confidence intervals in Fig. 6. While the analysis was performed on all parameters, this paragraph describes those parameters that exhibited a moderate to large effect size in differentiating between children with uCP and TDC with an interaction effect or main effect of group. The remaining outcomes can be found in appendix (see

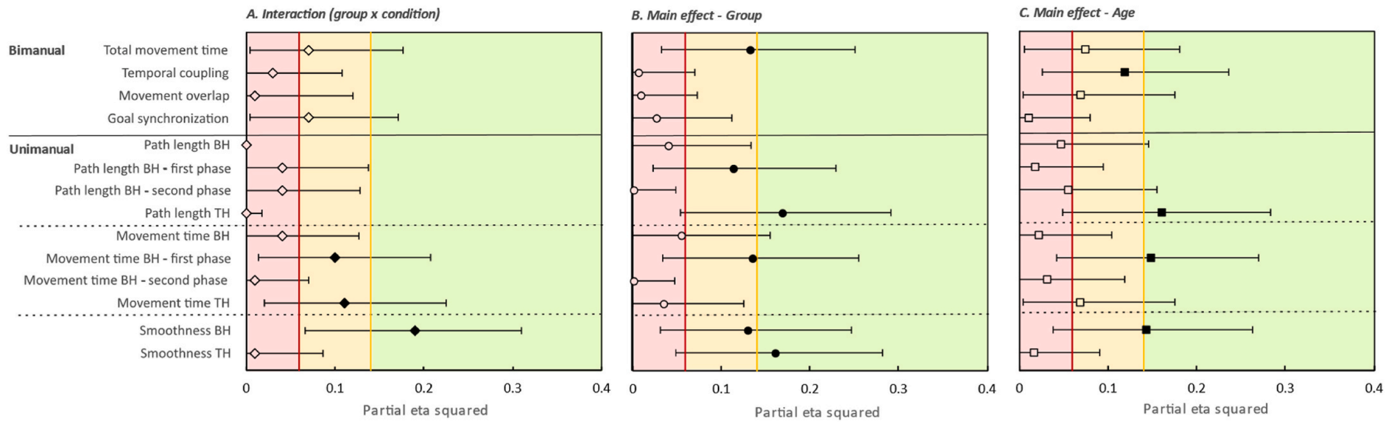

Fig. 4. Effect sizes (partial eta squared) with their 90 % confidence interval from the ANCOVA investigating the difference in box-opening task outcomes between children with uCP and TDC for the two-way interaction effect for group and condition (A), main effect of group (B) and age (C). Partial eta squared is classified and represented in red (low), yellow (medium) and green (large). Filled-in symbols represent a significant difference with a $p \leq 0.05$. BH = box hand, TH = trigger hand. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Box-opening task outcomes in children with uCP and TDC and results of two-way mixed ANCOVA.

Parameter		X (95 % CI)				Interaction effect		Main effect			
		TDC (N = 37)		uCP (N = 37)		Group x condition		Group		Age	
		DHC	NDHC	DHC	NDHC	F	p* (η_p^2)	F	p* (η_p^2)	F	p* (η_p^2)
Bimanual	**Total movement time**	1.55 (1.42–1.69)	1.51 (1.37–1.67)	1.84 (1.68–2.01)	1.94 (1.76–2.14)	5.32	0.07 (0.07)	10.76	**0.01** (0.13)	5.65	0.06 (0.07)
	Temporal coupling	0.08 (0.04–0.13)	0.11 (0.05–0.16)	0.13 (0.08–0.17)	0.11 (0.06–0.17)	1.78	0.33 (0.03)	0.52	0.61 (0.01)	9.57	**0.01** (0.12)
	Movement overlap	0.56 (0.51–0.61)	0.57 (0.51–0.63)	0.61 (0.65–0.66)	0.58 (0.52–0.64)	2.33	0.28 (0.01)	0.61	0.57 (0.01)	5.30	0.07 (0.07)
	Goal synchronisation	0.06 (0.04–0.09)	0.07 (0.05–0.09)	0.10 (0.08–0.13)	0.07 (0.05–0.09)	5.01	0.08 (0.07)	1.98	0.31 (0.03)	0.81	0.52 (0.01)
Unimanual	**Path length BH**	0.47 (0.43–0.50)	0.48 (0.45–0.51)	0.50 (0.47–0.54)	0.51 (0.48–0.54)	0.00	0.99 (0.00)	2.95	0.20 (0.04)	3.59	0.14 (0.05)
	Path length BH - first phase	0.23 (0.22–0.25)	0.24 (0.22–0.26)	0.26 (0.24–0.28)	0.29 (0.27–0.31)	3.13	0.18 (0.04)	9.07	**0.01** (0.11)	1.30	0.41 (0.02)
	Path length BH - second phase	0.23 (0.21–0.25)	0.24 (0.22–0.26)	0.24 (0.22–0.26)	0.22 (0.20–0.24)	2.71	0.22 (0.04)	0.15	0.83 (0.00)	4.10	0.11 (0.06)
	Path length TH	0.41 (0.39–0.44)	0.40 (0.38–0.42)	0.47 (0.45–0.51)	0.46 (0.43–0.48)	0.03	0.89 (0.00)	14.47	**0.002** (0.17)	13.64	**0.002** (0.16)
	Movement time BH	0.93 (0.91–0.95)	0.93 (0.91–0.94)	0.89 (0.87–0.91)	0.92 (0.90–0.94)	2.63	0.24 (0.04)	4.10	0.12 (0.06)	1.62	0.36 (0.02)
	Movement time BH-first phase	0.44 (0.42–0.45)	0.45 (0.43–0.46)	0.38 (0.36–0.40)	0.44 (0.42–0.45)	7.41	**0.03**[U,a] (0.10)	11.10	**0.01** (0.14)	12.48	**0.003** (0.15)
	Movement time BH - second phase	0.47 (0.45–0.49)	0.47 (0.44–0.49)	0.49 (0.47–0.51)	0.46 (0.44–0.49)	0.53	0.59 (0.01)	0.13	0.80 (0.00)	2.25	0.28 (0.03)
	Movement time TH	0.64 (0.59–0.69)	0.66 (0.60–0.71)	0.73 (0.69–0.78)	0.66 (0.61–0.71)	8.73	**0.01**[U,a] (0.11)	2.58	0.24 (0.04)	5.29	0.07 (0.07)
	Smoothness BH	5.40 (4.98–5.88)	4.94 (4.50–5.43)	5.96 (5.49–6.48)	6.59 (5.95–7.33)	16.28	**0.001**[U,T,b] (0.19)	10.49	**0.01** (0.13)	11.81	**0.005** (0.14)
	Smoothness TH	6.45 (5.56–7.49)	6.56 (5.46–7.90)	10.09 (8.69–11.73)	9.23 (7.67–11.10)	1.00	0.46 (0.01)	13.57	**0.002** (0.16)	1.15	0.43 (0.02)

A7 – A8).

First, for the bimanual parameters, significant two-way interactions with a large effect size were found for total movement time ($p = 0.03$, $\eta_p^2 = 0.21$) and goal synchronisation ($p = 0.04$, $\eta_p^2 = 0.19$). Post-hoc analysis demonstrated that children with a MACS level II had a slower performance of the NDHC condition ($p = 0.001$) and needed more time for goal synchronisation ($p = 0.008$) in the DHC compared to children with MACS level I.

Second, for the unimanual parameters, movement time of the first phase of the box hand showed a large significant two-way interaction ($p = 0.03$, $\eta_p^2 = 0.20$). Post-hoc analysis indicated that, in the DHC, children with MACS level II had a shorter movement time of the first phase of the box hand compared to MACS level I ($p < 0.001$). Additionally, a shorter movement time was present during the DHC compared to the NDHC in both groups (MACS l, $p = 0.04$; MACS ll; $p < 0.001$). Moreover, significant main effects with large effect sizes were found for path length of the first phase of the box hand, path length of the trigger hand and smoothness of the box and trigger hand ($p = 0.01–0.02$, $\eta_p^2 = 0.23–0.28$), suggesting that children with MACS level II had longer path lengths and a less smooth performance of both hands compared to children with a MACS level I.

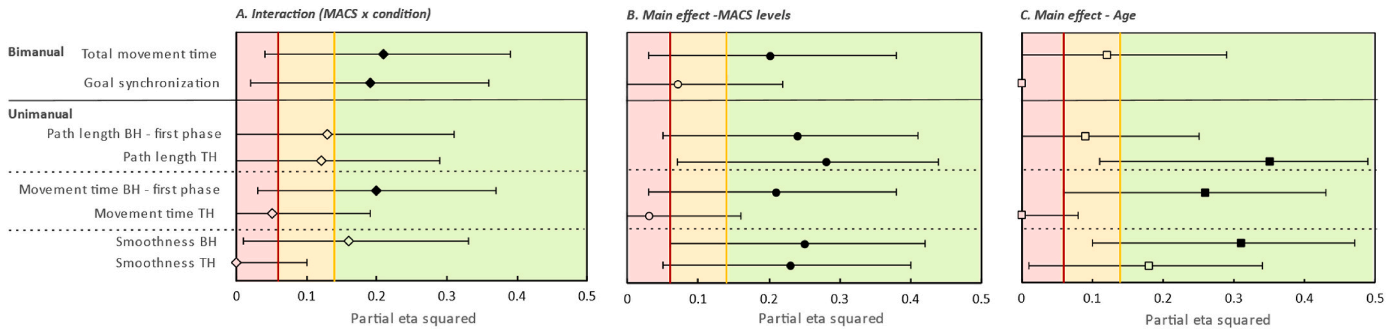

Fig. 5. Effect sizes (partial eta squared) with their 90 % confidence interval from the ANCOVA investigating the difference in box-opening task outcomes between children with uCP with MACS level l and ll for the two-way interaction effect for MACS levels and condition (A), main effect of MACS levels (B) and age (C). Only parameters with a moderate to large effect size between children with uCP and TDC are presented in this figure. Partial eta squared is classified and represented in red (low), yellow (medium) and green (large). Filled-in symbols represent a significant difference with a p ≤ 0.05. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. Relation between unimanual and bimanual parameters in children with uCP

To examine the relation between unimanual and bimanual parameters, we focused on parameters that exhibited a difference between children with uCP and TDC with moderate to large effect sizes. This included two bimanual parameters and 6 unimanual parameters for both conditions. An overview of the correlation coefficients of these parameters can be found in Fig. 6, with the correlation plots in appendix (A9). Additionally, an overview of the complete results can be found in appendix (A10).

First, total movement time was highly correlated with smoothness of the box hand in both conditions ($r_s = 0.80$, $p < 0.001$). Furthermore, in the DHC (Fig. 6A), higher total movement time was moderately related with faster movement time of the box hand in the first phase ($r = -0.59$, $p < 0.001$) and worse smoothness of the trigger hand ($r = 0.50$, $p = 0.001$). Low significant correlations were found between higher total movement time with longer path length of the first phase of the box hand ($r_s = 0.34$, $p = 0.04$) and longer path length of the trigger hand ($r_s = 0.36$, $p = 0.03$). Slower goal synchronisation was moderately correlated with faster movement time of the box hand ($r_s = -0.51$, $p = 0.001$) and weakly with worse smoothness of the trigger hand ($r_s = 0.36$, $p = 0.03$). In the NDHC (Fig. 6B), increased total movement time was moderately correlated with a longer path length of the first phase of the box hand ($r_s = 0.55$, $p < 0.001$). Low significant correlations were further found between higher total movement time with higher movement time of the first phase of the box hand ($r_s = -0.42$, $p = 0.01$) and reduced smoothness ($r_s = 0.45$, $p = 0.005$) and longer path length ($r_s = 0.48$, $p = 0.003$) of the trigger hand. Goal synchronisation was not related to the unimanual parameters in the NDHC ($r_s < -0.19$, $p > 0.26$).

4. Discussion

The overall aim of this study was to improve our understanding of spatiotemporal coordination deficits in children with uCP during the performance of an asymmetrical, bimanual, goal-directed task. Here, we found that children with uCP needed more time to execute the task, but did not show significant bimanual coupling deficits normalised for total movement time compared to TDC. Nevertheless, children with MACS level II needed more time to synchronize their hands at the end of the task compared to children with MACS level I. We further found significant unimanual spatiotemporal deficits in both upper limbs in children

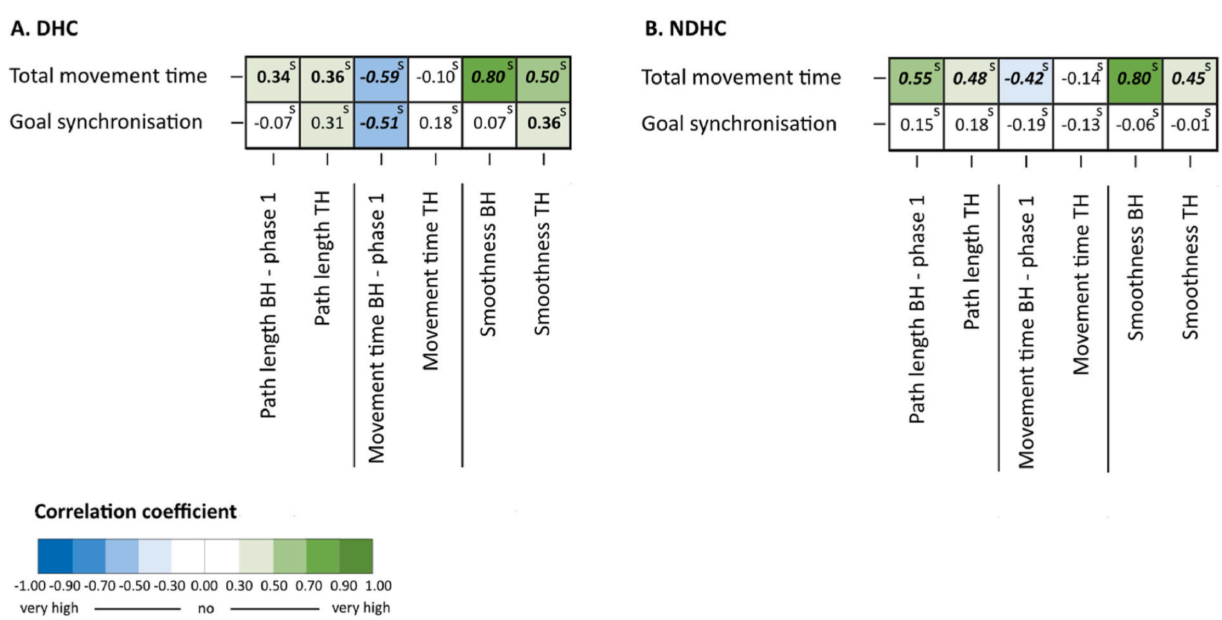

Fig. 6. Spearman's rank correlation coefficient of the bimanual and unimanual parameters of the box-opening task for the dominant hand condition (A, DHC) and the non-dominant hand condition (B, NDHC) of the parameters that have a moderate or high effect size difference between uCP and TDC. Bold correlation coefficients indicate a significance with p ≤ 0.05 and bold italic with p ≤ 0.01. BH = box hand, TH = trigger hand, s = spearman's rank correlation.

with uCP compared to TDC, which increased with lower manual abilities. Finally, slower total movement time was related with increased unimanual spatiotemporal deficits in both upper limbs. The novelty of this study stems from the quantification of spatiotemporal coordination in a large sample of children with uCP and age- and sex-matched TDC to examine both bimanual and unimanual spatiotemporal coordination using an asymmetrical, bimanual, goal-directed task.

First, the finding that children with uCP needed more time to execute this bimanual task in both conditions compared to TDC is in line with previous literature [7,18]. Surprisingly, we did not find significant differences for any of the bimanual coupling parameters which were normalised for total movement time (i.e. temporal coupling, movement overlap and goal synchronisation). Hence, our results overall suggest that even though children with uCP are slower, they maintain the ability to couple both hands well, relative to the time needed to perform the task. In contrast, Hung et al. [7] found a significantly more impaired movement overlap and goal synchronisation in children with uCP compared to TDC while performing the drawer-opening task. A potential explanation for this discrepancy, might be due to the difference in task used. Moreover, differences between studies with regard to level of impairment of the included participants with uCP could also explain this difference. Yet, Hung et al. [7] did not report the MACS levels of their 10 participants compromising study comparison.

Secondly, bimanual coordination differed depending on the manual ability level. Children with lower manual abilities (i.e. level II) were slower when performing the NDHC compared to children with better manual abilities (i.e. level I). In addition, children with MACS level II needed more time to execute the NDHC compared to the DHC. These findings are in line with Rudisch et al. [8] who also reported that the NDHC was performed slower compared to the DHC in children with uCP, and that only for the NDHC a slower performance corresponded with worse manual abilities. Moreover, we found a poorer goal synchronisation only during the DHC in children with MACS level II compared to the NDHC and compared to the DHC of children with MACS level I. Similarly, Hung et al. [7] also reported that, only for the DHC, children with more severe motor impairments needed more time to synchronize their hands, while they did not find such a relation for the NDHC. Together, these results suggest that even though the NDHC was performed slower, children with MACS level II have more difficulties with synchronising both hands at the end of the task performance of the DHC, while in children with MACS level I goal synchronisation was independent of the task condition. Since opening of the box is the most challenging part, it is hardly surprising that the NDHC, whereby the non-dominant, impaired hand opens the box, is performed slower with increasing levels of impairment. The dominant hand might subsequently align its performance to that of the non-dominant hand, still resulting in an adequate goal synchronisation, as previously suggested by Hung et al. [7] In contrast, during the DHC, the non-dominant, impaired hand needs to accurately press the button inside the box potentially prolonging goal synchronisation between both hands.

Previously, Birtles et al. [19] investigated the box-opening task in neurotypical adults and young children aged below 6 years, during which they opened the box with one hand and grasped a toy inside the box with the opposite hand. In their study, participants were allowed to choose how they performed the task. The authors found that adults preferred to use their non-dominant hand to open the box. As such they performed the second part of the task (i.e. toy grasping) with their dominant hand by means of anticipatory motor planning. In contrast, young children preferred to open the box with their dominant hand, most likely due to immature anticipatory planning abilities focussing on the initial task demands and thus starting with their dominant hand to open the box [19]. However, since in Rudisch et al. [8] and in our study, the toy grasping was replaced by a button press, the opening of the box was the most challenging part. Hence, Rudisch et al. [8] suggested that children with uCP might prefer to open the box with their dominant hand, as reflected by the faster performance of the DHC. However, our finding that goal synchronisation is less coupled in the DHC does not align with this hypothesis. Moreover, the question arises whether preferring the DHC would be a matter of selecting the dominant hand to perform the most challenging part, actually reflecting adequate motor planning, or whether it would be related to immature anticipatory planning abilities as seen in younger children. Indeed, it is well-described that children with uCP can have motor planning deficits [20]. Hence, investigating motor planning in relation to this task, as well as which is the preferred condition is needed to further understand how children with uCP plan and coordinate both hands.

Our study additionally provided more insights in the role of each hand during the performance of the bimanual box-opening task. First, we found that children with uCP performed the DHC with a faster box hand, but slower trigger hand compared to the NDHC, but also compared to the DHC in TDC. This difference was mainly due to the children with MACS level II, since these children had a faster box hand and slower trigger hand compared to children with MACS level I. It is not surprising that in the DHC children with uCP performed slower with their non-dominant, impaired hand as a trigger hand compared to their dominant hand as trigger hand in the NDHC; or compared to the non-dominant hand in TDC during the DHC. However, children with uCP were also faster with their dominant, less impaired hand as box hand during the DHC compared to TDC. This finding might indicate that during the DHC, children with uCP increase the movement speed of their dominant, less impaired hand (i.e. box hand) in an attempt to compensate for the slow performance of their non-dominant, impaired hand (i.e. trigger hand), which might also explain the overall faster performance of the DHC compared to the NDHC.

We further found that both path length and movement smoothness were worse for both upper limbs in children with uCP compared to TDC, as indicated by longer path lengths and reduced smoothness. Thus, in children with uCP not only the non-dominant, impaired side, but also the dominant side showed signs of reduced function compared to TDC. This has already been previously reported for unimanual tasks [21–24]. Our study additionally showed a decreased unimanual performance of the dominant upper limb during a bimanual task. The lower performance of the dominant upper limb might be explained by the presence of bilateral lesions seen in 30 %–50 % of children with a clinical presentation of uCP [25]. Moreover, our results further add to the literature that the decreased function of the dominant upper limb may worsen with decreasing manual abilities, since we also found longer path lengths and reduced smoothness of both upper limbs in children with MACS level II compared to MACS level I, independent of the task condition. Hence, this finding strengthens the idea that in children with uCP, assessment and treatment should not be limited to the impaired side only. Moreover, the increased path lengths and reduced smoothness of both upper limbs might be explained by a disturbed somatosensory and/or visual input. Beyond their motor problems, up to 80 percent of children with uCP present with additional somatosensory or visual impairments [21,26,27]. Moreover, it is well-known that sensory input is a key cornerstone for planning and finetuning motor actions [28,29]. Indeed, previous studies have already reported on the relation between increased somatosensory deficits and reduced bimanual function in children with uCP [5,30,31]. Still, an in-depth investigation of this association using quantitative outcome measurements of bimanual coordination is currently lacking.

The relevance of reduced path length and smoothness of both upper limbs for the performance of the box-opening task, and in particular smoothness of the box hand ($r_s = 0.80$) in both conditions, is also reflected in its relation with total movement time of the bimanual task. This indicates that children with reduced smoothness of the box hand need more time to complete the task. For goal synchronisation, only one moderate, but negative correlation was found with movement time of the first phase of the box hand in the DHC only, indicating that longer movement time of the box hand during the first phase was related to better goal synchronisation. This can be explained by the earlier finding that children with MACS level I had slower box hand movements, yet better goal synchronisation than children with MACS level II. Nevertheless, the lack of other significant correlations between goal synchronisation and the unimanual parameters implies that bimanual coordination is not solely the product of its unimanual components. Indeed, research has already shown that the neural network for bimanual coordination exceeds that of its unimanual movements, with the corpus callosum playing a prominent role [2,32]. So far, only Hung et al. [33] has investigated the relation between the corpus callosum and the drawer-opening task in children with uCP, showing that with decreasing connectivity of the corpus callosum, bimanual coordination worsens. Hence, further research examining the relation between bimanual coordination and its underlying neural network in children with uCP is warranted.

As a limitation we excluded children with MACS level III for the comparison of bimanual coordination between manual ability levels due to the low number of included children (N = 3). This was mainly due to an involuntary selection bias, as three children with MACS level III were excluded due to bad data quality, possibly because they wore medical instruments containing metal (braces, orthoses or mouth masks). Hence, the study results of the second research question are not generalizable to children outside of MACS levels I and II. However, for the first and third research question, these children were included in the analyses in order to have a more representative study sample of children with uCP which is in line with the population-based study of Arner et al. [34] Nevertheless, we acknowledge that based on our criteria to exclude children without the minimal ability to grasp and stabilize an object with their non-dominant hand, our sample does not fully represent the population of children with uCP. Hence, this needs to be taken into account when interpreting our results. Secondly, bimanual movements during daily life activity are highly variable and abundant. Hence, the box opening task alone cannot fully reflect bimanual daily life performance.

Nevertheless, this study provided more insights in bimanual and unimanual spatiotemporal coordination, and their relation, using a bimanual, asymmetrical task. First, this study showed that the box-opening task is able to detect differences in unimanual and bimanual parameters between children with uCP and TDC, as well as between MACS levels, establishing its discriminant ability. Hence, this task would be suited to quantitatively assess bimanual coordination during the performance of a functional task en to evaluate the efficacy of intervention programs addressing bimanual coordination. Secondly, this study confirmed that spatiotemporal coordination of also the dominant upper limb in children with uCP is less compared to the dominant upper limb of TDC. Moreover, the relation between a slower total movement time with increased unimanual spatiotemporal deficits of both upper limbs in terms of reduced path length and movement smoothness, suggests that also the reduced performance of the dominant upper limb contributes to bimanual difficulties seen in children with uCP, which is a novel finding in literature and warrants further investigation.

5. Conclusion

We can conclude that although children with uCP need more to time to execute the box-opening task, they did not show significant bimanual coupling deficits relative to their total movement time compared to TDC. Comparison between MACS levels further showed that goal synchronisation was mostly prolonged in children with MACS level II compared to children with MACS level I during the DHC. We also found significant between-group differences for most unimanual spatiotemporal deficits in both the non-dominant and the dominant upper limb, which increased with decreasing manual abilities. This finding underlines the importance to assess and treat both upper limbs in children with uCP. Finally, the relation between the bimanual and unimanual parameters was mostly weak to moderate, confirming that bimanual coordination goes beyond its unimanual components. Hence, this study provided more insights in bimanual and unimanual spatiotemporal coordination, and their relation, using a bimanual, asymmetrical task.

Author contributions

Conceptualization: all authors; Methodology: LM, LD, DG; Statistical analysis: LD, AK; Investigation, LD, LK, MC; Resources: AVC, EO, DG, KK, HF; Writing – original draft: LM, LD; Writing – review and editing: all authors; Supervision: KK, HF; Funding acquisition: LM, AVC, GV, EO, KK, HF.

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Declaration of competing interest

None.

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Appendices.

Appendix A1. STROBE Statement - Checklist of items that should be included in reports of ***cross-sectional studies***

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	1
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	2
Objectives	3	State specific objectives, including any prespecified hypotheses	2–3
Methods			
Study design	4	Present key elements of study design early in the paper	
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	3

(*continued on next page*)

(*continued*)

	Item No	Recommendation	Page No
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants	3
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	3–4
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	4
Bias	9	Describe any efforts to address potential sources of bias	X
Study size	10	Explain how the study size was arrived at	X
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	4–5
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	5
		(*b*) Describe any methods used to examine subgroups and interactions	5
		(*c*) Explain how missing data were addressed	6
		(*d*) If applicable, describe analytical methods taking account of sampling strategy	X
		(*e*) Describe any sensitivity analyses	X
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	6
		(b) Give reasons for non-participation at each stage	6
		(c) Consider use of a flow diagram	X
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	6
		(b) Indicate number of participants with missing data for each variable of interest	6
Outcome data	15*	Report numbers of outcome events or summary measures	6–9
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95 % confidence interval). Make clear which confounders were adjusted for and why they were included	6-9; Tables 1–2 and appendix
		(*b*) Report category boundaries when continuous variables were categorized	X
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	X
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	X
Discussion			
Key results	18	Summarise key results with reference to study objectives	9
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	12
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	9–12
Generalisability	21	Discuss the generalisability (external validity) of the study results	12
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	14

*Give information separately for exposed and unexposed groups.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

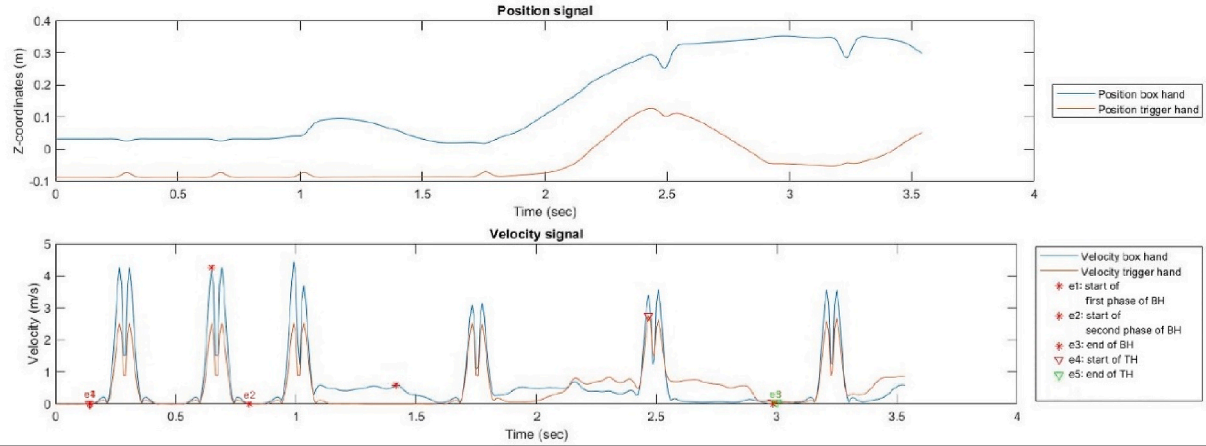
Appendix A2. Overview of transformation of the box opening task outcomes

Classification	Parameter	Transformation	
		Comparison uCP - TDC	Comparison MACS levels
Bimanual	**Total movement time**	Logarithm	Logarithm
	Temporal coupling	/	/
	Movement overlap	/	Square root
	Goal synchronisation	Square root	Square root
Unimanual	**Path length BH**	/	/
	Path length BH - first phase	Box-Cox	/
	Path length BH - second phase	/	/
	Path length TH	Box-Cox	Box-Cox
	Movement time BH	Box-Cox	Reverse logarithm
	Movement time BH- first phase	Reverse square root	/
	Movement time BH - second phase	/	/
	Movement time TH	/	Box-Cox
	Smoothness BH	Box-Cox	Logarithm
	Smoothness TH	Logarithm	Logarithm

uCP = unilateral cerebral palsy, TDC = typically developing children, MACS = manual ability classification system, BH = box hand, TH = trigger hand.

Appendix A3. Example of a bad quality trial in a child with unilateral cerebral palsy (CPB_12)

Appendix A3: Example of a bad quality trial in a child with unilateral cerebral palsy (CPB_12)



BH = box hand (blue), TH = trigger hand (orange), e=event.

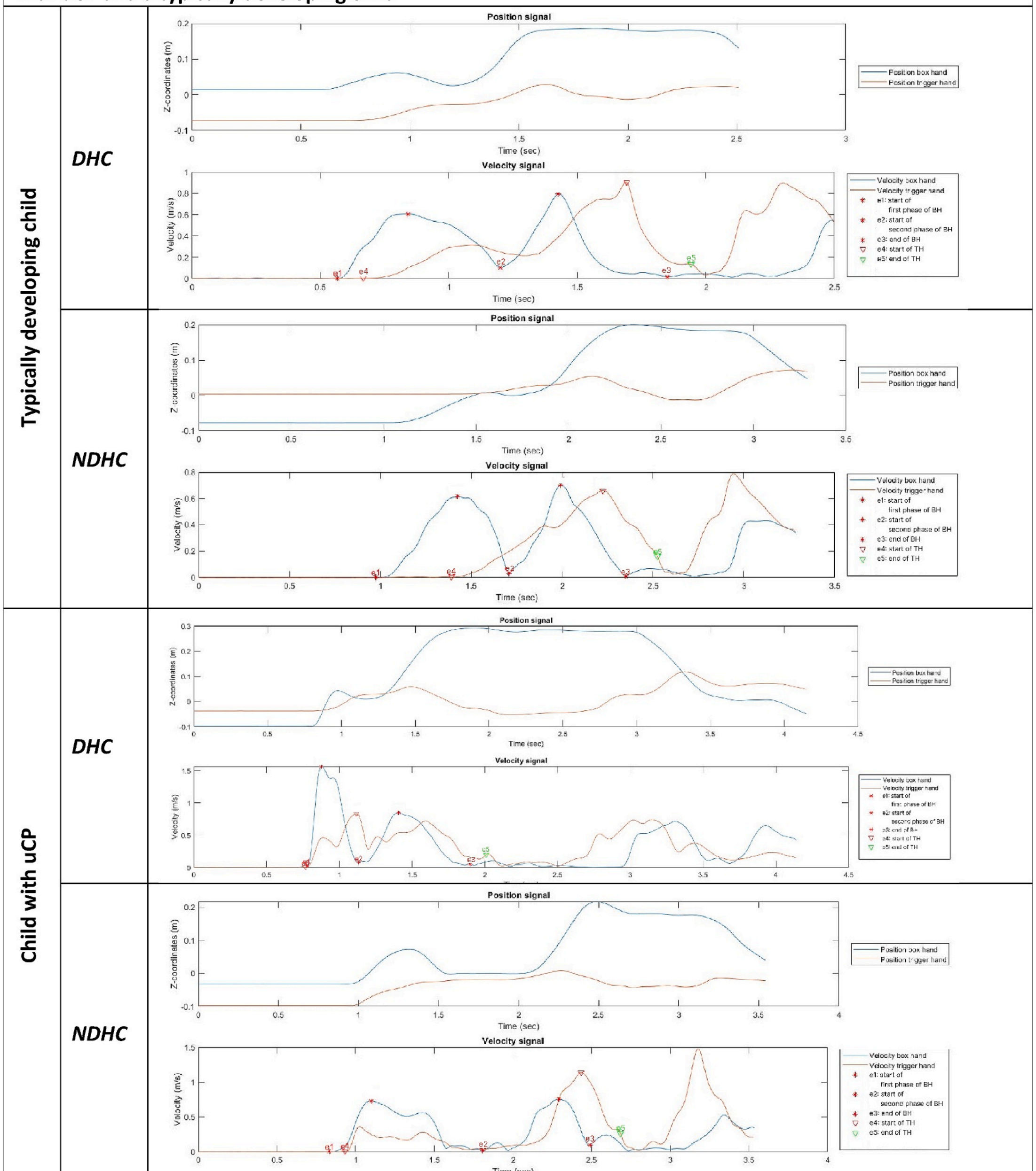
Appendix A4. Descriptives of excluded participants with bad quality data

Group	Participants	Age	Gender	DH	MACS-level	HFCS	Remarks
TDC	**TDC_31**	15y 4m	M	L	/	/	No metal nearby during assessment. Technical issues.
uCP	**CPB_12**	11y 1m	F	L	lll	4	Knee extension brace after surgery, glasses
	CPB_30	7y 6m	F	L	ll	5	No metal nearby during assessment. Technical issues.
	CPB_33	14y 10m	M	R	lll	4	Mouth mask during assessments
	CPB_47	13y 10m	M	R	ll	7	No metal nearby during assessment. Technical issues.
	CPB_48	14y 0m	M	R	lll	5	Ankle-foot orthosis
	CPB_51	14y 7m	F	L	ll	5	Ankle-foot orthosis

uCP = unilateral cerebral palsy, TDC = typically developing child, DH = dominant hand, MACS = manual ability classification system, HFCS = House Functional Classification System.

Appendix A5. Output of the position and velocity signal of one trial during the DHC and NDHC for a child with uCP and a typically developing child

Appendix A5: Output of the position and velocity signal of one trial during the DHC and NDHC for a child with uCP and a typically developing child

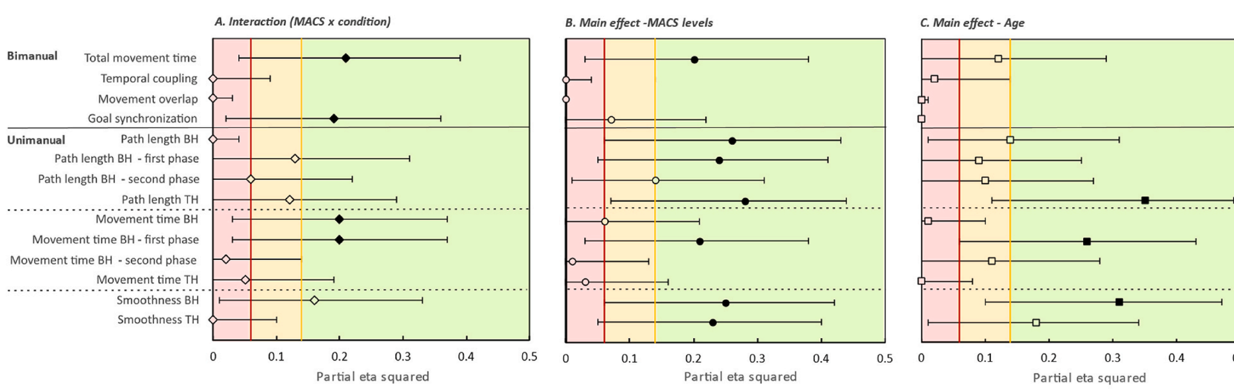


TDC = typically developing children, uCP = unilateral cerebral palsy, BH = box hand, TH = trigger hand, e = event.

Appendix A6. *Two-way mixed ANCOVA between children with uCP and TDC taking the two conditions into account*

Parameter		Mean (95 % CI)				Interaction effect		Posthoc (p)				Main effects			
		TDC		uCP		Group x condition		Within groups		Between groups		Group		Age	
		DHC	NDHC	DHC	NDHC	F	p* (η_p^2)	TDC	uCP	DHC	NDHC	F	p* (η_p^2)	F	p* (η_p^2)
Bimanual	**Total movement time**	1.55 (1.42–1.69)	1.51 (1.37–1.67)	1.84 (1.68–2.01)	1.94 (1.76–2.14)	5.32	0.07 (0.07)					10.76	**0.01** (0.13)	5.65	0.06 (0.07)
	Temporal coupling	0.08 (0.04–0.13)	0.11 (0.05–0.16)	0.13 (0.08–0.17)	0.11 (0.06–0.17)	1.78	0.33 (0.03)					0.52	0.61 (0.01)	9.57	0.01 (0.12)
	Movement overlap	0.56 (0.51–0.61)	0.57 (0.51–0.63)	0.61 (0.65–0.66)	0.58 (0.52–0.64)	2.33	0.28 (0.01)					0.61	0.57 (0.01)	5.30	0.07 (0.07)
	Goal synchronisation	0.06 (0.04–0.09)	0.07 (0.05–0.09)	0.10 (0.08–0.13)	0.07 (0.05–0.09)	5.01	0.08 (0.07)					1.98	0.31 (0.03)	0.81	0.52 (0.01)
Unimanual	**Path length BH**	0.47 (0.43–0.50)	0.48 (0.45–0.51)	0.50 (0.47–0.54)	0.51 (0.48–0.54)	0.00	0.99 (0.00)					2.95	0.20 (0.04)	3.59	0.14 (0.05)
	Path length BH - first phase	0.23 (0.22–0.25)	0.24 (0.22–0.26)	0.26 (0.24–0.28)	0.29 (0.27–0.31)	3.13	0.18 (0.04)					9.07	**0.01** (0.11)	1.30	0.41 (0.02)
	Path length BH - second phase	0.23 (0.21–0.25)	0.24 (0.22–0.26)	0.24 (0.22–0.26)	0.22 (0.20–0.24)	2.71	0.22 (0.04)					0.15	0.83 (0.00)	4.10	0.11 (0.06)
	Path length TH	0.41 (0.39–0.44)	0.40 (0.38–0.42)	0.47 (0.45–0.51)	0.46 (0.43–0.48)	0.03	0.89 (0.00)					14.47	**0.002** (0.17)	13.64	**0.002** (0.16)
	Movement time BH	0.93 (0.95–0.91)	0.93 (0.94–0.91)	0.89 (0.91–0.87)	0.92 (0.94–0.90)	2.63	0.24 (0.04)					4.10	0.12 (0.06)	1.62	0.36 (0.02)
	Movement time BH- first phase	0.44 (0.42–0.45)	0.45 (0.43–0.46)	0.38 (0.36–0.40)	0.44 (0.42–0.45)	7.41	**0.03** (0.10)	0.45	**<0.001**	**<0.001**	0.54	11.10	**0.01** (0.14)	12.48	**0.003** (0.15)
	Movement time BH - second phase	0.47 (0.45–0.49)	0.47 (0.44–0.49)	0.49 (0.47–0.51)	0.46 (0.44–0.49)	0.53	0.59 (0.01)					0.13	0.80 (0.00)	2.25	0.28 (0.03)
	Movement time TH	0.64 (0.59–0.69)	0.66 (0.60–0.71)	0.73 (0.69–0.78)	0.66 (0.61–0.71)	8.73	**0.01** (0.11)	0.43	**0.001**	**0.01**	0.91	2.58	0.24 (0.04)	5.29	0.07 (0.07)
	Smoothness BH	5.40 (4.98–5.88)	4.94 (4.50–5.43)	5.96 (5.49–6.48)	6.59 (5.95–7.33)	16.28	**0.001** (0.19)	**0.01**	**0.01**	0.10	**<0.001**	10.49	**0.01** (0.13)	11.81	**0.005** (0.14)
	Smoothness TH	6.45 (5.56–7.49)	6.56 (5.46–7.90)	10.09 (8.69–11.73)	9.23 (7.67–11.10)	1.00	0.46 (0.01)					13.57	**0.002** (0.16)	1.15	0.43 (0.02)

Appendix A7. *Effect sizes (partial eta squared) with their 90 % confidence interval from the ANCOVA investigating the difference in all the box opening task outcomes between children with uCP with MACS level l and ll*



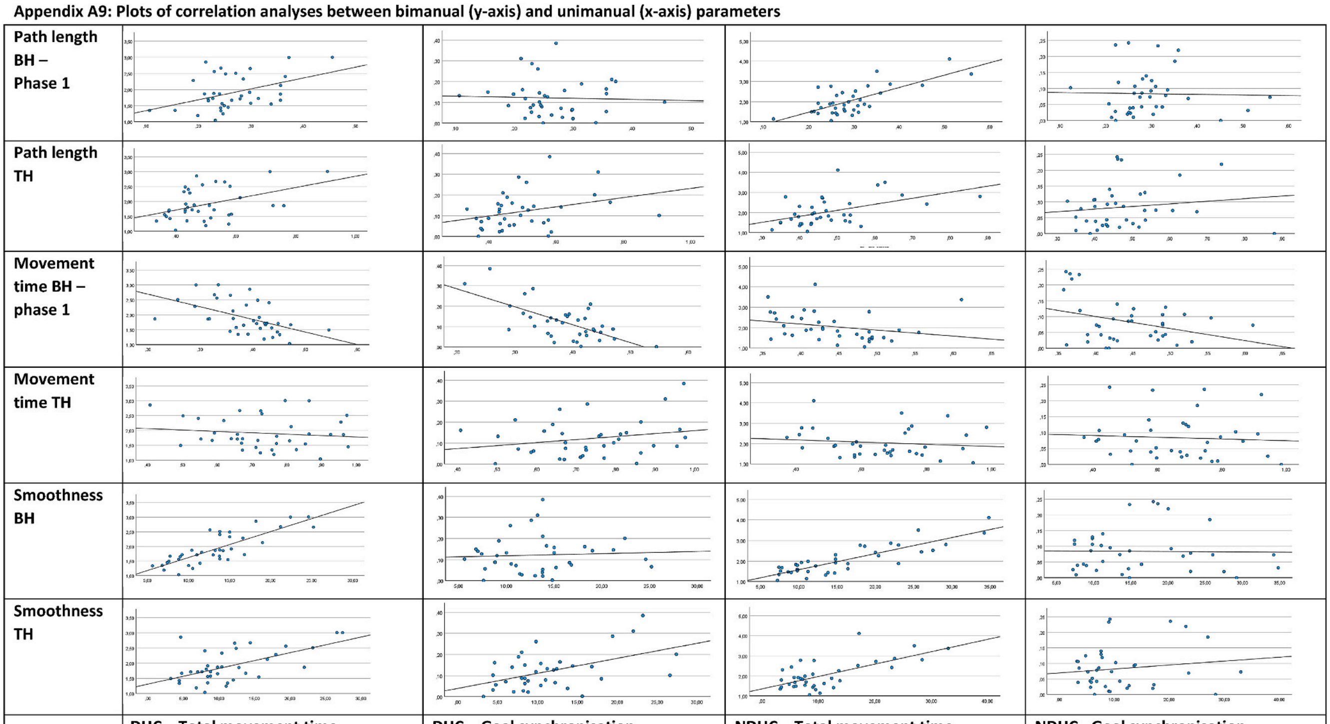
(A) Two-way interaction effect for group and condition, (B) main effect of group and (C) age. Partial eta squared is classified and presented in red (low), yellow (medium) and green (large). A filled in symbol (diamond or circle) represent a significant difference with a p≤0.05. MACS = manual ability classification scale.

Appendix A8. Two-way mixed ANCOVA between different MACS levels taking the two conditions into account

Parameter		Mean (95 % CI)				Interaction effect		Posthoc (p)				Main effect			
		MACS l		MACS ll		MACS x condition		Within groups		Between groups		MACS		Age	
		DHC	NDHC	DHC	NDHC	F	p* (η_p^2)	Level l	Level ll	DHC	NDHC	F	p* (η_p^2)	F	p* (η_p^2)
Bimanual	**Total movement time**	1.71 (1.52–1.93)	1.70 (1.50–2.14)	1.97 (1.72–2.26)	2.33 (2.02–1.43)	8.45	**0.03** (0.21)	0.83	**0.002**	0.08	**0.001**	7.95	**0.03** (0.20)	4.19	0.11 (0.12)
	Temporal coupling	0.12 (0.07–0.18)	0.10 (0.03–0.18)	0.12 (0.04–0.20)	0.09 (−0.03-0.19)	0.10	0.85 (0.00)					0.04	0.90 (0.00)	0.50	0.64 (0.02)
	Movement overlap	0.60 (0.53–0.67)	0.55 (0.47–0.63)	0.60 (0.50–0.71)	0.54 (0.43–0.67)	0.02	0.91 (0.00)					0.00	0.97 (0.00)	0.01	0.94 (0.00)
	Goal synchronisation	0.08 (0.05–0.11)	0.07 (0.04–0.10)	0.15 (0.11–0.21)	0.07 (0.03–0.11)	7.04	**0.04** (0.19)	0.69	**0.001**	**0.008**	0.77	2.14	0.27 (0.07)	0.00	0.99 (0.00)
Unimanual	**Path length BH**	0.47 (0.42–0.51)	0.47 (0.43–0.51)	0.56 (0.50–0.64)	0.57 (0.52–0.64)	0.04	0.91 (0.00)					10.93	**0.01** (0.26)	4.92	0.09 (0.14)
	Path length BH - first phase	0.25 (0.22–0.28)	0.26 (0.23–0.28)	0.29 (0.25–0.33)	0.34 (0.31–0.38)	4.78	0.09 (0.13)					9.71	**0.02** (0.24)	2.89	0.19 (0.09)
	Path length BH - second phase	0.22 (0.19–0.24)	0.21 (0.18–0.24)	0.27 (0.24–0.32)	0.23 (0.20–0.28)	2.10	0.27 (0.06)					4.86	0.08 (0.14)	3.51	0.14 (0.10)
	Path length TH	0.44 (0.46–0.43)	0.44 (0.46–0.41)	0.54 (0.63–0.47)	0.48 (0.55–0.43)	4.23	0.11 (0.12)					11.79	**0.01** (0.28)	15.23	**<0.001** (0.35)
	Movement time BH	0.91 (1.06–0.26)	0.92 (1.06–0.27)	0.84 (1.04–1.04)	0.93 (1.04–1.04)	7.50	**0.03** (0.20)	0.94	**0.002**	**0.01**	0.60	1.80	0.32 (0.06)	0.16	0.83 (0.01)
	Movement time BH- first phase	0.41 (0.39–0.44)	0.44 (0.42–0.47)	0.35 (0.31–0.37)	0.44 (0.40–0.47)	7.66	**0.03** (0.20)	**0.04**	**<0.001**	**<0.001**	0.63	8.28	**0.03** (0.21)	11.14	**0.01** (0.26)
	Movement time BH - second phase	0.49 (0.46–0.51)	0.46 (0.43–0.49)	0.48 (0.44–0.53)	0.48 (0.44–0.53)	0.51	0.64 (0.02)					0.36	0.69 (0.01)	3.87	0.12 (0.11)
	Movement time TH	0.71 (0.64–0.77)	0.65 (0.58–0.72)	0.78 (0.69–0.85)	0.66 (0.56–0.76)	1.46	0.37 (0.05)					0.82	0.54 (0.03)	0.08	0.86 (0.00)
	Smoothness BH	11.45 (9.85–13.30)	11.89 (9.96–14.20)	12.98 (11.52–14.63)	18.08 (15.04–21.74)	5.71	0.06 (0.16)					10.26	**0.01** (0.25)	14.03	**0.001** (0.31)
	Smoothness TH	8.54 (6.89–10.59)	7.31 (5.74–9.31)	12.45 (10.12–15.32)	11.66 (8.75–15.53)	0.13	0.84 (0.00)					9.37	**0.02** (0.23)	6.07	0.05 (0.18)

Appendix A9. Plots of correlation analyses between bimanual (y-axis) and unimanual (x-axis) parameters

Appendix A9: Plots of correlation analyses between bimanual (y-axis) and unimanual (x-axis) parameters



DHC = dominant hand, NDHC = non-dominant hand, BH = box hand, TH = trigger hand.

Appendix A10. Pearson and spearman's rank correlation coefficient of the bimanual and unimanual parameters of the box opening task for both conditions

A. DHC

	Path lenght BH	Path length BH - phase 1	Path length BH - phase 2	Path length TH	Movement time BH	Movement time BH - phase 1	Movement time BH - Phase 2	Movement time TH	Smoothness BH	Smoothness TH
Total movement time	**0,35** s	**0,34** s	0,17 s	**0,36** s	**-0,40** s	***-0,59*** s	0,05 s	-0,10 s	***0,80*** s	***0,50*** s
Temporal coupling	0,06	-0,08	0,17	0,06 s	0,03 s	-0,15	0,20	***0,89***	-0,21	**0,33** s
Movement overlap	0,21	0,00	**0,34**	0,12 s	**0,37** s	-0,15	***0,62***	***0,82***	-0,02	0,29
Goal synchronisation	-0,02 s	-0,07 s	-0,14 s	0,31 s	***-0,99*** s	***-0,51*** s	***-0,67*** s	0,18 s	0,07 s	**0,36** s

B. NDHC

	Path lenght BH	Path length BH - phase 1	Path length BH - phase 2	Path length TH	Movement time BH	Movement time BH - phase 1	Movement time BH - Phase 2	Movement time TH	Smoothness BH	Smoothness TH
Total movement time	**0,36** s	***0,55*** s	0,00 s	***0,48*** s	-0,21 s	***-0,42*** s	0,01 s	-0,14 s	***0,80*** s	***0,45*** s
Temporal coupling	0,06 s	0,13	0,06	0,17 s	0,03 s	**0,38**	-0,21	***0,94***	-0,17 s	***0,44*** s
Movement overlap	0,14 s	0,12	0,17	0,10 s	**0,36** s	0,19	0,20	***0,93***	-0,14 s	**0,42** s
Goal synchronisation	-0,02 s	0,15 s	-0,12 s	0,18 s	***-0,91*** s	-0,19 s	***-0,72*** s	-0,13 s	-0,06 s	-0,01 s

Correlation coefficient

-1.00 -0.90 -0.70 -0.50 -0.30 0.00 0.30 0.50 0.70 0.90 1.00

DHC = dominant hand, NDHC = non-dominant hand, BH = box hand, TH = trigger hand, s = spearman's rank correlation, bold = significant correlation with p≤0.05, bold italic = significant correlation with p≤0.01

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejpn.2024.10.003.

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