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RESEARCH ARTICLE

Eye movements show similar adaptations in temporal coordination to movement planning conditions in both people with and without cerebral palsy

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Abstract The effects of cerebral palsy on movement planning for simple reaching tasks are not well understood. Movement planning is complex and entails many processes which could be affected. This study specifically sought to evaluate integrating task information, decoupling movements, and adjusting to altered mapping. For a reaching task, the asynchrony between the eye onset and the hand onset was measured across different movement planning conditions for participants with and without cerebral palsy. Previous research shows people without cerebral palsy vary this temporal coordination for different planning conditions. Our measurements show similar adaptations in temporal coordination for groups with and without cerebral palsy, to three of the four variations in planning condition tested. However, movement durations were still longer for the participants with cerebral palsy. Hence for simple goal-directed reaching, movement execution problems appear to limit activity more than movement planning deficits.

Keywords Eye-hand coordination · Goal-directed reaching · Eye movements · Onset asynchrony · Cerebral palsy

Introduction

Cerebral palsy (CP) is a common physical disability and it appears to affect movement planning of reaching movements (Steenbergen and Gordon 2006). Cerebral palsy is an umbrella term for a group of movement disorders resulting in activity limitation including hand movements. It arises from non-progressive disturbances to the foetal or infant brain (Rosenbaum et al. 2007), and occurs in nearly 3 per thousand births (Yeargin-Allsopp et al. 2008). A more precise understanding of the effects of CP on movement planning and manual activities can inform therapies (Steenbergen and Gordon 2006) and assistive technology design.

Movement planning is complex, so it can be affected in different ways. Movement planning is the ability to assess the actions required to get from a current state to a desired future state and achieve an extrinsic task goal (Wolpert 1997). It is important since purely feedback control of reaching movements is not practical due to the time delays of the sensory system (Kawato 1999). It is complex since there are many levels of planning to be specified [from the task goal to neural commands, see Wolpert (1997)], almost infinite solutions to problems, and many different task conditions that alter what planning entails. This study specifically focuses on integrating various levels of spatial task information into movement plans, decoupling control of eye and hand movements, and altering muscle-effector mapping. These will be further elaborated later.

Movement planning is difficult to measure directly and quantifiably. Previous work on CP and movement planning has observed grip placement (Steenbergen et al. 2004; Mutsaarts et al. 2005; Steenbergen and Van Der Kamp 2004) and measured fingertip force regulation (Eliasson et al. 1991; Duff and Gordon 2003; Gordon et al. 1999, 2006a; Rosenbaum et al. 2001). Grip placement tasks investigated capacity to plan into the future. For participants with CP, it was shown that planning was directed at intermediate steps instead of the end goal of the task (Steenbergen and Gordon 2006). Fingertip force experiments investigated participants' ability to integrate weight information into

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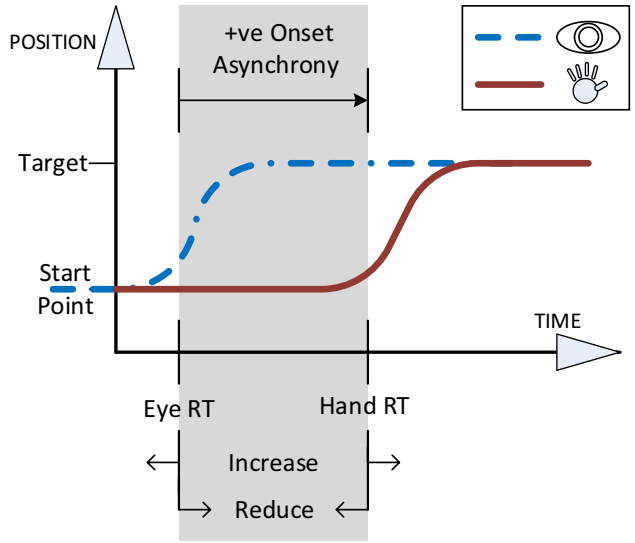

Fig. 1 Eye-hand movement onset asynchrony diagram. This shows positive onset asynchrony: the eye movement starts before the hand movement. *Arrows* at the *bottom* show how changes in onset times increase or reduce in onset asynchrony

movement plans and found that in some cases this was impaired.

We investigate the effects of CP on movement planning using a relatively novel method; we examine if people with CP adapt their temporal eye-hand coordination patterns in response to different planning conditions. Previous research (in participants without CP) has shown adaptations in the timing of eye-hand coordination in response to changes in movement planning conditions[1] (White et al. 2012; Adam et al. 2012; Gorbet and Sergio 2009). These adaptations do not directly represent planning ability, but they do demonstrate typical behaviours.

To assess temporal coordination, we measure eye-hand movement onset asynchrony (onset asynchrony for short). When a hand moves to a target, generally the eyes start moving towards the target just before the hand. Onset asynchrony is the temporal gap between the start of the eye movement and that of the hand (Fig. 1). It reflects the timing of eye-hand coordination adopted for a given situation. It can be calculated as the difference between eye reaction times and hand reaction times (Eq. 1). This measure has been used in populations with CP to study visual monitoring of the hand during an object transportation task (Verrel et al. 2008; Steenbergen et al. 2007). We also performed a case study investigating the repeatability of these measurements (Payne et al. 2015). In terms of movement planning, onset asynchrony is not directly a performance measure; thus value judgements cannot be made based on its magnitude. However changes in onset asynchrony between different task conditions are useful for demonstrating typical changes in behaviour (in response to different planning conditions). Since it is a measure taken at the very start of a movement, it should be relatively unaffected by a person's online motor control.

$$\text{Onset asynchrony} = \text{Hand RT} - \text{Eye RT} \quad (1)$$

In this research, four changes in planning condition are compared to a baseline measure. We altered the planning conditions of a discrete[2] movement and examined the effects on onset asynchronies of participants with and without CP. The four alterations we investigated were:

Known Direction facilitating the pre-planning of movements via known target locations,

Eyes Apart decoupling the direction of eye and hand movements by starting the eyes apart from thehand,

Mouse Blank-Slate altering the mapping between muscle recruitment and effector[3] output by using amouse and cursor instead of direct pointing, and

Possible Locations visible allowing partial knowledge of the target location by displaying possible target locations before trial start.

For Known Direction trials, pre-planning a movement before trial start should result in reduced onset asynchrony. Knowing where a target will appear prior to trial start makes pre-planning possible (Rosenbaum 1980) and is associated with decreased hand reaction times (Olivier and Bard 2000). Three studies have shown that making a target direction predictable reduces onset asynchrony in the general population (Deconinck et al. 2011; Wilmut and Wann 2008; Payne et al. 2015). However, Wilmut and Wann found that this effect was diminished for participants with developmental coordination disorder. Our previous case study was inconclusive about whether the participant with CP was able to effectively use this information (Payne et al. 2015).

Decoupling the direction of eye and hand movements in Eyes Apart trials may also affect onset asynchrony. Adam et al. (2012) decoupled movements by requiring the eye to start in a different location than the hand. They found onset asynchronies increased compared to when the eye and hand started together. They suggested this was due to weaker coupling of the control of each system when they started from separate locations. Another way

[1] *Movement planning conditions* are the situational demands of planning a movement.

[2] *Discrete* movements are one-off movements, as opposed to being part of a series of movements.

[3] An effector is the thing being controlled to act on the environment, e.g. a cursor.

of decoupling movement directions is by changing the relationship between hand movements and effector movements. Gorbet and Sergio (2009) mapped cursor movements to the reverse, or mirror, of hand movements. In contrast to Adam et al., Gorbet and Sergio found decoupling movements in this way reduced onset asynchronies. This was due to significantly increased eye reaction times which Gorbet and Sergio suggest resulted from additional planning requirements. No research has compared interaction effects of decoupling movements and neurological conditions on onset asynchrony measurements. However, isolated control of each system would be beneficial when coordinating decoupled movements. Saavedra et al. (2009) suggest that children with CP have more difficulty isolating control of eye and hand systems.

For Mouse Blank-Slate trials, planning for novel mapping between muscle recruitment and effector kinematics requires extra calculation and should affect onset asynchrony. In Gorbet and Sergio's (2009) cursor experiment, novel mapping between hand and effector movements resulted in reduced onset asynchronies. White et al. (2012) found similar effects when they compared movements under altered gravity and normal gravity. Onset asynchronies reduced under novel mapping conditions for both hypergravity and microgravity relative to normal mapping under normal gravity conditions. They suggested that providing visual feedback for the deceleration phase of a reaching movement drives eye onset. Since hand acceleration took longer under novel gravity conditions, onset asynchronies reduced because eye onset could be delayed.

A fourth factor that could potentially alter movement planning processes is partial knowledge of target locations (i.e. with Possible Locations Visible). In Wilmut and Wann's (2008) study, possible target locations were visible before trial start. They showed that onset asynchrony increased with the number of possible target locations for one, two, and four locations. However, with more and more possible locations being visible, does the task differ relative to one where no visual information is provided? This would answer the question: is there a difference between having many options to process, versus having no target location information? In our previous case study, results for the participant without CP suggest that for 14 possible target locations, prior awareness does not alter coordination (Payne et al. 2015).

These four conditions were compared to a baseline condition. This condition must not include any of the distinguishing factors of the other four conditions. The baseline was called Blank-Slate since control was highly familiar (direct pointing with the hand, with the eyes making the same movement) but planning could not occur until the target appeared (no prior knowledge of the target location).

Hypotheses

All of the following hypotheses are relative to Blank-Slate movements:

For the Known Direction trials, (H1) all participants will reduce their onset asynchronies when they know where the target will appear. (H2) The effect in H1 will be diminished for the participants with CP.

For the *Eyes* Apart trials, (H3) onset asynchronies will increase. (H4) The group with CP will maintain similar coordination to Blank-Slate movements due to impaired ability to isolate control of eye and hand systems.

For the Mouse Blank-Slate trials, (H5) all participants will reduce their onset asynchronies.

For the Possible Locations Visible trials, (H6) onset asynchronies will not change for any participants. We expect the same movement plan and temporal coordination to be viable for both Possible Locations Visible and Blank-Slate trial types.

Methods

Participants

There were 18 participants; 10 did not have CP (W/o CP), 8 had CP and minimal manual activity limitation (CP MACS I & II). All participants used their preferred hand.

The participants W/o CP (7 m, 30.6 ± 4.2 years old) all self-reported as having no neurological conditions, and were right handed. All had normal or corrected to normal vision except for one participant with a mild astigmatism.

The participants with CP self-reported their MACS level. See Eliasson et al. (2006) for information on the manual ability classification system, MACS. Additional demographics can be seen in Table 1.

Apparatus

Pointing tasks were performed on a Dell S2240T 21.5″ Touchscreen Monitor at a screen resolution of 1920×1080 pixels plugged into a Dell Latitude E6500 laptop computer. The screen was angled at 30° from the horizontal, and at desk height. All participants were comfortably seated for the task. All participants pointed or used a mouse with their preferred, or less affected hand.

To track eye movements, an Arrington GigE-60 Eye Tracker was used at a sampling frequency of 60 Hz. Hand position was approximated using the input of the touchscreen or the cursor and mouse. Sampling frequency varied since the PreviewStylusMove() event was used to sample time and position every time the cursor input (of the touchscreen or mouse) moved.

Table 1 Participant information for the group with CP MACS I & II

Participant	Hand used	Age	Gender	Vision	MACS level	Affected limbs
1	Right	39	F	N	I	Left side
2	Right	20	F	CTN	II	Left side
3	Right	18	M	N	II	Left side
4	Left	34	M	N	II	Right side
5	Left	13	M	Reduced binocular vision	I	Right side
6	Right	24	M	N	I	Right leg
7	Right	12	M	N	I	Both legs
8	Left	29	F	Amblyopia	II	All four

MACS Manual ability classification system (Eliasson et al. 2006), *F* female, *M* male, *N* normal, *CTN* corrected to normal

Targets were filled black circles, 60 pixels in diameter, and were presented at a set distance of 500 pixels (centre to centre) from the start point. The amplitude was chosen to be large enough that the participant would look at the target rather than just use their peripheral vision. The hand start point was at the centre of the bottom edge of the screen. It was represented by a '+' which persisted throughout the trial (see Fig. 2). The task software was written in VB.NET and based on Arrington's SDK (software development kit). Microsoft Excel 2013 was used to process results data.

Trial types

There were five separate trial set-ups, as per Table 2. We consider four trial types (Known Direction, Eyes Apart, Mouse Blank-Slate, Possible Locations Visible) that, based on previous studies, may alter participants' onset asynchronies. We also consider a baseline planning condition (Blank-Slate).

For all trial types (except Known-Direction) target direction varied in a semi-circular arc with 14 possible directions (see Fig. 2). This was based on ISO 9241-9 (ISO 2002) which suggests presenting targets in 25 directions along a circular path to negate possible confounds of movement direction. A complete circle was not used for this testing, since it would result in some targets being occluded by the arm at trial start. The target area was blank until the target appeared. Sets of trials involved 28 discrete trials with each direction being presented twice. Previous evidence for a participant with CP showed significant variance between testing sessions (Payne et al. 2015). For this study the number of trials was doubled.

For the baseline trial type (Blank-Slate trials), movement planning was as simple as possible. The goal was to ensure participants had all the information they needed to plan a movement as soon as the target appeared. As such, the participant was certain of the effector's position and the appropriate muscle movements to control it. Direct pointing was chosen and the participants were instructed to look at the fingertip of their preferred hand whilst they waited for trials to start.

Discrete pointing movements negated the distractions of checking the success of a previous movement, or undertaking auxiliary operations such as grasping. By quasi-randomising the target location and leaving the target

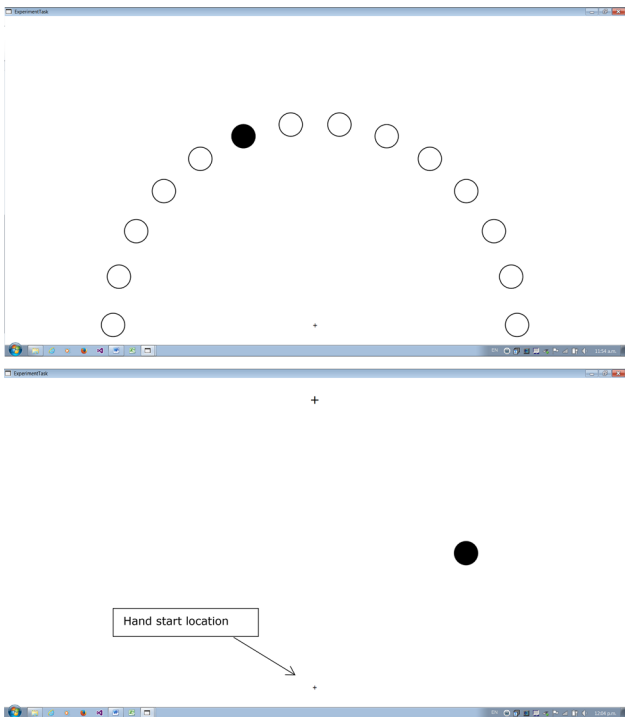

Fig. 2 *Top* all trials used these 14 target locations (except for Known Direction trials where the target was always directly upwards from the hand start location), but only the *Possible Location Visible* trials used the outlines of circles showing the possible target locations. *Bottom* the cross at the top of the screen is the eye start location for the Eyes Apart trials. For all other trials the eyes started at the hand start location (the small cross at the *bottom* of the screen equidistant from all the target locations)

Table 2 Trial types

Trial type	Trials in set	Sets per participant	Target directions	Possible target locations visible	Eye starts apart from hand	Input used	# Valid trials	
							W/o CP	CP MACS I & II
Blank-slate	28	2	14	N	N	Hand	527	407
Known direction	10	2	1	N	N	Hand	183	132
Eyes apart	28	2	14	N	Y	Hand	529	409
Mouse blank-slate	28	2	14	N	N	Mouse	501	409
Possible locations visible	28	2	14	Y	N	Hand	517	394

All participants performed $28\times2\times4+10\times2=244$ trials. Note the number of valid trials is less than the number performed

presentation area completely blank until trial start, participants could only undertake planning after trial start.

Known-Direction trials aimed to facilitate pre-planning of movements; the target was always directly upwards from the start point. For these trials, there were 10 trials per set.

Eyes Apart trials decoupled the direction of eye and hand movements. For Eyes Apart trials, a '+' at 50 pixels from the top of the screen served as a starting eye location (see Fig. 2, bottom). As with the hand start location, the '+' persisted throughout the trial.

For most of the trials the mapping was highly familiar; participants pointed directly at a touchscreen using their preferred hand. In the Mouse Blank-Slate trials, participants used a mouse and cursor to select targets. Thus, an extra level of planning was required. All participants had previous experience with using a mouse.

Possible Locations Visible trials allowed the participant to be aware of the possible target locations. For these trials only, a black outline of the 14 possible target locations was visible before trial start, and persisted until trial completion (see Fig. 2, top).

Procedure

To familiarize themselves with the touchscreen, participants performed a join-the-dots task in Paint before starting the experiment. Additionally, participants practiced each trial set-up until they were comfortable with the task. They performed all set-ups twice in a counterbalanced order. The order of trial set-ups was also counterbalanced among participants.

For all trials, participants were instructed to select the target "as quickly as possible without making mistakes" once it appeared.

For hand pointing trials, a wait period was initiated when participants placed their pointing finger on a green 'Ready?' button at the start point location. During the wait period the 'Ready?' button changed to a '+' sign. After a randomised wait of 1000–1900 ms (at 100 ms intervals) the target would appear. Throughout the trial the '+' sign at the start point persisted. The hand had to be touching the screen for the target to appear: if the finger lifted from the screen during the wait period, the wait timer stopped until the hand made contact with the screen again. If the hand was lifted for more than 500 ms then the wait period reset. For the Mouse Blank-Slate trials, the participant clicked the 'Ready?' button to activate the same randomised wait period.

A trial finished once the target was successfully selected, then the target was replaced by a feedback icon. Either a happy face or fruit was displayed as positive feedback to encourage accuracy. If the participant selected a point outside the target during the trial (an error), once they were successful in selecting the target, a neutral face was shown. After a trial, the completion time was displayed to encourage quick movements.

Participants were instructed to take breaks whenever they felt the need. Participants were offered food and beverages during these breaks. Testing took approximately one hour.

Analysis

For all trials, onset asynchrony was determined by subtracting the eye reaction time (eye RT) from the hand reaction time (hand RT). Thus, positive values indicate eye onset occurred before hand onset (see Fig. 1).

Data was processed off-line. When the touchscreen was used, hand RT was defined as the time when the finger first lifted from the screen once the trial had started (using the program event PreviewMouseUp()). Time and position measurements were also recorded every time the input position changed (using the PreviewStylusMove() event). If the finger slid towards the target, after trial start but before it was first lifted, then an earlier hand RT was determined based on threshold criteria of instantaneous speed and the distance covered over the following 10 data points. When

the mouse was used, this criteria of speed and distance was always used to determine hand RT.

Pupil time and position measurements were taken at 60 Hz by the eye tracker. Eye RT was determined based on threshold criteria of instantaneous jerk and the distance covered over the following 3 data points. Jerk was used instead of a velocity threshold since Verrel et al. (2008) suggest jerk is a more reliable method for detecting saccades than just velocity or acceleration. Both hand and eye onsets were determined automatically, but verified graphically and visually. Forty trials were discarded because eye onset occurred before trial start (17 were Known Direction trials). Trials were also discarded when there was noise in the eye recording, or when eye onset could not be determined. See Table 2 for numbers of valid trials.

Hand movement times (MT) were defined as the time from hand onset to the time the finger first touched the target. Completion times (CT) were defined as the time from the target appearing to when the finger first touched the target (i.e. CT = MT + hand RT). For mouse movements depression of the mouse button was registered instead of the finger touching the screen.

Statistics

Mixed linear models were used to analyse the results using IBM SPSS Statistics version 22 software. All individual measurements were used rather than means since data sets were variable in size (see Table 2). A combination of *Trial Type* and *Trial#* were used as the repeated variable. *Participant* was used as a random variable.

For the overall results, fixed factors were *Trial Type* and *Neurological Condition* and an interaction of the two.

To make planned comparisons, the data set was split up by participant groups and *Trial Type* was the only fixed factor.

Hand RT, eye RT and MT values were transformed via a natural log (ln) function to improve normality and kurtosis. For the same reason, CT values were transformed via a reciprocal function ($1/x$). For all variables, outliers that were 3.29 standard deviations outside the mean were deleted. For variables that were transformed, outlier classification occurred post transformation. Bonferroni correction was used.

Results

Overall

When analysing the two groups together (W/o CP, CP MACS I & II), there was a significant main effect of *Trial Type* [$F(4,1059) = 128.4$; $p < 0.001$] on onset asynchronies. The effects of *Trial Type* are discussed in the results of specific planned comparisons.

Neurological condition was not a main effect for onset asynchrony [$F(1,16.20) = 0.931$; $p = 0.349$], eye RTs [$F(1,16.06) = 2.252$; $p = 0.153$], or hand RTs [$F(1,16.03) = 0.549$; $p = 0.469$]. However, it was a main effect for MTs. The group with CP displayed significantly longer MTs [$F(1,16.06) = 6.545$; $p = 0.021$; 574 vs. 458 ms]. A similar pattern was evident with CTs where the difference approached significance [$F(1,16.09) = 3.893$; $p = 0.066$; 898 vs. 799 ms].

For onset asynchronies, there was a significant interaction of *Trial Type*Neurological Condition* [$F(4,1059) = 13.04$; $p < 0.001$]. The group W/o CP displayed significantly reduced ($p = 0.007$) onset asynchronies for the Eyes Apart trial type compared to the group with CP. For all other trial types, there were no significant differences in onset asynchronies between the two groups.

Planned comparisons

Planned comparisons were made within the two groups comparing the different planning conditions to the Blank-Slate reference trial type (Fig. 3).

For the group W/o CP, *Trial Type* was a significant factor for onset asynchrony [$F(4,526.9) = 100.7$; $p < 0.001$], eye RT [$F(4,604.8) = 52.02$; $p < 0.001$], hand RT [$F(4,531.8) = 171.3$; $p < 0.001$], MT [$F(4,535.7) = 171.9$; $p < 0.001$], and CT [$F(4,509.1) = 52.34$; $p < 0.001$].

For the group with CP, *Trial Type* was a significant factor for onset asynchrony [$F(4,521.3) = 46.24$; $p < 0.001$], eye RT [$F(4,531.4) = 7.343$; $p < 0.001$], hand RT [$F(4,511.5) = 126.7$; $p < 0.001$], MT [$F(4,473.3) = 135.4$; $p < 0.001$], and CT [$F(4,1206) = 60.39$; $p < 0.001$].

The following sections report pairwise comparisons from the within participant group analyses. Table 3 shows the linear regression values for these models. Since the Blank-Slate trials are set as the redundant values, the b_1 values of other trial types represent the difference in means relative to Blank-Slate trials.

Opportunity to pre-plan movements; Known Direction vs. Blank-Slate

For the group W/o CP, onset asynchronies reduced significantly ($p = 0.036$) for the Known Direction trial type compared to the Blank-Slate one (96 and 111 ms respectively). The mean hand RT significantly ($p = 0.014$) decreased by 16 ms for the Known Direction trials, although there were no significant differences in values of eye RTs ($p = 1.000$), MTs ($p = 1.000$) or CTs ($p = 0.230$).

For the group with CP, onset asynchronies did not significantly reduce ($p = 0.387$). However, the value of the

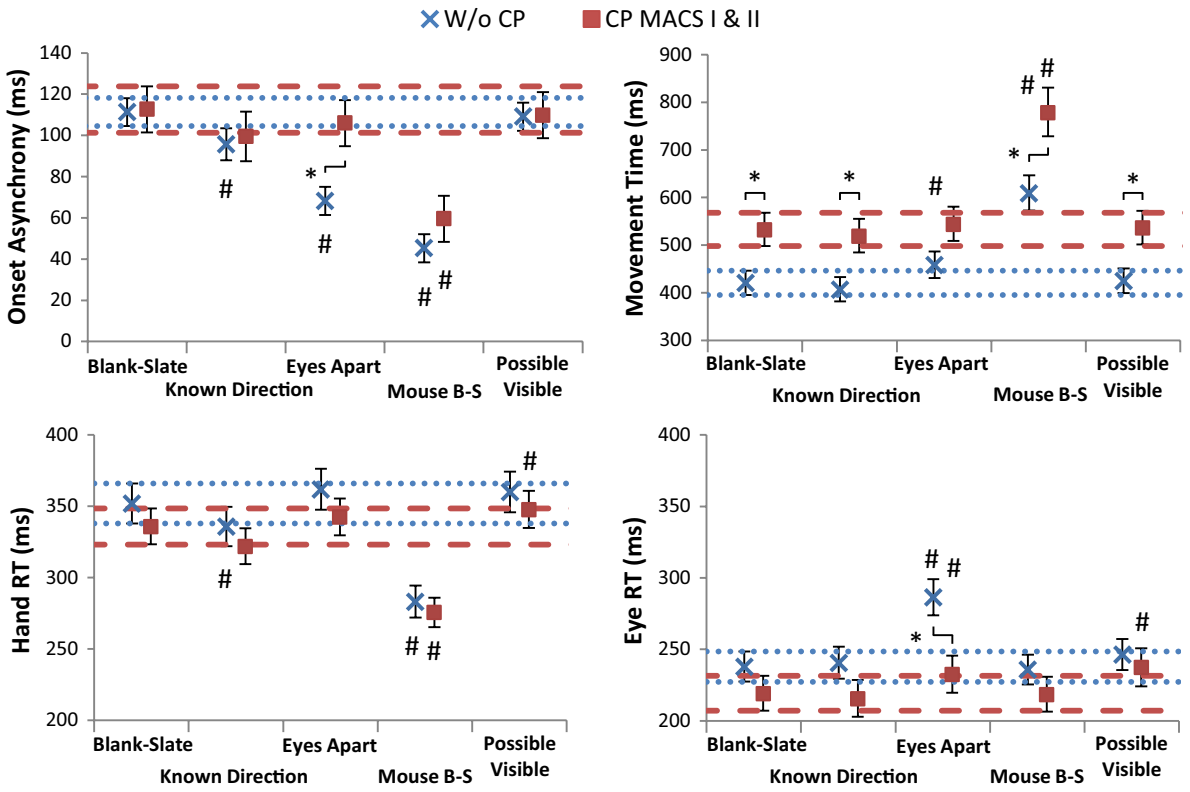

Fig. 3 *Top left* mean onset asynchronies. *Top right* mean MTs. *Bottom left* mean hand RTs. *Bottom right* mean eye RTs. Group means for different trial types in ms, with *error bars* showing the standard error. *Squares* are the results for the group with CP MACS I & II. Crosses are the results for the group W/o CP. The horizontal lines show the standard error for the reference Blank-Slate trials (dashed *lines* are for the group with CP, *dotted lines* are for the group W/o CP). *Significant difference between participant groups. #Significant difference compared to Blank-Slate trials

Table 3 Linear regression values for the pre-planned comparisons of each outcome measure

	Intercept		Blank-Slate		Known Direction		Eyes Apart		Mouse Blank-Slate		Possible Locations Visible	
	b_1 (SE)	p	b_1 (SE)	p	b_1 (SE)	p	b_1 (SE)	p	b_1 (SE)	p	b_1 (SE)	p
Onset asynchrony												
W/o CP	111.3 (6.8)	<0.001	0 (0)	–	−15.6 (5.4)	0.036	−43.1 (3.9)	<0.001	−66.0 (4.0)	<0.001	−2.2 (3.9)	1.000
CP MACS I & II	112.6 (11.2)	<0.001	0 (0)	–	−13.2 (6.4)	0.387	−6.7 (4.5)	1.000	−53.1 (4.5)	<0.001	−2.9 (4.5)	1.000
Eye RT												
W/o CP	237.7 (7.5)	<0.001	0 (0)	–	2.7 (5.1)	1.000	48.5 (4.4)	<0.001	−2.1 (3.7)	1.000	8.5 (3.8)	0.237
CP MACS I & II	218.9 (12.3)	<0.001	0 (0)	–	−3.6 (6.1)	1.000	13.3 (4.7)	0.038	−0.7 (4.4)	1.000	18.2 (4.8)	0.001
Hand RT												
W/o CP	351.7 (14.0)	<0.001	0 (0)	–	−16.2 (4.9)	0.014	9.9 (3.9)	0.096	−68.7 (3.1)	<0.001	8.1 (3.9)	0.338
CP MACS I & II	335.6 (12.6)	<0.001	0 (0)	–	−13.8 (5.4)	0.120	6.7(4.0)	0.937	−60.1(3.3)	<0.001	12.0 (4.1)	0.033
MT												
W/o CP	420.2 (25.5)	<0.001	0 (0)	–	−13.8 (9.2)	1.000	37.8 (7.5)	<0.001	188.4 (10.2)	<0.001	4.2 (7.0)	1.000
CP MACS I & II	531.8 (34.9)	<0.001	0 (0)	–	−13.2 (14.4)	1.000	11.9(10.8)	1.000	246.2(15.5)	<0.001	4.0 (10.6)	1.000
CT												
W/o CP	772.7 (29.2)	<0.001	0 (0)	–	−25.0 (10.6)	0.230	46.1 (9.3)	<0.001	114.7 (11.1)	<0.001	11.8 (8.5)	1.000
CP MACS I & II	863.3 (37.8)	<0.001	0 (0)	–	−28.3 (15.3)	0.730	24.7 (12.4)	0.397	186.0 (17.4)	<0.001	20.1 (12.3)	0.944

The Blank-Slate values are set to zero since they are redundant. All slope (b_1) and standard error (SE) values are in ms. All values (except onset asynchronies) required conversion to ms from transformed values

mean reduced by 13 ms (from 113 to 100 ms) for Known Direction trials, which is similar to the 16 ms reduction for the group W/o CP. There was no significant difference in either RT but there was a 14 ms decrease in the mean hand RT ($p=0.120$) for Known Direction trials. As with the group W/o CP, there were no significant differences in MTs ($p=1.000$) or CTs ($p=0.730$) between the two trial types.

Decoupling direction of eye and hand movements; Eyes Apart vs. Blank-Slate

For the group W/o CP, onset asynchronies were significantly ($p<0.001$) reduced for Eyes Apart trials compared to Blank-Slate trials (68 and 111 ms respectively). The eye RTs significantly ($p<0.001$) increased for Eyes Apart trials whilst there was no significant difference in the hand RTs ($p=0.096$). Both MTs and CTs significantly (each $p<0.001$) increased by 38 and 46 ms respectively for the Eyes Apart trials.

For the group with CP, onset asynchronies did not change significantly ($p=1.000$). Similar to the group W/o CP, there was not a significant difference in hand RTs ($p=0.937$) but there was a significant ($p=0.038$) increase in eye RTs by 13 ms. Both MTs ($p=1.000$) and CTs ($p=0.397$) did not significantly change.

Altered muscle-effector mapping; Mouse Blank-Slate vs. Blank-Slate

For the group W/o CP, onset asynchronies were significantly ($p<0.001$) reduced for Mouse Blank-Slate trials compared to Blank-Slate trials (45 and 111 ms respectively). The hand RTs significantly ($p<0.001$) decreased by 69 ms for Mouse *Blanks-Slate* trials whilst there was no significant difference in the eye RTs ($p=1.000$). Both MTs and CTs significantly (each $p<0.001$) increased by 188 and 115 ms respectively for the Mouse Blank-Slate trials.

For the group with CP, there was also a significant ($p<0.001$) reduction in mean onset asynchrony from 113 to 60 ms. Similar to the group W/o CP, there was a significant decrease ($p<0.001$, by 60 ms) in hand RTs but no significant difference in eye RTs ($p=1.000$). Both MTs and CTs also increased significantly (each $p<0.001$) for the Mouse *Blanks-Slate* trials by 246 and 186 ms respectively.

Visibility of possible target locations; Possible Locations Visible vs. Blank-Slate

There appeared to be no effects of displaying possible target locations prior to trial start for the group W/o CP. There were no significant differences between the Blank-Slate and Possible Locations Visible trials for onset asynchronies, eye RTs, hand RTs, MTs, and CTs. Both hand RTs ($p=0.033$) and eye RTs ($p=0.001$) significantly increased for the group with CP, although there was no significant change in onset asynchronies.

Discussion

Overall

We sought to evaluate potential effects of cerebral palsy on the ability to adapt eye-hand coordination to different movement planning conditions. The adaptations in onset asynchrony to different movement planning conditions made by the group with CP MACS I & II were similar to the group W/o CP for all but one trial type (Eyes Apart). Verrel et al. (2008) also found similar onset asynchrony patterns between participants without CP and those with hemiparetic CP using a less affected hand. They investigated visual monitoring of the hand in response to the presence of an obstacle for an object transport task.

Given there was minimal difference in onset asynchrony between groups when varying planning conditions, it is notable that the group with CP still took significantly longer to make movements. This implies that for lower levels of impairment and simpler tasks, movement execution problems seem to limit activity more than any movement planning deficit.

Opportunity to pre-plan movements; Known Direction vs. Blank-Slate

We expected that facilitating pre-planning would reduce onset asynchronies for all participants (H1), but this effect would be weaker for the group with CP (H2). Only the group W/o CP significantly reduced onset asynchronies and hand RTs. Therefore we cannot confirm H1. Although knowing the target location only significantly reduced onset asynchronies for the group W/o CP, the effect size was very similar for the group with CP (15.6 and 13.2 ms respectively). Furthermore, the standard error was bigger for the group with CP, so even if the effect size were the same, there would not have been a significant difference in onset asynchronies. This increased error could be due to CP causing larger variability in participants' responses. Regardless, our results are inconclusive for H2.

For pre-planning to be effective, people need to be capable of creating a movement plan, temporarily storing it, then accessing it when necessary. Whilst grip planning experiments (Steenbergen et al. 2004; Mutsaarts et al. 2005) have shown that hemiparetic CP can affect how far movements are planned into the future, our results suggest that for simpler movements, the basic mechanisms of pre-planning movements based on past experience are

not severely impaired in the population we tested. These results also agree with the anticipatory fingertip force regulation abilities of people with hemiparetic CP using their less affected hand (Gordon et al. 2006b). While anticipatory fingertip force regulation required participants to be able to integrate dynamic properties into their movement plans, our task required the integration of spatial properties into movement plans.

Decoupling direction of eye and hand movements; Eyes Apart vs. Blank-Slate

We expected decoupling eye and hand movement to result in increased onset asynchrony for the group W/o CP (H3), although we expected no significant change for the group with CP (H4). Contrary to expectations, the W/o CP group significantly reduced onset asynchronies. This was only significant for the group W/o CP (so H3 is rejected, although H4 appears to be true), but clearly neither group increased their onset asynchronies as occurred in the study of Adam et al. (2012). This probably occurred due to different geometries of task set-up. In that study, when the movements were decoupled, the eyes started within the vicinity of the target. This possibly incentivised delaying hand onset until the target was foveated. In our Eyes Apart trials, often the eyes started further from the target than the hand did. Crucially, participants could not use experience to expect the target to appear near the eye start location. This is demonstrated by significant increases in eye RTs but not hand RTs by both participant groups. Our results indicate that Adam et al.'s experiment did indeed investigate the effects of sensory noise (as was their intention) and not specifically the effects of decoupling movements. We repeat the findings of Gorbet and Sergio (2009) when they decoupled movements by reversing the mapping of hand to cursor movements; participants adapted by increasing eye RTs resulting in reduced onset asynchronies.

Adaptations to the Eyes Apart trial type provided the only clear interaction between trial type and participant groups for onset asynchrony measurements. Whilst both groups significantly increased eye RTs, the magnitude of the increase was much greater for the group W/o CP, resulting in significantly different onset asynchronies between the two groups. It is debatable whether decoupling the movements affected movement planning of the group with CP since they did not significantly reduce their onset asynchronies. Saavedra et al. (2009) proposed that children with CP have more difficulty isolating control of eye and hand systems (this was the basis of H4). Perhaps this resulted in participants generally maintaining similar coordination patterns to when the directions were coupled.

Altered muscle-effector mapping; Mouse Blank-Slate vs. Blank-Slate

We expected both groups to reduce their onset asynchronies when the extra spatial transformation of mapping a mouse and cursor was required (H5). The results indeed showed a reduction. This agrees with reductions in onset asynchronies found by Gorbet and Sergio (2009) and White et al. (2012) when they recorded coordination under novel mapping conditions. The main exception to this accordance is that our results stemmed from both groups significantly decreasing their hand RTs, which was not the case in Gorbet and Sergio's experiment.

Determining hand RTs differently between the two tasks (when the finger was lifted vs. when the cursor moved) potentially contributed to this result. However, it may be expected that the mouse movement is registered later in the movement than the hand movement, since the mouse onset is only registered after it is already moving. Also, this was the largest effect size on onset asynchronies for both groups. In any case, there are many other potential factors that were not considered (e.g. friction, inertia, biomechanics). Regardless, it seems both groups adapted their eye-hand coordination to using a mouse in the same manner.

Regarding MTs and CTs, they were significantly longer for both groups when using the mouse and cursor. Given targets were relatively large, this finding is not new (Sears and Shneiderman 1991).

Visibility of possible target locations; Possible Locations Visible vs. Blank-Slate

Varying visual awareness of possible target locations prior to trial start investigated whether it was better to have too much spatial information than none. However, we expected no discernible differences in onset asynchrony (H6). Rosenbaum (1980) suggests that pre-planning does not occur by multiple plans being generated and then one being selected. He supported the idea of only known parameters being used for pre-planning, and specifying unknown parameters when they become known. For all our coordination measures, this appeared to be the case since there was no effect of the possible target locations being visible (H6 is accepted).

Limitations and robustness

The main limitation of this study is the array of diagnoses within the group with CP MACS I & II. These results may not be repeatable for more specific groups. For example, Steenbergen and Gordon (2006) suggested planning impairments are specific to people with damage to the left hemisphere. Lastly, these findings do not necessarily apply

to each individual participant they are based upon; they are only valid as pre-planned group comparisons.

However, we expect the measurements presented in this study to be repeatable with these participants. The onset asynchronies for the two primary participant groups in this study are similar to those of the participant without CP in our previous case study (Payne et al. 2015). His onset asynchronies did not vary significantly between any two of the six testing sessions (even though his hand movement times did).

Conclusions

For the group with CP MACS I & II, participants did not significantly alter their eye-hand coordination compared to people without CP when given the opportunity to pre-plan movements. Likewise, eye-hand coordination was adjusted in similar ways when an added layer of complexity was added to muscle-effector mapping. Despite these similarities, participants with CP still took significantly longer to make movements. Given that the eye-hand coordination patterns were adjusted according to different planning conditions, this implies movement execution problems have a greater impact on activity limitation than movement planning.

Our results also demonstrate people with CP do not decouple movements in the same way as people without CP. The only significant difference in onset asynchronies between the group W/o CP and the group with CP occurred when the direction of eye movements was decoupled from the direction of hand movements.

Compliance with ethical standards

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Conflict of interest The authors declare that they have no conflict of interest.

Informed consent Informed consent was obtained from all individual participants included in the study.

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