Repeatability of Eye-Hand Movement Onset Asynchrony Measurements and Cerebral Palsy: A Case Study

Alexander R. Payne
Mechanical Engineering,
University of Auckland
Private Bag 92019, Auckland
1142, New Zealand
apay876@aucklanduni.ac.nz

Beryl Plimmer
Computer Science,
University of Auckland
Private Bag 92019, Auckland
1142, New Zealand

T. Claire Davies
Mechanical Engineering,
University of Auckland
Private Bag 92019, Auckland
1142, New Zealand

ABSTRACT
In this paper we investigate if a participant with cerebral palsy displays a deficit in movement planning for simple pointing and gesture actions that are required to interact with a touchscreen. We performed a repeated measures case study with one participant with CP, and one typically developed (TD) participant. Measurements of the relative timing of eye and hand movements were made to see how they vary when participants have the opportunity to preplan a movement (by knowing where a target will appear), and to see if they were repeatable. As expected, the typically developed participant changed their coordination patterns when they could preplan a movement. This did not occur for the participant with cerebral palsy and suggests he has a reduced ability to preplan movements, or at least a preference to avoid doing so. This implies gesture based interaction to imagined targets could be less accessible to people with cerebral palsy. Visual affordances may help overcome this potential barrier. The relative timing of movements varied from session to session for the participant with CP, but not the TD participant.

Author Keywords
Eye-hand coordination, Cerebral palsy, Movement planning

ACM Classification Keywords
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms
Human Factors, Experimentation, Measurement.

CEREBRAL PALSY AND PLANNING
Cerebral palsy (CP) is an umbrella term for a group of movement disorders causing activity limitation. It arises from non-progressive disturbances to the foetal or infant brain [13], and is one of the most common congenital physical disabilities [17]. A more precise understanding of its effects on manual activities is important for informing design of assistive technologies for computer interaction.

Movement execution problems associated with CP are well documented, but research has shown that movement planning disorders are also present [16]. To investigate this, experiments aiming to isolate anticipatory plans have measured several variables like anticipatory fingertip force, and grip position planning [16].

Accessibility to computers has greatly increased allowing individuals with CP better communication and interaction. Is this planning deficit also apparent for simple interactive movements, such as one-off pointing at a touchscreen? Such movements are particularly important on touchscreens as they are used for both target acquisition (e.g. button presses) and abstract functional gestures such as swipe. We investigate if prior knowledge of a target location affects the eye-hand coordination at the beginning of a movement.

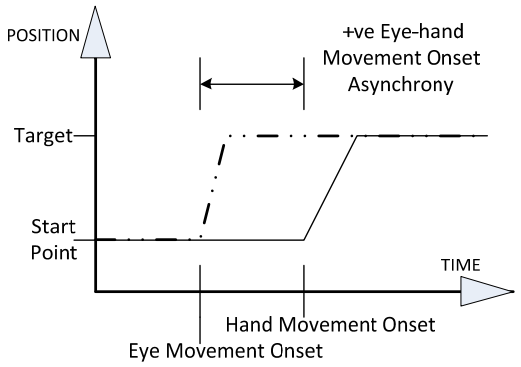

Figure 1. Eye-hand movement onset asynchrony diagram. This shows a positive eye-hand movement onset asynchrony since the eye moves before the hand.

When pointing, there is a general coordination pattern whereby the eyes saccade towards the target just before hand movement is initiated. Eye-hand movement onset asynchrony (onset asynchrony for short) is the measurement of this latency (see Figure 1). This

CHINZ 2015, September 03 - 04, 2015, Hamilton, New Zealand

ACM 978-1-4503-3670-3/15/09…$15.00
DOI: http://dx.doi.org/10.1145/2808047.2808058

measurement is made by comparing hand and eye reaction times. This measure reflects the timing (and conceivably strategy) of eye-hand coordination adopted for a given situation. Thus, it focuses on how people make movements, rather than the results or performance of the movements. The timing of the eye movement relative to the hand varies depending on what visual information is most important to serve the hand movement [12]. Theoretically, knowledge of a target location should reduce the latency between the eye movement and hand leaving (reduced onset asynchrony), since the movement can be preplanned before the target has even appeared.

In a study investigating developmental coordination disorder (DCD) and onset asynchronies, participants with DCD had more difficulty integrating spatial information into their movement plans [20]. Participants with DCD and typically developed (TD) participants had similar onset asynchronies when the target location was unpredictable. But, when the location was predictable, the participants with DCD were not able to make use of this information; they could not reduce their onset asynchronies as effectively as the TD participants did. This suggests they were more likely to act out a new movement than a preplanned one.

We seek to investigate if people with CP exhibit similar coordination patterns and difficulties in integrating spatial information into their movement plans. Compared to previous work investigating CP and movement planning, our experiment focuses on one-off pointing movements rather than grasping movements. This is a simpler movement with less potentially confounding factors, and it is more relevant to computer interaction.

If people with CP adjust their eye-hand coordination patterns based on spatial task information, it would suggest that CP does not affect movement planning at this level. It would also suggest previous findings based on anticipatory fingertip force, and grip position planning measurements may instead be due to movement execution problems. However, Jenks et al. [9] reported that children with CP have deficits in the visual spatial sketch pad of their working memory. If this deficit results in a reduced ability to preplan movements based on spatial task information, then results similar to the DCD study [20] can be expected.

BETTER UNDERSTANDING ONSET ASYNCHRONY

Since only one other research group has measured onset asynchronies of people with any type of CP, we decided to perform a repeated measures case study with one TD participant, and one participant with CP, to investigate three key questions that require better understanding:

1 - How do onset asynchrony values for people with CP typically compare to those for TD people?

2 - Are onset asynchrony measurements repeatable?

3 - What type of spatial task information is required to preplan a movement?

1. Normal values for people with CP

Research into other neurological conditions as well as DCD has consistently shown that participants displayed increased onset asynchronies for discrete movements compared to TD participants [2, 14, 15, 19].

Contrary to this, the only research involving participants with CP reported reduced onset asynchronies compared to TD participants; it was suggested that they use their vision to more closely monitor their hand when making a movement [18]. In their research, participants were performing a task with a previous movement that involved grasping an object.

Their findings may have occurred because participants were monitoring whether they had successfully grasped an object, rather than their hand per se. If there is an increase in onset asynchrony for our task, it would suggest that more visual attention is actually paid to the target.

We hypothesise that providing advance notice of target location provides sufficient information to plan a path for a discrete pointing gesture.

2. Testing reliability

For TD participants, De Boer et al. [4] showed that eight trials are enough to reliably measure eye and hand reaction times for goal-directed pointing tasks. Yet, this analysis has not been done explicitly for eye-hand movement onset asynchrony, or for non-TD participants, such as those with CP.

We expect measurements for a participant with CP to differ between test sessions. It is well known that a TD person's hand movement times for goal-directed pointing will adhere to Fitts's Law [7]. This is not the case for participants with CP [3]. This non-adherence has been attributed to various behaviours for which Fitts's law does not normally take into account; missing the target, additional submovements, slipping off the target, and curved movements [1]. Whilst none of these behaviours relate to reaction times, they presumably relate to planning and executing a movement reliably.

3. Useful Target Information

Two studies have previously shown that TD participants reduce their onset asynchrony when target direction is predictable [5, 20]. Wilmut and Wann [20] used visual cues before the trial started to show which target needed to be selected whilst Deconinck et al. [5] relied on repetition for participants to be able to predict where a target would appear. Our experiment involves repeating trials in one direction so participants can predict the target location.

Furthermore, we investigate if seeing the range of possible locations can be used to preplan movements in many

directions. From an HCI perspective, we want to investigate if this display information has any effect on participants' behaviour and performance.

METHODS

Participants:

There were 2 participants, one with cerebral palsy (CP) and the other typically developed (TD). Both participants are male and self-reported as having normal vision. The participant with CP is 44 years old, has spastic cerebral palsy (Manual Ability Classification System Level III [6] & IV, Gross Motor Function Classification System Level V [11]). He used his preferred left arm for pointing. The TD participant is 21 years old with no neurological conditions and used his preferred right arm for pointing.

Designing the Experiment:

Pilot testing was performed with the participant with CP, and the experiment design was tailored to him.

Firstly, the range of motion and activity limitations specific to the participant with CP had to be taken into account. Some adaptations to this were simple. The participant normally uses a wooden pointer about 30cm long to perform many daily tasks. So, using a stylus attached to this pointer is a natural way for him to use a touchscreen. A suitable movement amplitude was also chosen.

The participant's range of motion results in the screen placement being a compromise between being optimal for the hand and optimal for the eye. The participant found that hand movements were most comfortable when the screen was closer to, and angled towards his hand. This was due to the stylus not registering the point expected by the participant when contacting the screen on an angle.

For eye movements, it was preferable to have the screen at eye level and directed towards the participant's face. When the screen was placed at desktop level, it was harder for the participant to look at, and harder for the eye tracker to pick up his pupil. The participant cannot move his neck very easily so a lower screen placement, near where his preferred left hand would normally rest, resulted in the participant looking down and left. When people look down, their eyelids reflexively start to cover their eyes. The Arrington Research Inc. GigE-60 eye tracker we used only has a camera mounted on the right eye. Looking down and left seemed to be the least optimal direction for it to reliably detect a user's pupil.

Next, when holding down the Ready button before a trial, the participant with CP would occasionally lift the stylus off the screen momentarily by accident. Originally, the pilot test program was set-up so this loss of contact would result in the wait timer resetting. This was changed so the wait timer would only reset if the stylus was lifted off the screen for 500*ms*.

Finally, the testing took too long and the participant lost focus. So the session was shortened; only 10 trials were used per set instead of 28, and repeating trial set-ups within sessions for counterbalancing purposes was abandoned.

Apparatus:

Pointing tasks were performed on a Dell S2240T 21.5" Touchscreen Monitor at a screen resolution of 1920 x 1080 pixels. The screen was approximately vertical; it was positioned at eye level and adjusted to the participant's comfort.

The participant with CP was comfortably seated in his motorized wheel chair. The TD participant sat in a standard desk chair adjusted to a comfortable position.

The stylus used by the participant with CP was attached to the participant's everyday wooden pointer (see Figure 2). The end of the pointer rests on the upwards facing surface of the participant's left elbow, and is held between the participant's middle finger and index finger.

The TD participant used a stylus in his right hand with a pen like grip.

Figure 2. The longer pointing device was used by the participant with CP, the TD participant used the smaller one.

To track eye movements, an Arrington Research Inc. GigE-60 Eye Tracker was used at a sampling frequency of 60 Hz. The input of the touchscreen was used as a proxy for the hand position.

The task ran on custom software that also processed results data. There were three separate trial conditions:

Visible Locations 10 trials, 14 target directions, possible target locations visible before, and during trial.

Blank-Slate 10 trials, 14 target directions, possible target locations not visible.

Known Direction 10 trials, 1 target direction, possible target location not visible.

Circular targets 60 pixels in diameter were presented at a set distance of 300 pixels (centre-to-centre) from the start point. The start point was at the centre of the bottom edge of the screen. For conditions *Visible Locations* and *Blank-Slate*, target direction varied in a semi-circular arc with 14 possible directions (see Figure 3). This was based on ISO

9241-9 [8] which suggests presenting targets in 25 directions in a circle. A circle was not used as it would result in targets being occluded by the hand or pointer. For the *Known-Direction* trial set-up, the target was directly up from the start point.

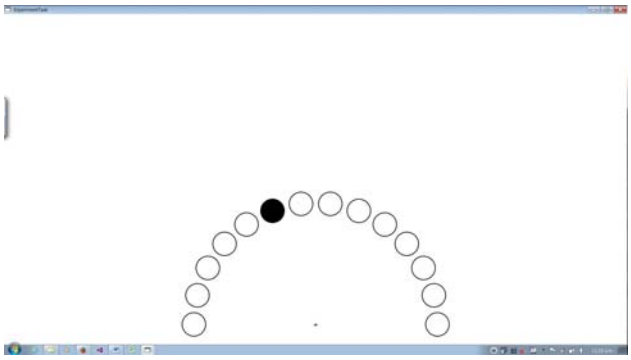

Figure 3 A target appears as a filled black circle just after trial start.

The target was a solid black circle and the screen background was white. For the *Visible-Locations* tasks, possible target locations were visible before and during trials as a black outline. For the other tasks the target area was blank apart from the actual target appearing.

Procedure:

The participants performed trials at 6 different testing sessions, at least one day apart. At each session participants performed the 3 conditions. For each condition, two sets of 10 trials were performed. All trials were recorded. The order of tasks was counterbalanced across testing sessions.

For all trial conditions, participants were instructed to look at the pointer which was positioned at the home location until a target appeared, and then to select the target "as quickly as possible without making mistakes."

When a participant was ready to start a trial, he would place the pointer on the green 'Ready?' button at the start point location. This initiated a wait period, during which the 'Ready?' button changed to a '+' sign. After a randomised wait period of 1000*ms* – 1900*ms* (at 100*ms* intervals) the target would appear. Throughout the trial the '+' sign at the start point persisted as per an overlap condition. If the stylus lifted from the screen during the wait period then the wait timer stopped during that period ensuring the stylus had to be on the screen at trial start. If the stylus was lifted for more than 500*ms* then the trial was aborted and the 'Ready?' button would need to be re-selected.

Once the target was selected, the trial finished; the target button disappeared and was replaced by an icon to give feedback to the participant on trial success. If successful, either a smiley face or fruit was displayed as positive feedback to encourage the participant to make accurate movements. If the participant selected a point outside the target during the trial, a neutral face was shown upon selecting the target (see Figure 4). Participants were told about this. Also after a trial, the time the participant took to select the target was displayed to them to give them feedback about how quick they were.

Figure 4. Images used for feedback of successful target selection. The neutral face on the left was used if a participant touched the screen outside the target before selecting it.

Analysis:

For all trials, onset asynchrony was determined by subtracting the eye reaction time (eye RT) from the hand reaction time (hand RT). As such, positive values indicate that the eye onset occurred before hand onset.

Hand RT was determined post-hoc as the time when the stylus was first lifted from the screen after the target had appeared. If the stylus slid towards the target, after trial start, but before it was first lifted, then an earlier hand onset was registered. This was based on threshold criteria of speed, and the distance covered.

Eye RT was determined post-hoc based on threshold criteria of jerk and the distance covered.

Both hand and eye onsets were determined automatically, then verified graphically. In cases where eye onset occurred before a trial started, the trial was discarded.

Hand movement times (hand MT) and task completion times (completion time) were also considered. Hand MTs were defined as the time from hand onset to the stylus first touching the target. Completion times were defined as the time from trial start to the stylus first touching the target.

Statistics:

Since there was a large variation in the number of valid trials for the participant with CP, a mixed linear model was used to analyse the results using IBM SPSS Statistics software. All measurements were used rather than means. A combination of *Condition*, *Trial#*, and *Session* were used as the repeated variable. Fixed factors were *Condition, Neurological Condition*, and *Session*. The only random variable was *Trial#*.

To make preplanned comparisons, sometimes the data set was split up. Either *Neurological Condition* was excluded to make observations for one particular participant.

RESULTS

In this section we present the results for the onset asynchrony measurements, followed by those for the hand movement times and task completion times.

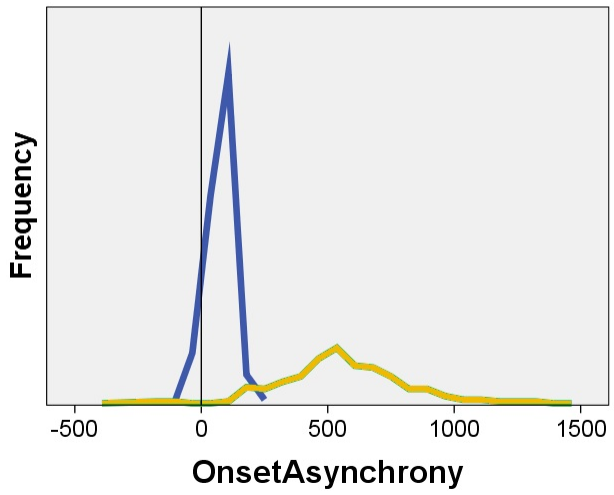

Figure 5. Frequency plot of onset asynchronies for different *Neurological Conditions*. (TD: blue line, higher peak. CP: orange line, more widely distributed.)

Onset Asynchronies (and Reaction Times)

A clearly significant ($p<0.01$) main effect of *Neurological Condition* was found. The participant with CP displayed significantly increased onset asynchrony relative to the TD participant. While the mean for the TD participant was 77*ms*, the CP participant's mean was 562*ms*, a difference of 485*ms*. Figure 5 shows distributions for each participant.

Whilst the eye RTs are significantly longer (94*ms* difference, $p<0.01$) for the participant with CP, the increase in hand RTs is much greater (579*ms* difference, $p<0.01$), thus the participant with CP had higher onset asynchronies.

A significant main effect of *Condition* was also found ($p<0.01$), but an interaction with *Neurological Condition* was also present ($p<0.01$). See Figure 6.

Knowing where the target would appear had varying effects on the different participants. The participant with CP displayed similar onset asynchronies to his *Blank-Slate* trials. Whereas the TD participant significantly reduced his onset asynchrony (31*ms* difference, $p<0.01$) for *Known*

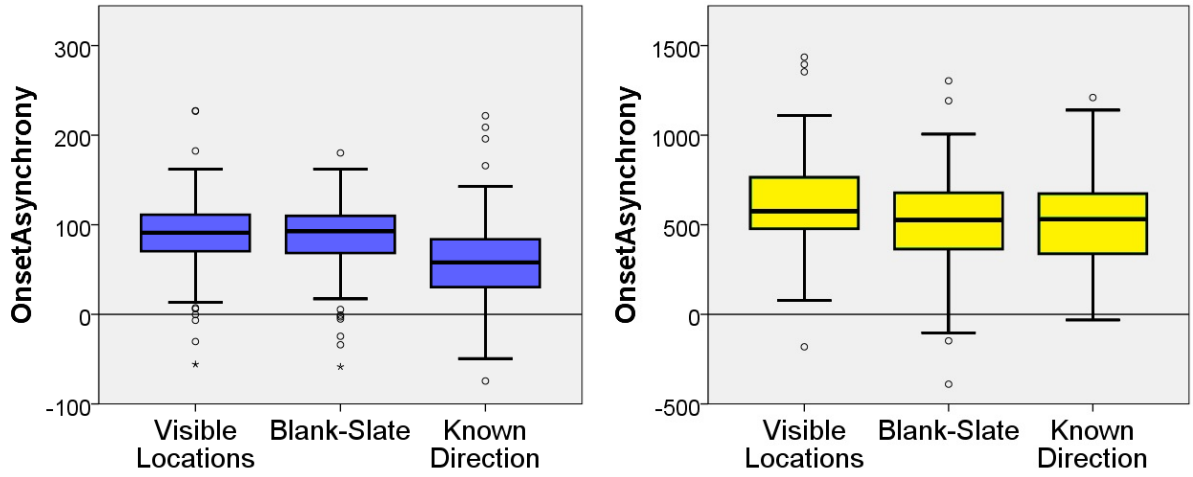

Figure 6. Onset asynchronies across trial types for each participant (TD: blue/left, CP: yellow/right).

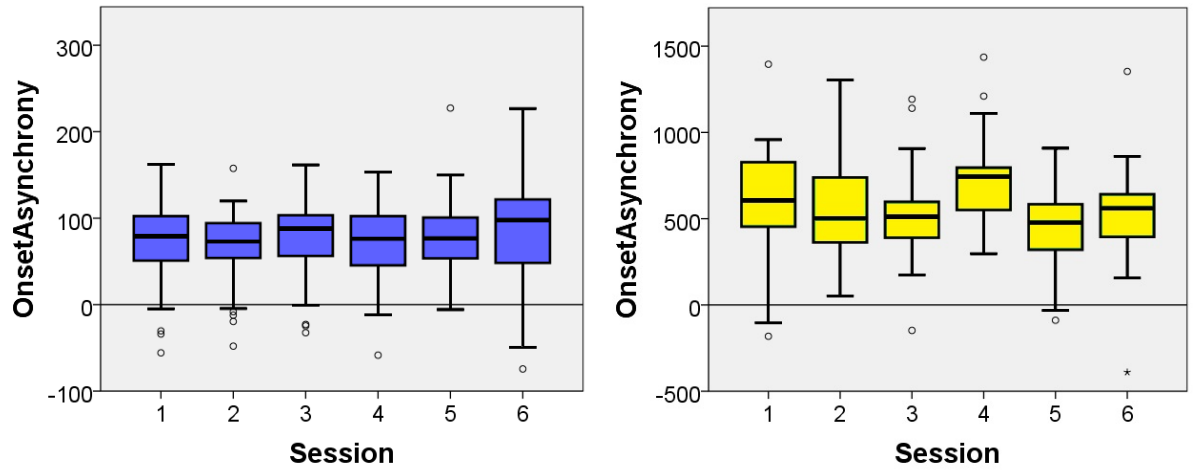

Figure 7. Session to session variation in onset asynchronies for each participant (TD: blue/left, CP: yellow/right).

Direction trials; he significantly reduced his hand RTs (29*ms* difference, $p<0.01$), whilst Eye RTs remained similar (2*ms* difference, $p=1.00$).

There was no effect of the possible target locations being visible prior to trial start for the TD participant. Yet, onset asynchrony increased significantly for the participant with CP (104*ms* difference, $p<0.05$). This difference was due to a decrease in eye RTs (109*ms* difference, $p=0.051$), whilst hand RTs stayed the same (4*ms* difference, $p=1.00$).

Session had a main effect on onset asynchrony values ($p<0.01$), and it interacted with *Neurological Condition* ($p<0.01$). This resulted from session to session variations in the onset asynchronies of the participant with CP ($p<0.01$). Session 4 had significantly increased onset asynchronies compared to sessions 2, 3, 5, and 6 (all $p<0.05$). There appears to be no overall trend, as per Figure 7. However, the variations are quite large, which is important given that we are looking for effect sizes in the order of 30*ms* to compare the effect of knowing the target location.

By comparison the means of the onset asynchronies for the TD participant were consistent from one session to the next. None of the sessions were significantly different from any other (maximum difference in session means was 19*ms* compared 298*ms* maximum difference in session means for the participant with CP).

Hand Movement Times and Completions Times

As expected, the hand MTs of the participant with CP were significantly longer than those of the TD participant (1,758*ms* difference, $p<0.01$), as were task completion times (2,347*ms* difference, $p<0.01$).

There was no main effect of *Condition* on hand MTs, this was also true for each participant.

Nor was there a main effect of *Condition* on task completion times. However, when the data was split up by *Neurological Condition*, the TD participant completed trials significantly faster in the *Known-Direction* condition than the *Blank-Slate* one (57*ms* difference, $p<0.01$). At least part of this improvement can be attributed to reduced hand reaction times. For the participant with CP, there were larger differences in means of completion times between *Conditions,* but none of them were significant.

Overall there was no main effect of *Session* on hand MTs, but there was for completion times ($p<0.02$). There was an interaction with *Neurological Condition* ($p<0.02$). For the TD participant, *Session* affected hand MTs and completion times (both $p<0.01$).

The participant with CP exhibited larger differences in means of hand MTs task and completion times across different sessions but they were not significant.

DISCUSSION

1. Normal values for people with CP

It is clear that for discrete movements, onset asynchronies were increased for the participant with CP compared to the TD participant. This is the opposite of what Steenbergen et al. [17] and Verrel et al. [18] found for participants with CP performing a semi-reciprocal task that involved grasping. Yet, it agrees with what has been found for other neurological conditions for discrete movements [2, 14, 15, 19, 20].

Our task significantly differed from the studies that included participants with CP in the past [17, 18]. Our task did not involve grasping, or completing a previous movement, so there was no need to visually monitor the success of any other actions. Furthermore, the participant was looking at the stylus prior to trial start, and undertook a relatively direct movement, so there was little need to visually monitor the start of the pointing movement. As such, visual attention was directed towards the target location; it is new information to be processed and the end of the movement must be monitored.

This increase in onset asynchrony is potentially a compensatory strategy, which could explain why similar trends have been found for various neurological conditions.

In any case, it was presumably possible for the participant with CP to delay their eye onset to reduce their onset asynchrony if this was desirable, as was the case in Verrel et al's [18] study.

2. Testing reliability

The repeatability of eye-hand movement onset asynchrony measurements for participants with this level of CP may be problematic. Anecdotally it seems session to session variability for this participant may have occurred due to fundamental variations in coordination patterns. Performing more trials is not necessarily a solution, since fatigue could further affect within session variability.

The variability in the onset asynchronies between sessions for the participant with CP may be partly due to the inability to take measurements consistently. Only 58% of trials led to measurements being possible. The *Known Direction* trials were particularly inconsistent with only 47% of trials resulting in measurements. As mentioned in the method section, the eye tracker could not always detect the participant's pupil which led to missing data in the eye recording, and no eye RTs being distinguishable. The other main reason that trials were discarded was unexpected performance of the given task. Generally this occurred because they looked at the target location before trial start, or they did not make one clear eye movement towards the target. It is unclear whether these behaviours were intentional and the instructions were not clear enough, or whether it was the result of reduced response inhibition which is affected by CP [10].

On the other hand, the TD participant's measurements were repeatable. This is a positive result since 38 studies have already used this measurement as a dependent variable [12]. By comparison 98% of trials resulted in a successful measurement for the TD participant.

Concerning the effect of *Session* on hand MTs and completion times, there was significant variation for the TD participant. For at least Session 5 (one of the slowest sessions), the participant reported being tired before starting the session, even though it was done at the same time of day. This did not have an effect on his onset asynchronies, suggesting they are robust measurements.

3. Useful Target Information

As expected, the TD participant reduced his onset asynchrony when the target direction was predictable. This is in line with previous research [5, 20]. It mainly came about due to reduced hand RTs which also resulted in completing the task faster. This can be seen as the effects of being able to preplan the movement before a trial starts, then acting it out once the stimulus has been perceived.

None of these changes seemed to occur in the participant with CP. According to Wilmut & Wann's [20] study on children with DCD, we might expect the participant with CP to have a smaller magnitude reduction in onset asynchrony if they were making use of the target position information in the *Known Direction* trials. Given that his behaviour was more variable, it is extremely difficult to differentiate if he was making use of the directional information a little bit, or not at all.

Regardless, there are several possible reasons why the participant with CP did not seem to act out a preplanned movement for the *Known Direction* trials. Presumably he can generate the movement plan since this needs to be done at some point anyway, but perhaps he was unable to store it, or retrieve it when needed. Another possibility is that he is capable of this, but it was merely not preferable.

Being visually aware of the possible target locations did not allow either participant to preplan a movement. The participant with CP even displayed significantly increased onset asynchronies, largely due to a decrease in eye reaction time. Yet, the hand RTs and MTs were very similar to the *Blank-Slate* trials. The accuracy of the eye movements was not measured, so if the participant tried to anticipate where the target would appear it could have affected their eye RTs. A similar eye movement problem occurred with the *Known-Direction* trials.

Overall we suggest that seeing possible target locations without knowing which target they wanted to select was not important for the eye-hand coordination of either participant. Especially since no decision making on the part of the user was involved in determining the correct target; it was highlighted by the task.

Potential Application of Findings

These results indicate a preference for the participant with CP to make new movements to a visible target location, rather than using a stored movement plan to a remembered location. This implies that interactions that rely on acting out stored movement plans, such as gesture based interfaces, may be less accessible to users with CP due to movement planning deficits.

Therefore a gesture based stylus system such as EdgeWrite [21], which does an excellent job of addressing movement execution difficulties, could be further improved if there were a way for it to display clear targets to users. This would be more suited to users with planning deficits.

More generally, our results also suggest that interface affordances should be perceivable to users, and not rely on users acting out stored movements since this is not preferable to all users.

CONCLUSIONS

In this study, the participant with CP increased, rather than decreased, his onset asynchrony compared to the TD participant for the discrete reaching tasks. This was true for all tasks and similar to what has been found for other neurological conditions. This is surely not purely a by-product of delayed motor output since a previous study showed people with CP reducing onset asynchrony. It seems likely that this increase is a compensatory strategy.

However, the measurements for the participant with CP did vary significantly between test sessions, suggesting they are not entirely repeatable. Comparatively, the TD participant had much more repeatable measurements. This shows that whilst onset asynchrony measurements may be useful for TD participants, the results from the participant with CP are not as reliable.

There seemed to be no effect of the target direction being predictable on the onset asynchronies of the participant with CP. It seems the participant with CP was not able to make use of knowing where the target would appear. On the other hand, the TD participant reduced their onset asynchrony when the target direction was known.

Combined, these results suggest that the participant with cerebral palsy preferred executing a new movement to a visible target, rather than a movement which was preplanned to an imagined target location. Relying on users to execute preplanned movements with no visible goal, such as gestures, may result in a barrier to accessibility for some users with cerebral palsy. Visual affordances for interactive actions may overcome this problem.

The effect of the possible target locations being visible was minimal for both participants. However, the participant with CP did display significantly increased onset asynchronies when the locations were visible; this should be investigated further with more participants.

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