# Hand-Eye Coordination in Bimanual Goal-Directed Tasks in Children with Cerebral Palsy

Major thesis

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**W. J. (Welmoet) de Ruijter[1]**

**Supervisors:**
**Dr. F. W. (Frans) Cornelissen[2]**
**Prof. dr. A. M. (Andrew) Gordon[3]**
**M. (Mirjan) van Dijk, MSc[2,4]**

Faculty of Mathematics & Natural sciences – University of Groningen

[1]Research Master Behavioural & Cognitive Neurosciences, B/N track

[2]Laboratory for Experimental Ophthalmology, School of Behavioural and Cognitive Neurosciences, University of Groningen

[3]Professor of Movement Sciences and Neuroscience and Education, Department of Biobehavioural Sciences, Teachers College, Columbia University

[4]Department of Otorhinolaryngology, School of Behavioural and Cognitive Neurosciences, University of Groningen

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## Abstract

This study concerns children with unilateral spastic cerebral palsy (CP). They are known to have impaired motor functioning; however many of these children also have visual field defects (e.g. hemianopia) (Guzetta et al., 2001; Costa et al., 2003). Current research and therapies disregard the high incidence of visual impairments in this patient group and are therefore incomplete. Consequently, little is known about the role of visual impairment on (impaired) motor functioning. Here, I use eye tracking to study the influence of impaired vision on performance in bimanual motor tasks in children with CP. Eleven children with unilateral spastic CP, ten age-matched typically developing (TD) children and ten healthy adults participated in this study. Participants performed two goal-directed bimanual tasks. Gaze direction was assessed using a head-mounted binocular eye-tracker (Pupil Pro). The most striking finding was that compared to both adult controls and TD children, children with CP showed a higher percentage of task irrelevant fixations in both conditions. Besides, children with CP executed many more head movements. My findings suggest that children with CP not only use compensatory motor mechanisms to perform bimanual tasks, but also that their visuomotor coordination is different from that of TD children and healthy adults. Better understanding of the mechanisms and strategies of hand-eye coordination in bimanual tasks can provide more detailed information of how these children can perform routine activities of daily living more effectively. Hence, further visuomotor research in children with CP is necessary to further develop and improve current therapies.

KEYWORDS: cerebral palsy; hand-eye coordination; eye-tracking; bimanual performance; compensatory mechanisms

## List of abbreviations

| | |
|---|---|
| AC | adult control |
| CI(MT) | constraint-induced movement therapy |
| CM | compensatory mechanism |
| CP | cerebral palsy |
| CVI | cerebral visual impairment |
| DH | drawer hand |
| HABIT | Hand and Arm Bimanual Intensive Training |
| TD | typically developing |
| TH | task hand |

# INTRODUCTION

Many daily life activities require fine motor skills executed by a well-functioning motor system. Moreover, most daily activities involve movement coordination between the two hands. The motor system is a complex system that controls the precision, direction, strength and velocity of movements according to information provided by sensory systems (Tükel, 2013).

Despite general acknowledgement of the importance of visual input for the motor system, eye movement research regarding hand and eye coordination in everyday activities is quite scarce. At the end of last century a first attempt was made by two studies that addressed the involvement of vision in coordinating bimanual activities in everyday settings. The first study involved tea making (Land, Mennie & Rusted, 1999), in the second study participants made peanut butter and jelly sandwiches (Hayhoe, 2000). In a review, Latter and Hayhoe (2001) compared the two studies and looked for the relation between ongoing motor actions and the eye movements that accompany them. Some of the important findings will be discussed here, for the details of the studies the reader is referred to the articles mentioned.

A remarkable finding in both studies was that subjects directed gaze almost exclusively to the objects involved in the task. Second, subjects hardly ever fixate on their hands while performing the task. This suggests that proprioceptive information is presumably adequate to know one's hand position. Furthermore it was noticed that once the hands grasped an object, that object was no longer fixated.

In order to get an idea of the functions of fixations in ongoing behaviour, Latter and Hayhoe (2000) studied where the eyes fixated on, and observed what happened in the period immediately after each fixation. They concluded that the roles of different fixations could be classified into four categories: (1) *locating*: the establishment of objects to be used in the future (i.e. later in the task); (2) *directing*: many actions are preceded by a single fixation on the object, the eye usually moves away from the object just before the hand reaches it; (3) *guiding*: if the action involves manipulation of (more than) two objects, a number of fixations are made, often alternating between the objects; and (4) *checking*: checking operations require the eye to dwell on some appropriate

region of an object (e.g. if filling a bottle with water, the top of the bottle is fixated on to check whether the bottle is full).

Already in early childhood, visuomotor coordination is fundamental in many behaviours and learning tasks such as grasping objects and graphomotor skills (e.g. writing). Visuomotor coordination in fine motor skills includes (a) motor processes, including the eye, head, and hand movements; (b) sensory processes, including the visual, vestibular, and somatosensory systems; (c) internal representations of sensory perception and action; and (d) higher-level processes for adaptive and anticipatory aspects of fine motor functions (Shumway-Cook & Woollacott, 2001).

Studies into infant's reaching behaviour suggest an early coupling between visual and motor systems. Infants reach towards an object more accurately when visually locating the object, showing a clear effect of vision on movement control (Shumway-Cook & Woollacott, 2001). Age, novelty and complexity of task, and amount of practice are important factors that change the role of the visual system in motor tasks (Newman et al., 2001; Shumway-Cook & Woollacott, 2001; Von Hofsten & Rosander, 2007).

Although the coordination of precise fine motor movements is highly demanding, in typical developing children they seem to appear without any effort (Tükel, 2013). In contrast, for children with neurological dysfunctions execution of fine motor movements is highly challenging due to impaired (visual-) motor coordination.

In this study, subjects from a specific patient group were included: children with unilateral spastic cerebral palsy. In brief, cerebral palsy is a neurological disorder that appears in infancy or early childhood that permanently affects muscle control. Since many of these children also have visual field defects (e.g. hemianopia) (Guzetta et al., 2001; Costa et al., 2003), I believe it is interesting to study the role of the visual system in (impaired) motor functioning in this group.

In the next subsections first the term cerebral palsy will be explained. Thereafter the current states of affairs regarding therapies will be discussed.

### Cerebral Palsy

Cerebral Palsy (CP) is an umbrella term covering a number of neurological disorders that appear in infancy or in early childhood and permanently affect body movement and muscle control but don't worsen over time (Bax et al., 2005). There are several different types of CP and symptoms can be very different between people. An overview of different types of CP according to different classification systems is provided in Table 1.

CP is the most common cause of severe physical disability in childhood, with a prevalence of about 2-2.5/1000 live births (Koman et al., 2004; Lin, 2003; Steenbergen & Gordon, 2006).

The current study included children with unilateral spastic cerebral palsy. These children have early non-progressive lesions of the brain that result in a number of impairments predominantly on one side of their body (e.g., Coluccini et al., 2007). In principle motor impairments occur contralesional, i.e. if a person has a lesion in the left hemisphere of the brain; the right side of the body is affected. This is shown in Box 1.

In addition, children with CP have bimanual coordination problems with less synchronized and more sequential movements of their two hands (e.g., Charles & Gordon, 2006; Ricken et al., 2005), which affect their functional independence and quality of life. The motor disorders of CP are often accompanied by disturbances of sensation, cognition, communication, perception and/or behaviour, and/or by a seizure disorder (Bax et al., 2005).

According to amongst others Van Roon et al. (2005) the difficulties individuals with CP have in performing accurate upper limb movements can be a consequence of either disordered motor coordination or impaired proprioception or both. Experienced movement difficulties result in an increased need for compensatory mechanisms (CM) to correct movements. These corrective movements can be made on the basis of proprioceptive and/or visual feedback. However, since proprioception in persons with CP is impaired (e.g. Cooper et al., 1995), visual feedback is the most likely compensatory mechanism for them to rely on. Indeed, it has been observed several times that compared to control participants, persons with CP rely more on visual guidance of the moving hand during upper limb movements as compared to control participants (e.g. Steenbergen & Van der Kamp, 2004).

However, Van Roon et al. (2005) investigated whether persons with CP really *need* visual information of the moving limb to be able to move accurately. Despite many (clinical) observations showing increased reliance on visual guidance of the moving limb in persons with CP, they concluded that they do not depend on visual guidance to make accurate upper limb movements: removing of the possibility for visual guidance did not decrease movement accuracy. In contrast, they did find that when visual information was removed, persons with CP made use of CM. The authors concluded that persons with CP could successfully compensate for the loss of visual information by extending the movement time.

Thus, although this study suggests visual guidance is not *necessary*, it might still help persons with CP to perform a certain task better or faster. Moreover, it should be noticed that the study by Van Roon et al. (2005) tested unimanual performance in a two-dimensional task. It is possible that in a more complex task visual guidance of the moving limb is more important or even necessary. Since little is known about visual strategies in goal-directed bimanual tasks, in this study I explored the role of eye movements in two three-dimensional bimanual tasks.

## Current state of affairs regarding therapies

Duff and Gordon (2003) showed that children with cerebral palsy suffering from hemiplegia might benefit from intensive unimanual practice. Initially designed for adults with hemiplegia, Constraint-Induced Movement Therapy (CI therapy) showed promise for the treatment of unimanual hand function. This therapy involves restraint of the non-involved upper extremity with intensive targeted practice of the involved extremity (Charles & Gordon, 2006). However, Charles and Gordon (2006) emphasize that children with cerebral palsy suffering from hemiplegia show bimanual coordination impairments beyond unilateral impairments. CI therapy only focuses on unilateral training and was therefore argued to have some important limitations (Charles & Gordon, 2006). To improve bimanual coordination and, therefore, functional independence and quality of life of this population, Charles and Gordon (2006) developed a bilateral intensive rehabilitation strategy: Hand and Arm Bilateral Intensive Training (HABIT). HABIT methodology focuses on: (1) provision of structured practice increasing in complexity; (2) provision of functional activities that necessitate bimanual hand use; and (3) remaining a child-friendly intervention protocol that takes into account children's goals and parental involvement.

Systematic reviews of studies comparing CI and HABIT therapy revealed that both therapies produced similar improvements in the bimanual and unimanual capacities of the affected arm and overall functional performance (Dong et al., 2013; Gordon et al., 2011). A potential benefit from HABIT is that participants may improve more on self-determined goals (Gordon et al., 2011).

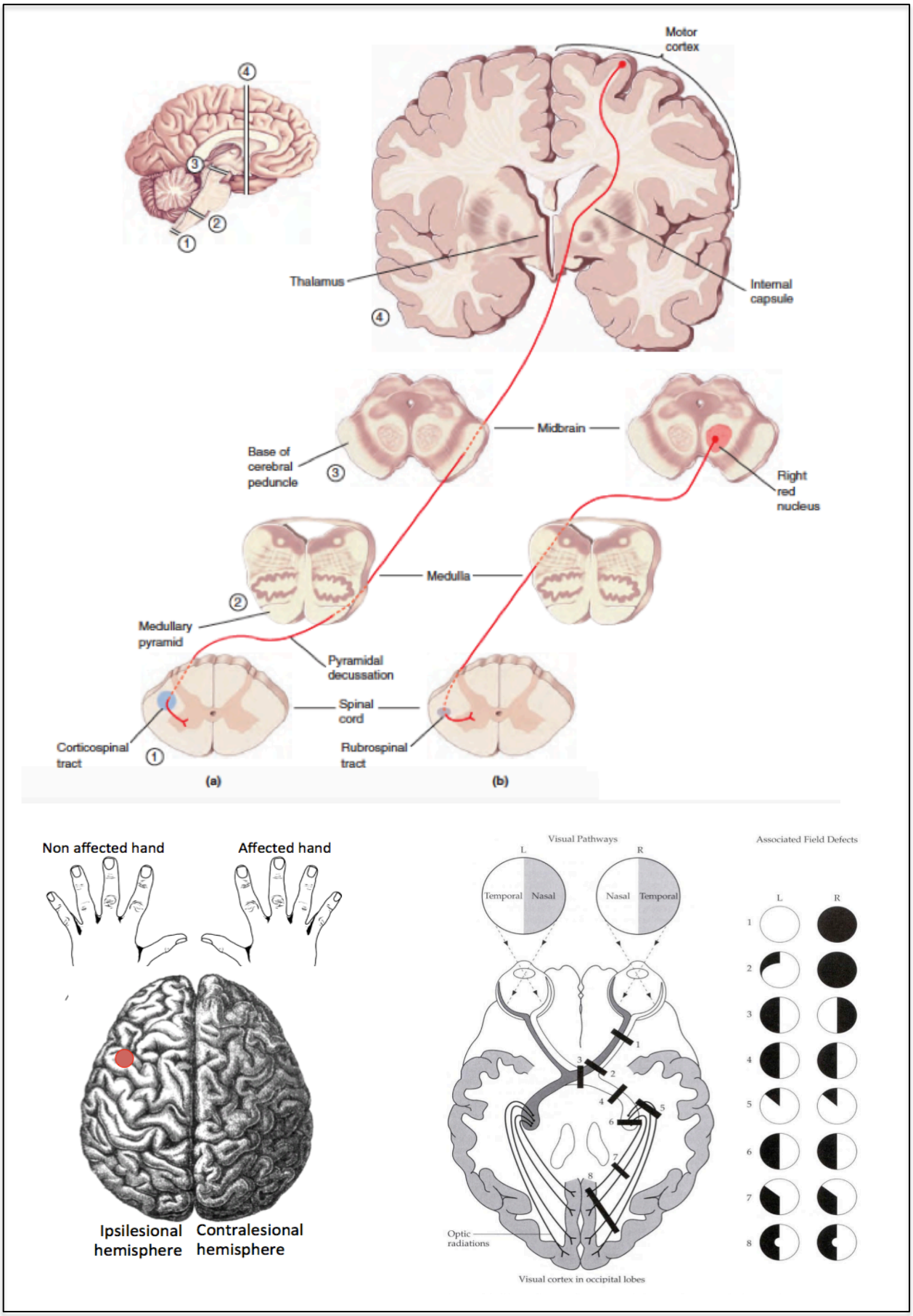
Up to now, therapies for CP children do not take into account visual field defects and visuomotor research is scarce. Moreover, most studies exclude children with visual field defects. This is quite surprising regarding the high incidence of visual field defects in children with CP (e.g. Black, 1982). Beside a variety of visual abnormalities (e.g.

nystagmus, gaze palsy etc.) approximately 17 % of children with CP have visual field defects (e.g. hemianopia) (Black, 1982). Whereas current therapies are solely based on motor research in children with CP without visual field defects, these therapies are also applied to children with CP with visual field defects.

Varrel and colleagues (2008) argue that the role of visual perception during motor action and development is very important. They found that children with CP show increased visual monitoring when performing actions with the affected hand. Moreover, developmental milestones that normally require vision, e.g. reaching and walking, are often delayed in children with visual impairments (Varrel et al., 2008; Salavati et al., 2014).

To my knowledge, there is only one study that compared motor function in children with CP with and without cerebral visual impairment (CVI). Salavati and colleagues (2014) investigated whether functional skills and caregiver assistance in a group of children with combined CP and CVI were lower compared to a matched group of children with only CP. Their study clearly demonstrated that children with combined CP and CVI achieved lower scores in all dimensions of gross motor function including laying and rolling, sitting, crawling and kneeling, standing, walking, running and jumping when compared with children with only CP. They conclude that limitations in physical activity in children with CP could not only be caused by a delay in motor or mental development but also by CVI. Therefore, it is very important that physicians, counselors and parents take into consideration that the child may be experiencing a visual impairment such as CVI. Whereas Salvati et al. (2014) focused on gross motor function differences, my current study focuses of the current study is on hand-eye coordination in three-dimensional bimanual goal-directed tasks.

In this study I investigate whether children with CP with and without visual field defects differ in visuomotor behaviour and whether impaired vision affects bimanual motor performance. Results might lead to future improvement and personalization of motor and/or visual therapies.




**Box 1. Crossing motor and visual pathways: lesions affect contralateral limbs and field defects respectively.** Upper image: lateral motor pathways. (a) Corticospinal tract and (b) rubrospinal tract. These tracts control fine movements of the arms and fingers. Both tracts cross; therefore control movement contralateral to the hemisphere (Image derived from Bear et al. 2001). Lower left: affected limb contralateral to lesion side. Lower right: visual pathways and associated field defects. Due to crossing of visual pathways, associated field defects are contralesional.

| **Classification system** | **Type of cerebral palsy** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Severity level | Mild<br>- *Move without assistance*<br>- *Daily activities not limited* | | | Moderate<br>*Need braces, medicine and adaptive technology to accomplish daily activities* | | | Severe<br>- *Require wheelchair*<br>- *Significant challenges to accomplish daily activities* | | |
| Topographical distribution | Monoplegia/ -paresis[1] | Di (-) | Hemi(-) | Para(-) | Tri(-) | Double(-) | Tetra(-) | Quadri(-) | Penta(-) |
| *Part affected:* | *One limb* | *Two limbs (often both legs)* | *Arm and leg on one side of body* | *Lower half body* | *Three limbs* | *All four limbs, but one side of body more severe* | *All four limbs, but three more than the other* | *All four limbs* | *- All four limbs, head and neck*<br>*- Eating and breathing complications* |
| Motor function | Pyramidal/ spastic<br>*Increased muscle tone* | Extrapyramidal/non-spastic<br><u>Ataxic</u><br>*Coordinated movements affected* | | Athetoid<br>*Involuntary movements* | | <u>Dyskinetic</u> | Dystonic<br>*Fixed, twisted posture* | | |
| Gross motor function classification system (GMFCS) | GMFCS Level I<br>*Walks without limitations* | GMFCS Level II<br>*Walks with limitations, no running and jumping* | | GMFCS Level III<br>*Adaptive equipment assistance* | | GMFCS Level IV<br>*Self-mobility with use of powered mobility assistance* | | GMFCS Level V<br>*Severe head and trunk control limitations, extensive use assisted technology and physical assistance* | |

**Table 1. Different types of cerebral palsy according to different classification systems**

[1] Paresis means weakened. Plegia means paralyzed.

# Methods

## Location

The study was performed within the Center for Cerebral Palsy Research, Columbia University, New York. The Center is committed to improve the lives of children with CP through research. These include both speech and motor disorders associated with CP. Based on research studying the underlying mechanism of impaired hand function in children with CP, the center developed intensive rehabilitation techniques. These interventions have proven to significantly improve hand function in children with hemiplegia (i.e. unilateral paralysis of the body) (e.g. Charles & Gordon, 2006).

## Participants

Eleven children with unilateral spastic CP (mean age 9y 7mo [range 6-15y]; 4 males, 7 females; affected side: 10 right, 1 left) and ten age-matched right-handed typically developing (TD) children (mean age 9y [range 5-15y]; 6 males, 4 females) participated in this study. Participants were recruited from schools and rehabilitation clinics in the New York City area. Written informed consent was obtained from all participating children and their parents/care givers. The study was approved by the Institutional Review Board of Teachers College, Columbia University.

Since in general very little research has focused on the relationship between hand and eye movements in ordinary activities in everyday settings, we also included a group of ten healthy adult subjects (mean age 29y 2mo [range 20-39y]; 6 males, 4 females; 9 right-handed). These subjects were included to get a better idea of what kind of eye movements we could expect during the two goal-directed bimanual tasks. Besides, it enabled us to compare visual strategies of the three populations. Written informed consent was obtained from all participating subjects.

## Experimental setup

### Task 1: Drawer task

I used the experimental setup as previous described by Hung et al. (2010). The task was designed by Perrig et al. (1999), but modified to be accomplishable for children with CP. Previous results (kinematics) from the drawer-opening task in CP patients are shown in Box 2. Participants were seated 15cm in front of a table with their elbows flexed at right angles and hands positioned at 30cm apart at the edge of the table. The participants were asked to open a spring-loaded drawer (load 0.3kg; size 15x15cm) with one hand (drawer hand; DH) and to insert their contralateral hand (task hand; TH) in the drawer to activate a push-button light switch (Figure 1). To manipulate accuracy demands of the TH and to change visual information, either a large (14x10cm) or a small (1.5x2cm) push-button light switch was placed inside the drawer.

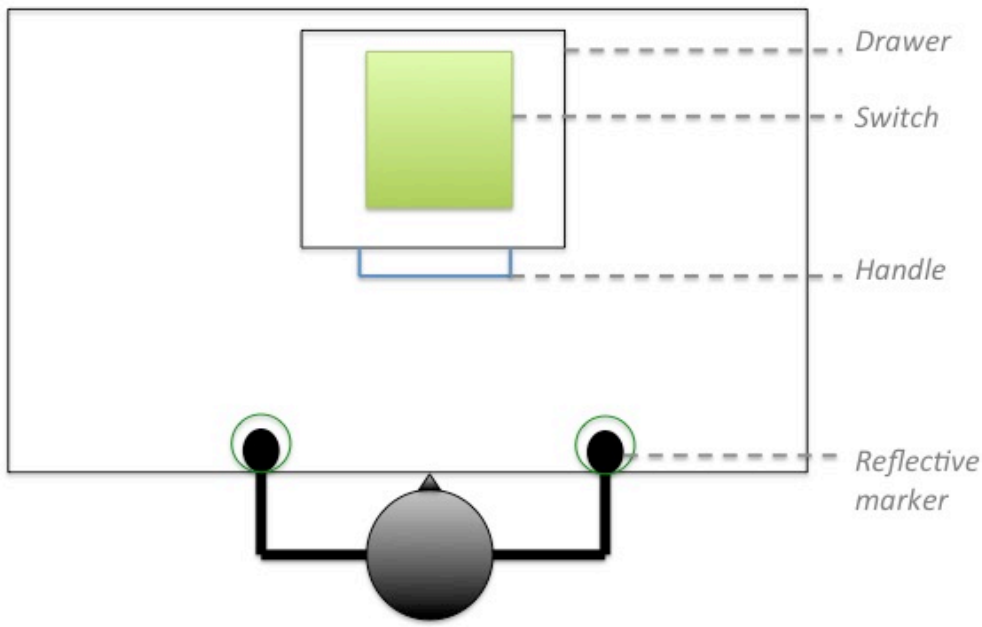



**Figure 1. Experimental setup drawer task.**

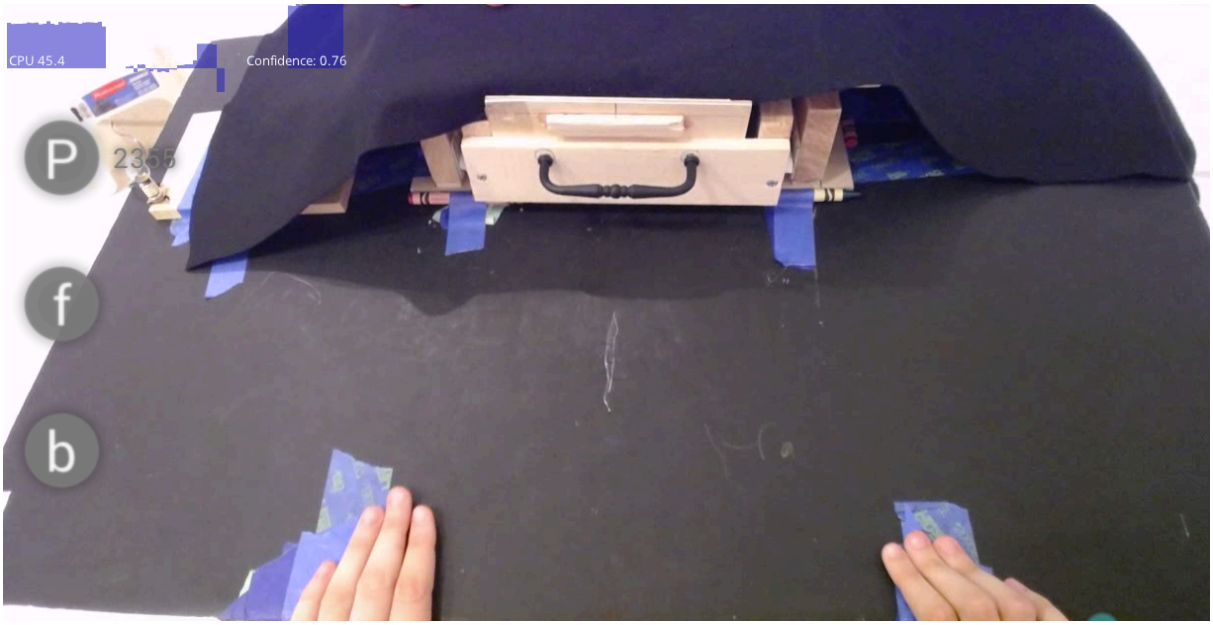



**Image 1. Experimental set-up drawer task from participant's point of view.** Image derived from screenshot scene camera Pupil Pro; scene camera was positioned on the middle of the participant's forehead.

### *Procedure*

Participants were asked to reach forward and open the drawer with their drawer hand (DH) (either dominant/non-involved or non-dominant/involved) and activate the light switch inside the drawer with the task hand (TH) following an auditory start-signal. A little light placed on the left side of the table was switched on before every trial in order to be able to synchronize the motion analysis and the eye tracking system. After the light was off the auditory 'Ready, go' signal was given. A trial ended when the light switch inside the drawer was activated. A 2x2 block design was used such that each participant performed the task with each switch (small/large) and with each hand opening the drawer. The participants were asked to perform the task at normal speed. After three practice trials, five trials were collected for each condition, i.e., a total of 20 trials. Conditions were randomized for each participant. Rest periods between the conditions were provided at the participant's request.

## Task 2: Tray task

The tray task (Figure 2) was developed by professor Hung (*unpublished*). Participants were seated 15cm in front of a table with their elbows flexed at right angles and hands positioned at 30cm apart at the edge of the table. Participants were asked to grasp and lift a wooden tray (load 0.3kg; size 25x12cm) ten centimeters for two seconds and put it down on the table again. A plastic tube (volume 50ml, dimensions 120x17mm) filled with water was secured in the middle of the tray. Participants were asked to not spill the water. To manipulate accuracy demands of the task, the tray had either large (30mm diameter) or small (15mm diameter) handles and the tube filled with water was either covered with a lid or not.

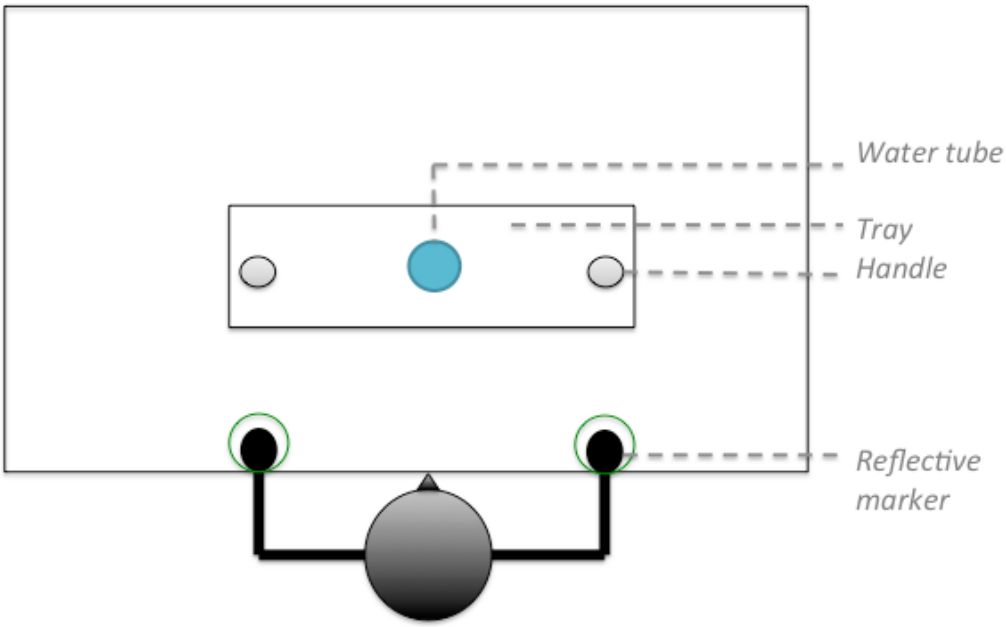



**Figure 2. Experimental setup tray task.**

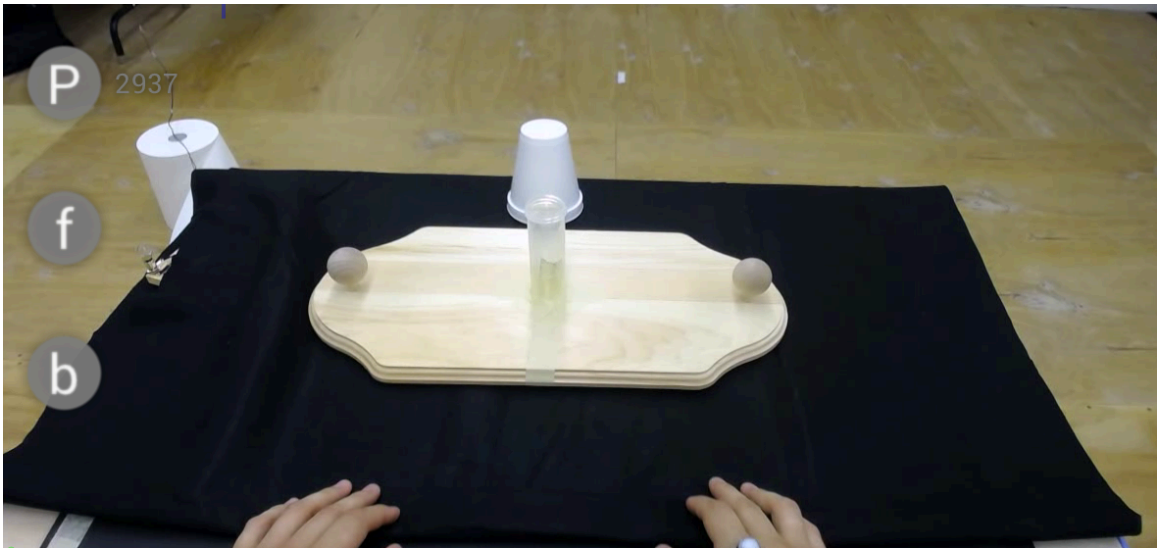



**Image 2. Experimental set-up drawer task from participant's point of view.** Image derived from screenshot scene camera Pupil Pro; scene camera was positioned on the middle of the participant's forehead.

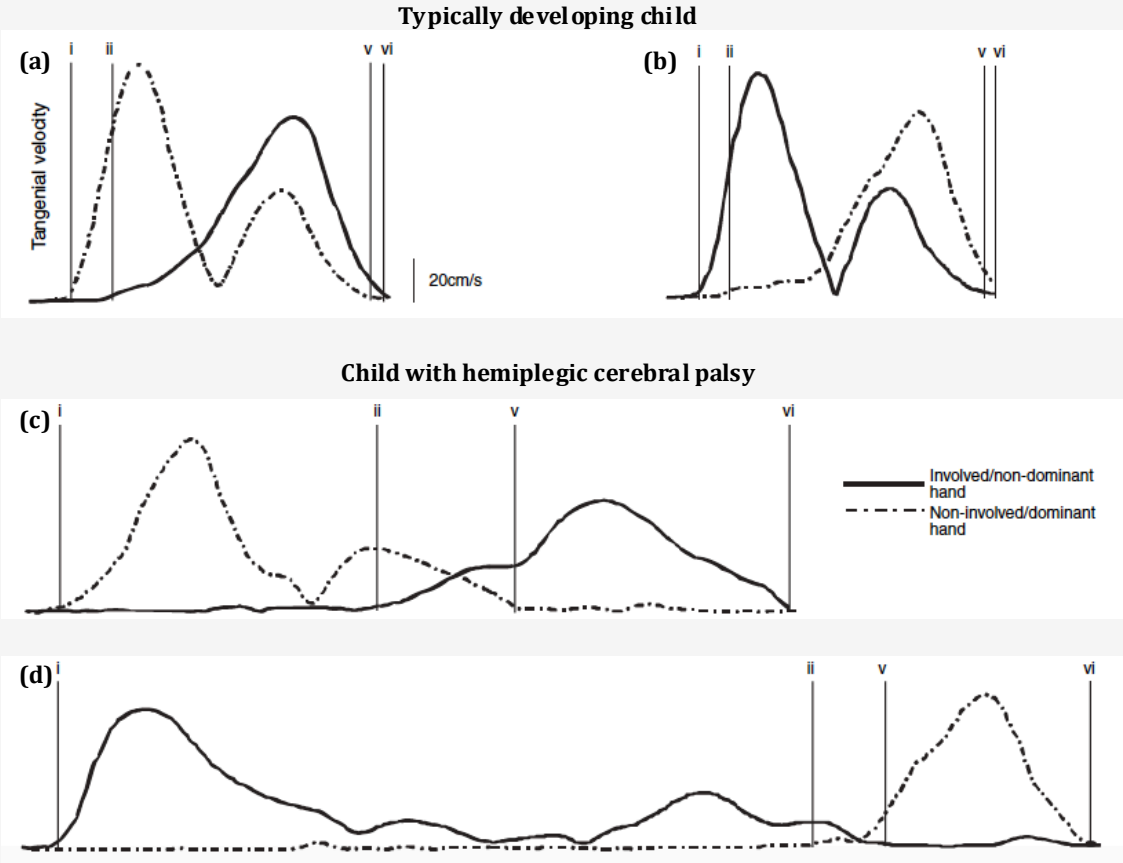
### *Procedure*

Participants were asked to reach forward and lift the tray ten centimeters for two seconds following an auditory start-signal. A little light placed on the left side of the table was switched on before every trial in order to be able to synchronize the motion analysis and the eye tracking system. After the light was off the auditory 'Ready, go' signal was given. A trial ended when the tray was placed back on the table. A 2x2 block design was used such that each participant performed the task with each handle (small/large) and with or without a lid covering the tube. The participants were asked to perform the task at normal speed. After three practice trials, five trials were collected for each condition, i.e., a total of 20 trials. Conditions were randomized for each participant. Rest periods between the conditions were provided at the participant's request.

The drawer-opening task developed by Hung and colleagues (2004) is used to assess bimanual coordination in children with CP. The task is a modified version from the task previously designed by Perrig et al. (1999). In order to be achievable for children with CP, both the drawer and handle size are enlarged. Studies in healthy subjects performing the drawer-opening task demonstrated a high degree of bimanual coupling (e.g. Perrig et al., 1999).

In a study by Hung and colleagues (2010) bimanual performance in the drawer-opening task of children with CP was compared to performance of typically developing (TD) children. The figures depict tangential velocity kinematic traces of drawer and hands of a TD (a/b) and CP (c/d) child. Graphs (a) and (c) represent the tasks where the participants used the dominant/non-involved hand to open the drawer, graphs (b) and (d) the tasks where the non-dominant/involved hand was used to open the drawer. Vertical lines depict: (i) movement onset of drawer hand; (ii) movement onset of task hand; (v) movement offset of drawer hand when drawer is completely opened; and (vi) movement offset of task hand. The period between (ii) and (v) is the movement overlap time for the two hands. The period between (v) and (vi) is the goal synchronization duration.

Clearly, children with CP were overall much slower and more sequential, with the task hand initiating movement after the drawer hand reached the drawer and began pulling it open (i.e. less movement overlap (ii-v) and longer goal synchronization time (v-vi). Thus, compared to TD children, children with CP are found to be less coordinated.




**Box 2. Previous kinematic findings in drawer-opening task. Figures and data from Hung et al. (2010).** Upper figures: hand movement velocity TD child. Lower figures: hand movement velocity child with CP. Solid line shows movement velocity of involved (CP)/non-dominant (TD) hand. Dashed line shows movement velocity of non-involved (CP)/dominant (TD) hand.

## Data acquisition

### *Kinematics*

Kinematic data was collected with a three-dimensional Vicon motion analysis system. Reflective markers were placed on participant's wrists, hands, elbows, and shoulders bilaterally. At the time of writing, the kinematic data was not analyzed yet and is not part of this thesis.

### *Eye-tracking*

Gaze direction was assessed using a head-mounted binocular Pupil Pro (sampling frequency 48 Hz (24 fps) from Pupil Labs, Berlin, Germany (Kassner & Patera, 2012). Pupil Pro is an accessible, affordable, and extensible open source platform for mobile eye tracking and gaze-based interaction. Pupil comprises 1) a lightweight headset with high-resolution cameras, 2) an open source software framework for mobile eye tracking, as well as 3) a graphical user interface (GUI) to playback and visualize video and gaze data. Pupil features high-resolution scene and eye cameras for monocular and binocular gaze estimation. The software and GUI are platform-independent and include state-of-the-art algorithms for real-time pupil detection and tracking, calibration, and accurate gaze estimation. Results of a performance evaluation show that Pupil can provide an average gaze estimation accuracy of 0.6 degree of visual angle (0.08 degree precision) with a latency of the processing pipeline of only 0.045 seconds (Kassner & Patera, 2012).

For calibration we used the method *Natural Features Calibration* to calibrate gaze parameters using features in the subjects' environment. Nine calibration points were taken to cover the subjects' field of view. The calibration procedure was performed before the first task and repeated when switched to the second task.

### *Visual field test*

Visual fields of children with CP were tested using the online test of Neurological Vision Loss Test (http://vision.helpforvisionloss.com/NVisionTest.html). The test was shown on a 15'' screen while participants were seated on a height-adjustable chair at a 13'' distance to the screen. Participants had to focus on a green dot in the middle of the screen. If the green dot changed to a yellow triangle, participants had to respond by pressing the space bar. Stimuli appeared in clear white dots in a random order all over

the screen. Again participants had to respond to stimuli by pressing the space bar. Following a correct response a high-pitched sound was played, following an incorrect one a low-pitched sound was played. A short practice test to check whether the children understood the instructions was taken before the actual test was conducted.

Beside the vision test, children performed a neglect test, however this data is not analyzed yet.

## Analysis

The program Pupil Player was used to visualize the eye-tracking data. The following settings were used to analyze the movies: scan path (duration 0.5sec), gaze polyline (line thickness 1), gaze circle (radius 14, stroke width 2, fill: on), gaze cross (inner offset length 1, outer length 0, stroke width 0), REC FPS was automatically fixed on 24 (Image 3).

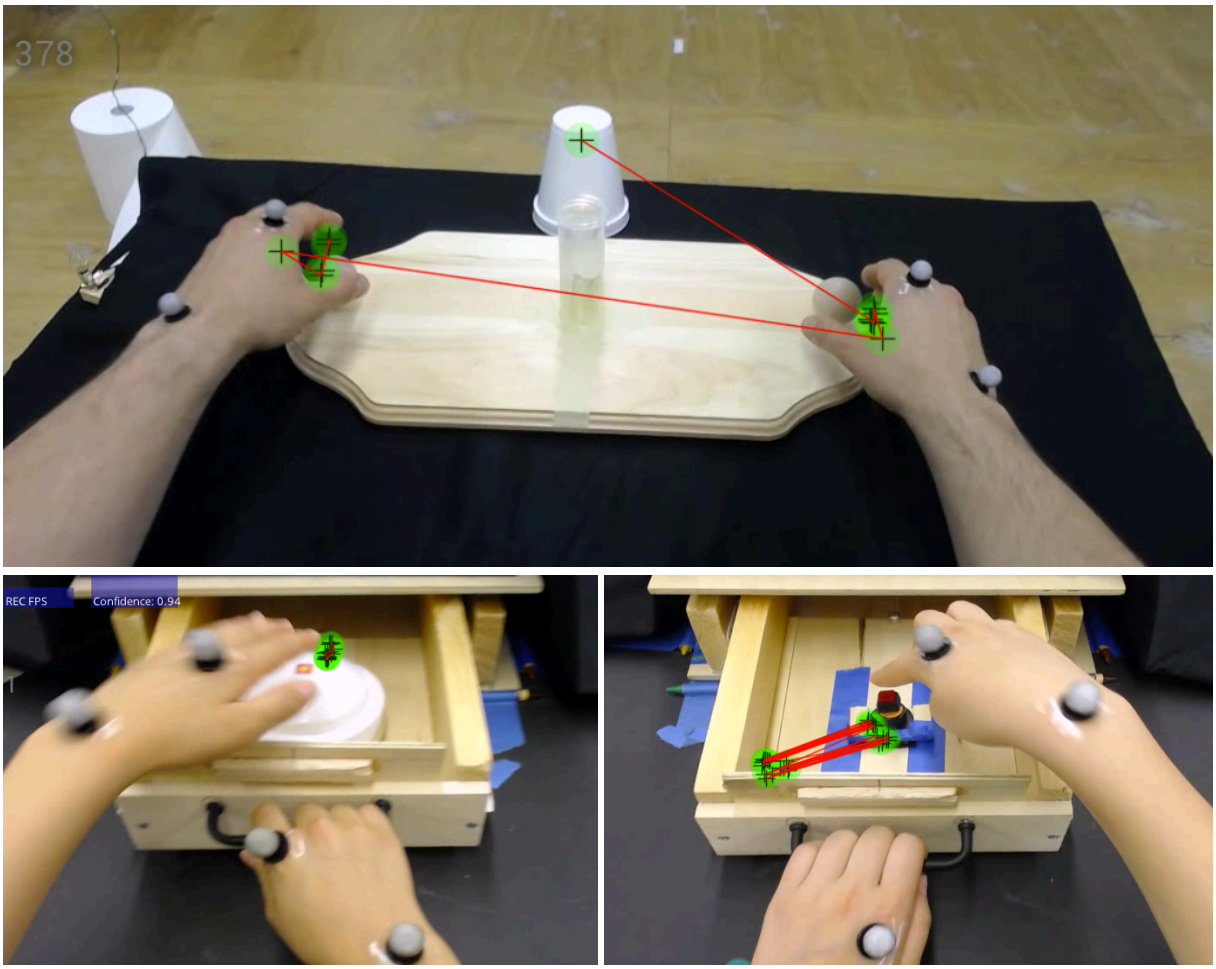



**Image 3. Screen shots from Pupil Player.** Upper: tray task; condition large with water. Lower left: drawer task; condition right large. Lower right: drawer task: condition left small.

Since participant's heads were not fixated, the field of view could change as a consequence of (head) movements. Therefore eye movement behaviour could not be compared on the basis of coordinates in the subject's visual field. Every trial was analyzed separately. For both tasks several variables where the subject could look at were defined. For the drawer task the variables (1) drawer/handle; (2) switch; (3) left hand; (4) right hand, and (5) task irrelevant were defined. For the tray task the variables were: (1) water tube; (2) left handle; (3) right handle; (4) left hand; (5) right hand; (6) table, and (7) task irrelevant. For every trial the average percentages of time the subject was fixating at all variables was calculated. A trial started when the light was switched off and ended when the switch was turned on (drawer task) or the tray was placed back on the table (tray task).

For every trial the number of gaze shifts was counted. A gaze shift was defined as a shift of focus to another object (i.e. from drawer to switch and back is two gaze shifts).

Due to problems with Pupil Capture (e.g. disconnected cables) or inability of subjects to perform a certain condition, some trials are missing. If less than two trials per condition were available, the condition was dismissed.

Differences were statistically evaluated using one-way ANOVA with group as a between subject factor. Post-hoc Bonferroni tests were applied to determine whether one or all groups were deviating from each other. An alpha level of 0.05 was used for all statistical tests.

## Results

For two goal-directed bimanual motor tasks I measured the percentage of time that subjects fixated on the different task features and hands as well as the number of gaze shifts. The most striking finding is that compared to both adult controls and typically developing (TD) children, children with CP showed a higher percentage of task irrelevant fixations and a larger number of gaze shifts. Below, these findings are described in detail for the two tasks separately.

Two independent persons naïve of the research analyzed part of the data to out rule a possible observer bias. No significant observation differences were found.

### Task 1: Drawer task

Results from the drawer task are depicted in figures 3-8. The figures show the percentage of time that subjects fixated on the different features. The most striking finding is that compared to both adult controls and typically developing (TD) children, children with CP showed a higher percentage of task irrelevant fixations in all four conditions (left-large: $F(2, 26) = 9.90$, $p = 0.001$; right-large: $F(2, 26) = 8.88$, $p = 0.001$; left-small: $F(2, 28) = 10.10$, $p = 0.000$; right-small: $F(2, 27) = 7.38$, $p = 0.003$). Post-hoc Bonferroni tests revealed that for all conditions children with CP differed significantly from both control groups. There were no significant differences between control groups (mean values and standard deviations described in figure legends).

For the children with CP, percentages of fixation did not depend on whether the task was performed with either the right hand (involved hand for 10/11 children) or the left hand as drawer hand.

Control participants hardly ever fixated on their hands. Only in the latter condition (drawer hand: right, switch: small) children with CP (M 8.55, SD 12.19) showed more hand-guided fixations. Noticeably, these fixations were only directed to their right hand, which for ten out of the eleven children was their affected hand.

Moreover, in all four conditions, children with CP exhibited more gaze shifts than adult control participants (left-large: $F(2, 26) = 3.40$, $p = 0.049$; right-large: $F(2, 26) = 4.01$, $p = 0.030$; left-small: $F(2, 28) = 3.64$, $p = 0.039$; right-small: $F(2, 27) = 7.00$, $p = 0.004$). Compared to TD children, the children with CP exhibited more gaze shifts only in the right-small condition ($F(2, 27) = 7.00$, $p = 0.004$). The number of gaze shifts per condition is shown in Figure 7.

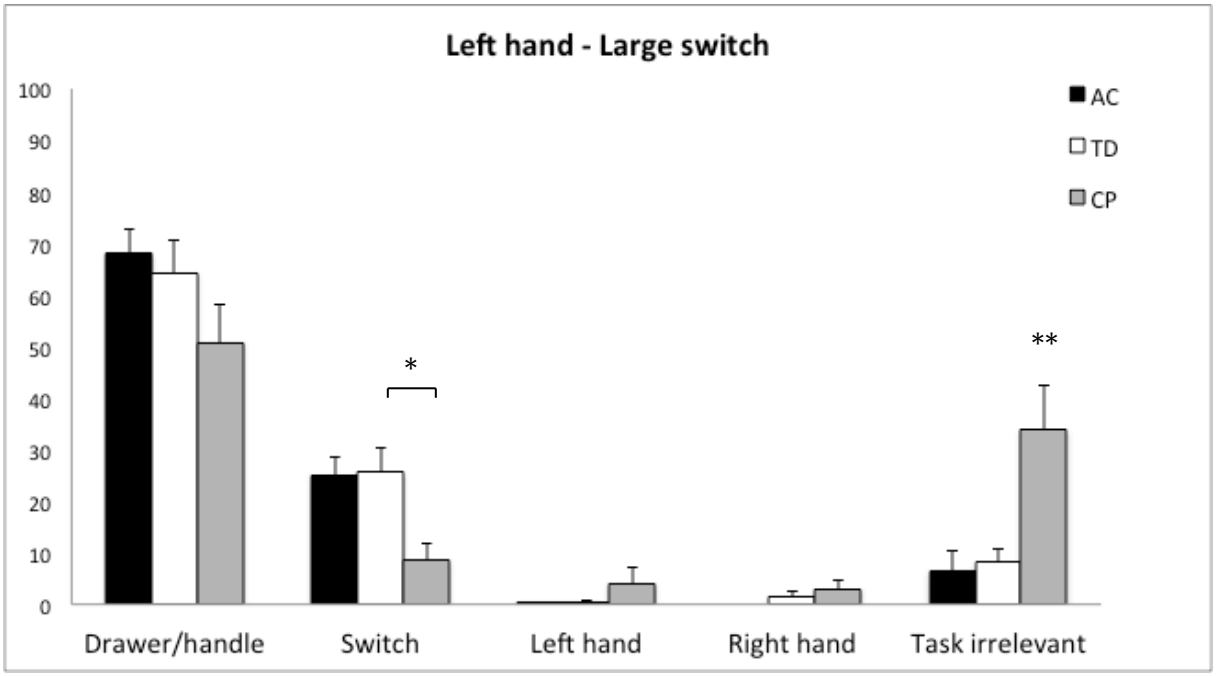



**Figure 3. Results drawer task.** Condition (1): drawer hand: left; task hand: right; switch: large. Bars show percentage fixated on the different variables shown on the X-axis. Error bars show standard error. Black bars: adult control (n=10). White bars: typically developing children (n=10). Grey bars: children with CP (n=9). Asterisks on top of bars indicate significance (*p<0.05; **p<0.01; ***p<0.001). CP children (M 8.44, SD 9.57) fixated less on the switch than TD children (M 25.56, SD 4.74) (F (2, 26) = 4.44, p = 0.022). CP children (M 33.77, SD 26.12) showed more task irrelevant gazes than both AC (M 3.98, SD 5.64) and TD (M 8.09, SD 8.40) (F (2, 26) = 8.88, p = 0.001).

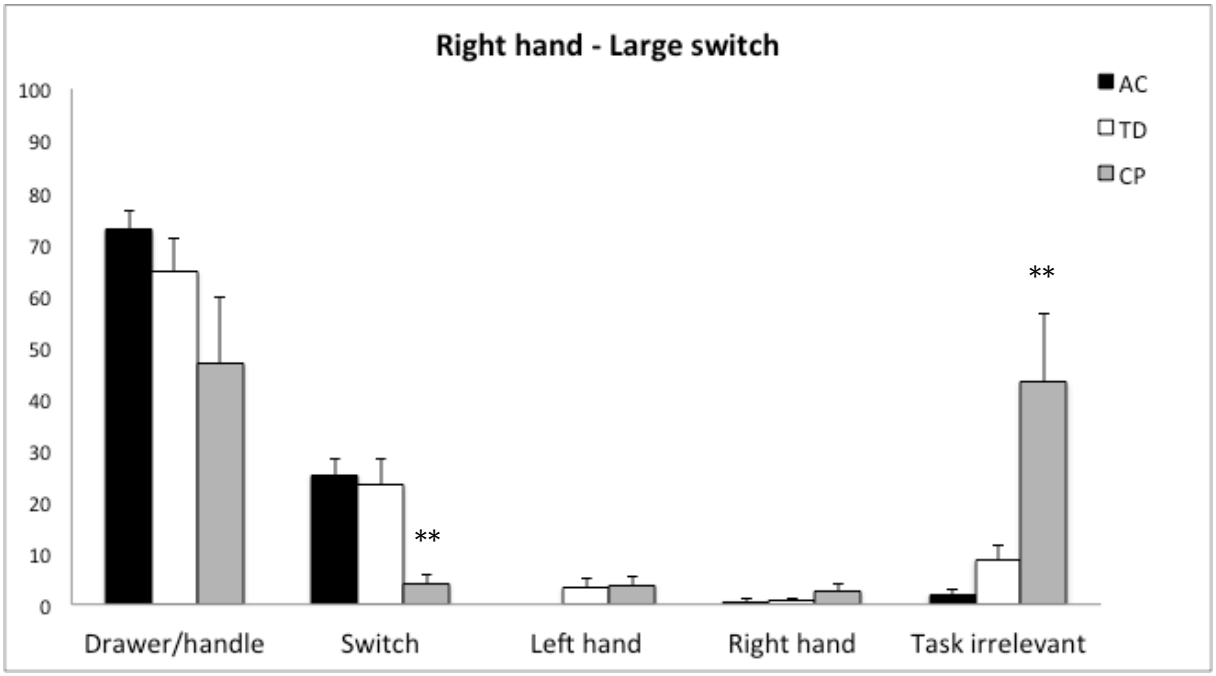



**Figure 4. Results drawer task.** Condition (2): drawer hand: right; task hand: left; switch: large. Bars show percentage fixated on the different variables shown on the X-axis. Error bars show standard error. Black bars: adult control (n=10). White bars: typically developing children (n=10). Grey bars: children with CP (n=9). Asterisks on top of bars indicate significance (*p<0.05; **p<0.01; ***p<0.001). CP children (SD 18.87, SD 14.38) fixated less on the switch than both AC (M 24.97, SD 10.35) and TD children (M 23.25, SD 15.22) (F (2, 26) = 10.04, p = 0.001). CP children (M 43.10, SD 39.62) showed more task irrelevant gazes than both AC (M 1.81, SD 3.03) and TD (M 8.57, SD 9.13) (F (2, 26) = 9.90, p = 0.001).

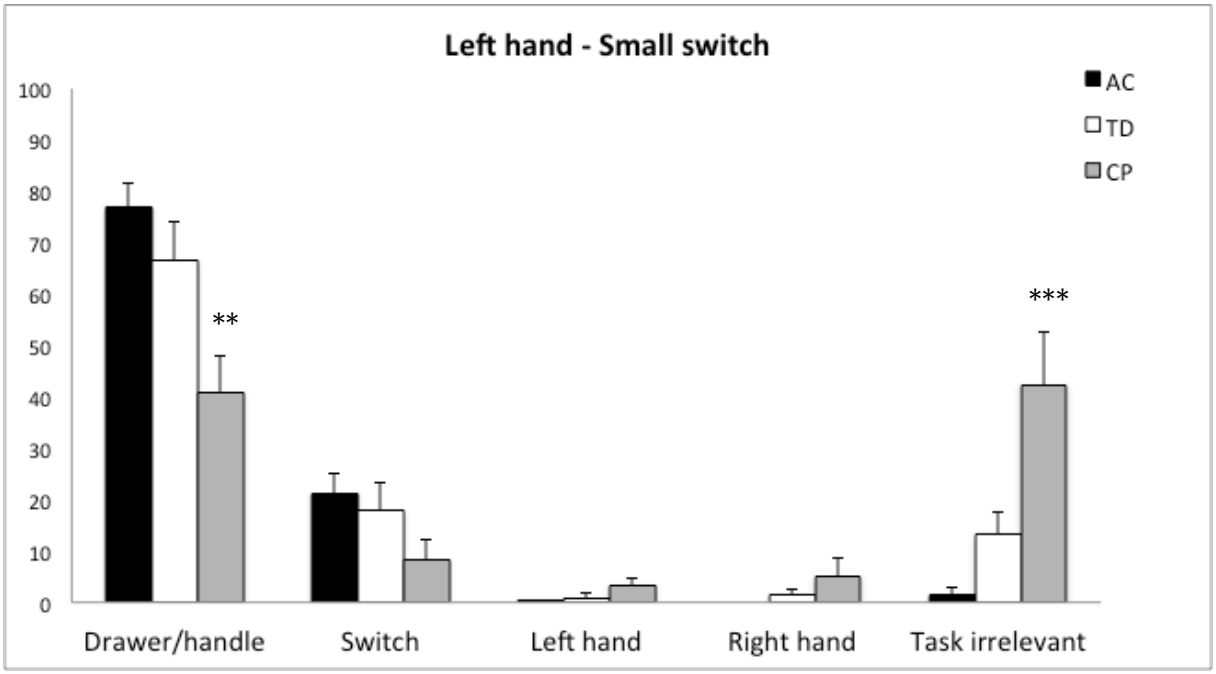



**Figure 5. Results drawer task.** Condition (3): drawer hand: left; task hand: right; switch: small. Bars show percentage fixated on the different variables shown on the X-axis. Error bars show standard error. Black bars: adult control (n=10). White bars: typically developing children (n=10). Grey bars: children with CP (n=11). Asterisks on top of bars indicate significance (*p<0.05; **p<0.01; ***p<0.001). CP children (M 40.67, SD 24.57) fixated less on the drawer/handle than both AC (M 76.95, SD 14.23) and TD children (M 66.50, SD 23.99) (F (2, 28) = 7.93, p = 0.002). CP children (M 42.41, SD 33.41) showed more task irrelevant gazes than both AC (M 1.45, SD 4.56) and TD (M 13.18, SD 13.85) (F (2, 28) = 3.64, p = 0.039).

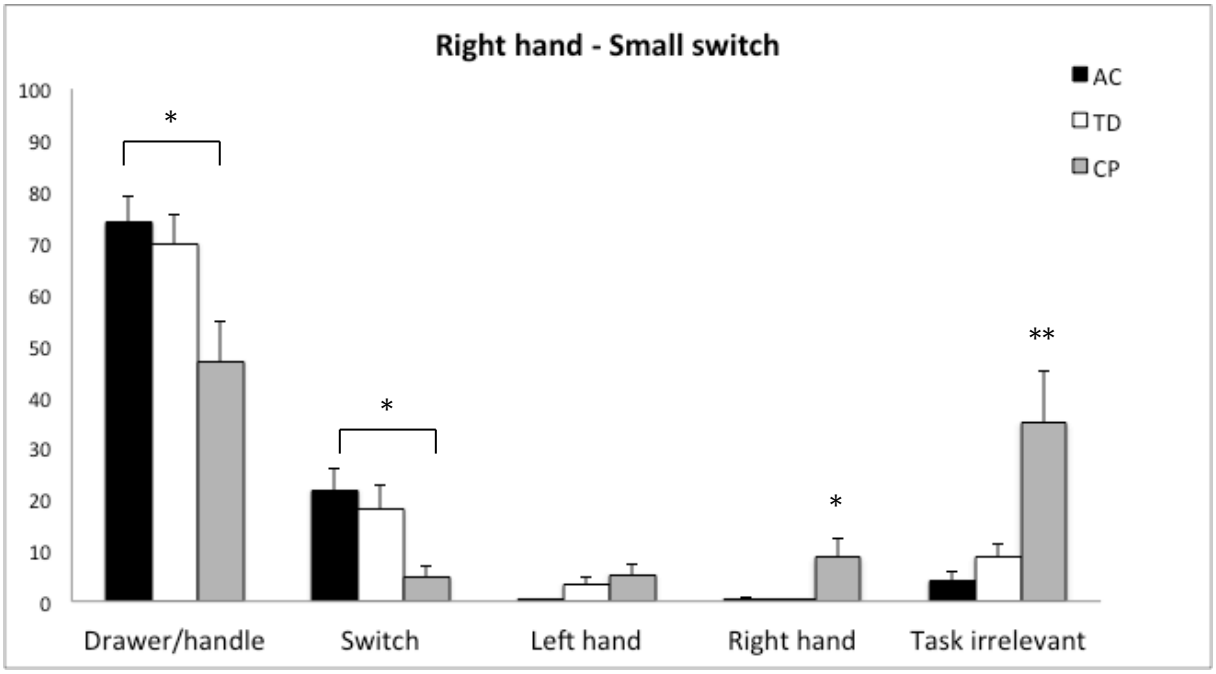



**Figure 6. Results drawer task.** Condition (4): drawer hand: right; task hand: left; switch: small. Bars show percentage fixated on the different variables shown on the X-axis. Error bars show standard error. Black bars: adult control (n=10). White bars: typically developing children (n=10). Grey bars: children with CP (n=10). Asterisks on top of bars indicate significance (*p<0.05; **p<0.01; ***p<0.001). Compared to AC (M 73.87, SD 16.53) children with CP (M 46.83, SD 24.87) fixated less on the drawer/handle (F (2, 27) = 5.24, p = 0.012) and on the switch (AC: M21.65, SD 13.78) (CP: M 4.69, SD 6.50) (F (2, 27) = 5.39, p = 0.011). CP children (M 8.55, SD 12.19) showed more fixation on the right hand than both AC (M 0.32, SD 1.01) and TD (M 0.28, SD 0.89) (F (2, 27) = 4.52, p = 0.020). For nine of the ten children the right hand is the involved/affected hand. Also, CP children (M 34.79, SD 32.05) showed more task irrelevant gazes than both AC (M 3.98, SD 5.64) and TD (M 8.59, SD 8.01) (F (2, 27) = 7.38, p = 0.003).

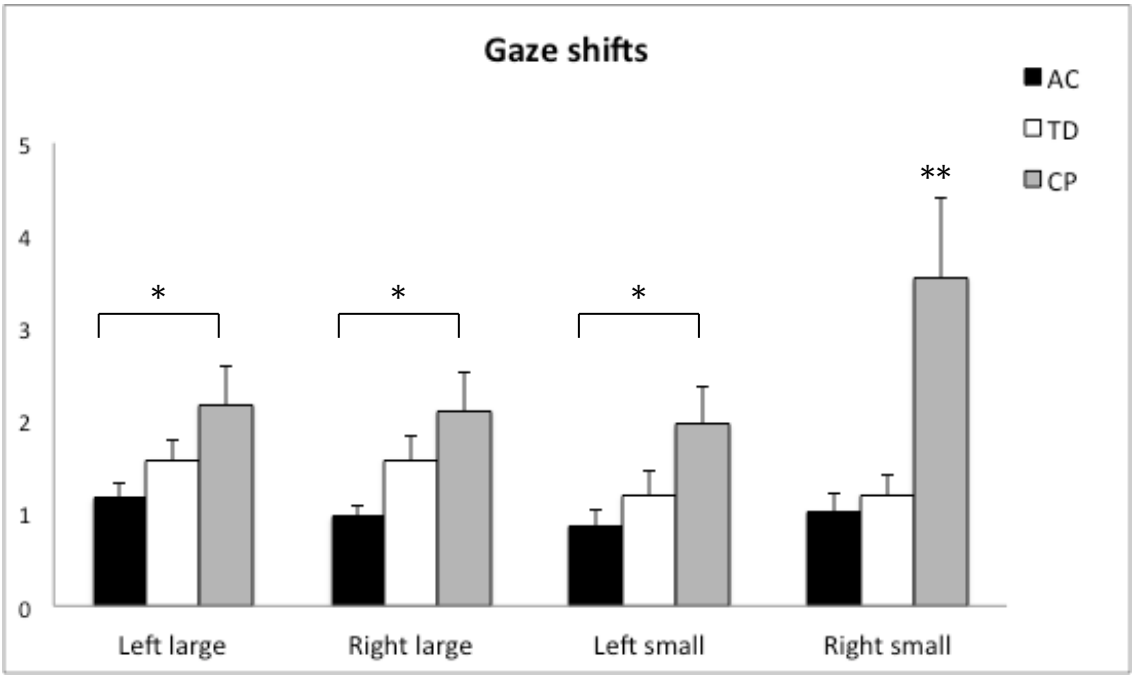



**Figure 7 Number of gaze shifts in drawer task.** Bars show average amount of gaze shifts made in every condition (shown on x-axis). Error bars show standard error. Black bars: adult control (n=10). White bars: typically developing children (n=10). Grey bars: children with CP (n=9). Asterisks on top of bars indicate significance (*p<0.05; **p<0.01; ***p<0.001). In all four conditions, children with CP exhibited more gaze shifts than adult control participants (left-large: F (2, 26) = 3.40, p = 0.049; right-large: F (2, 26) = 4.01, p = 0.030; left-small: F (2, 28) = 3.64, p = 0.039; right-small: F (2, 27) = 7.00, p = 0.004). Compared to TD children, the children with CP exhibited more gaze shifts only in the right-small condition (F (2, 27) = 7.00, p = 0.004).

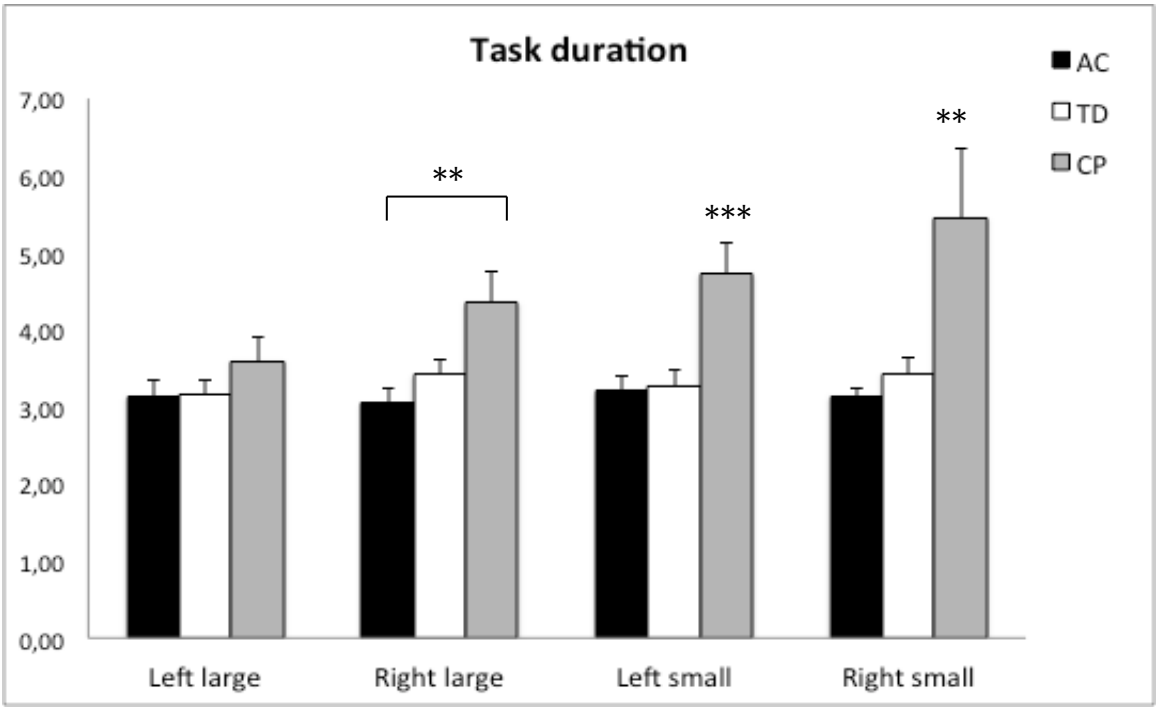



**Figure 8. Task duration drawer task.** Bars show average task duration in seconds per condition (shown on x-axis). Error bars show standard error. Black bars: adult control (n=10). White bars: typically developing children (n=10). Grey bars: children with CP (n=11). Asterisks on top of bars indicate significance (*p<0.05; **p<0.01; ***p<0.001). Compared to adult controls (M 3.05, SD 0.48), children with CP (M 4.35, SD 1.15) needed more time in the right large condition (F (2, 26) = 6.61, p = 0.005). For both conditions with small switches, children CP (left: M 4.73, SD 1.26; right: M 5.45, SD 2.83) were slower than both adult controls (left: M 3.20, SD 0.59; right: M 3.13, SD 0.47) and TD children (left: M 3.28, SD 0.53; right: M 3.43, SD 0.52) (left: F (2,28) = 10.24, p =<0.001); right: F (2,27) = 5.59, p = 0.009).

## Task 2: Tray task

Results from the tray task are depicted in figures 9-14. Again, the most striking result is that compared to both control groups, children with CP show significantly more task irrelevant gazes in all four conditions (large: F (2,27) = 15.67, p =<0.001; small: F (2, 25) = 13.89, p =<0.001; large water: F (2,24) = 12.52, p =<0.001; small water: F (2, 25) = 10.71, p =<0.001).

Again, although not as clear as in the drawer task, children with CP exhibited more gaze shifts than adult control participants (large: F (2, 27) = 5.34, p = 0.011; small: F (2, 25) = 3.10, p = 0.063; large water: F (2, 24) = 3.07, p =0.065; small water: F (2, 25) = 4.37, p = 0.024). The number of gaze shifts per condition is shown in Figure 13.

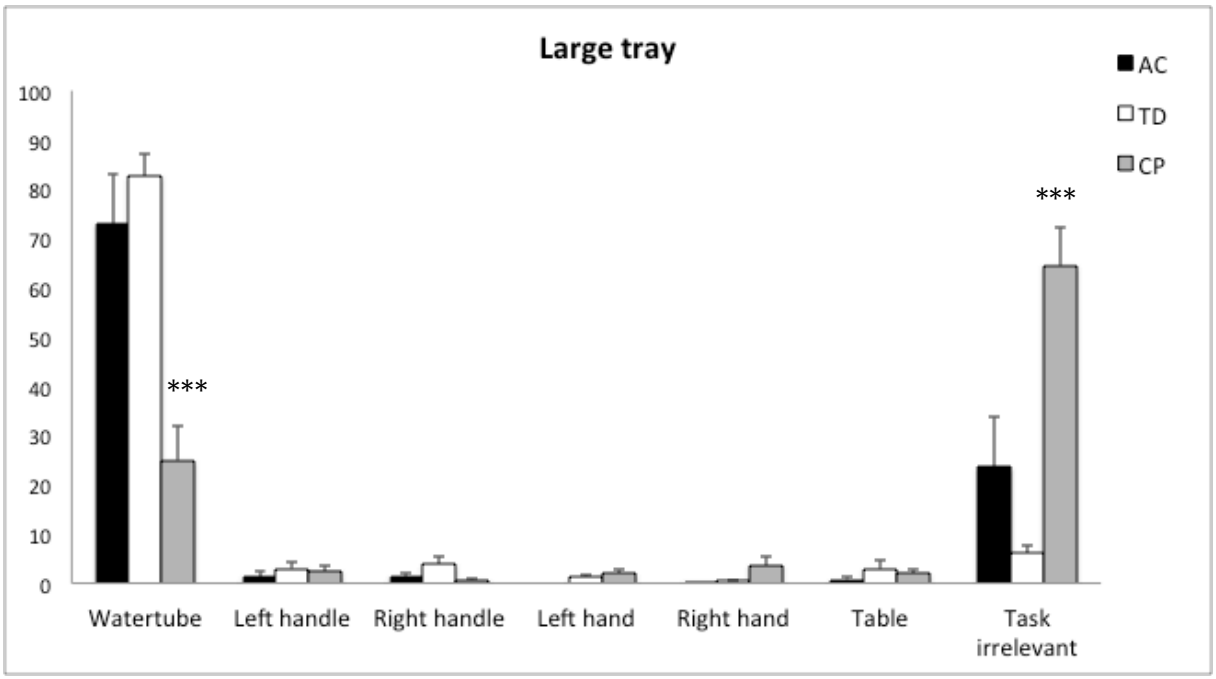



**Figure 9. Results tray task.** Condition (1): handle size: large, water tube: covered. Bars show percentage fixated on the different variables shown on the X-axis. Error bars show standard error. Black bars: adult control (n=10). White bars: typically developing children (n=10). Grey bars: children with CP (n=11). Asterisks on top of bars indicate significance (*p<0.05; **p<0.01; ***p<0.001). Compared to both AC (M 73.00, SD 31.43) and TD (M 82.69, SD 13.75), children with CP (M 24.95, SD 23.12) fixated less on the water tube (F (2, 27) = 16.93, p =<0.001). Children with CP (M 64.47 , SD 25.31) showed more task irrelevant gazes than both AC (M 23.56, SD 31.96) and TD (M 5.98, SD 5.26) (F (2,27) = 15.67, p =<0.001).

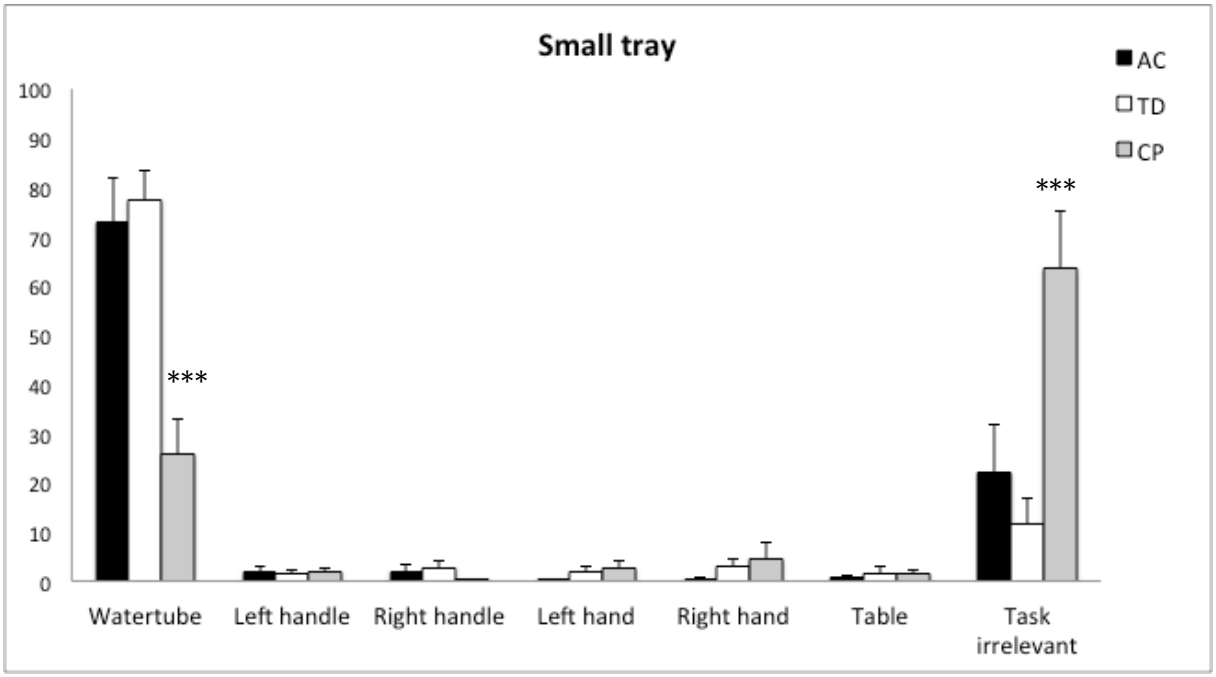



**Figure 10. Results tray task.** Condition (2): handle size: small, water tube: covered. Bars show percentage fixated on the different variables shown on the X-axis. Error bars show standard error. Black bars: adult control (n=9). White bars: typically developing children (n=10). Grey bars: children with CP (n=10). Asterisks on top of bars indicate significance (*p<0.05; **p<0.01; ***p<0.001). Compared to both AC (M 73.00, SD 27.23) and TD (M 77.53, SD 17.83), children with CP (M 25.90, SD 22.03) fixated less on the water tube (F (2, 25) = 15.34, p =<0.001). Children with CP (M 63.45, SD 21.73) showed more task irrelevant gazes than both AC (M 22.11, SD 29.08) and TD (M 11.67, SD 15.69) (F (2, 25) = 13.89, p =<0.001).

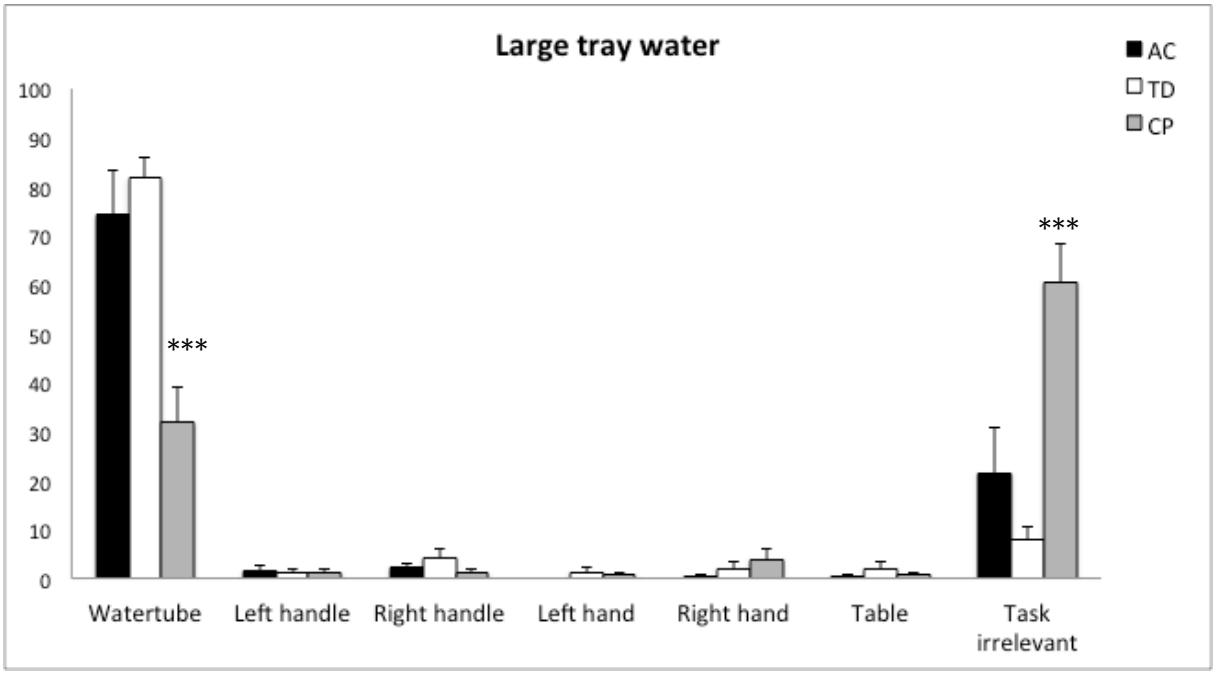



**Figure 11. Results tray task.** Condition (3): handle size: large, water tube: open. Bars show percentage fixated on the different variables shown on the X-axis. Error bars show standard error. Black bars: adult control (n=10). White bars: typically developing children (n=10). Grey bars: children with CP (n=8). Asterisks on top of bars indicate significance (*p<0.05; **p<0.01; ***p<0.001). Compared to both AC (M 74.17, SD 29.09) and TD (M 81.73, SD 12.45), children with CP (M 31.81, SD 20.09) fixated less on the water tube (F (2, 24) = 12.48, p =<0.001). Children with CP (M 60.60, SD 22.29) showed more task irrelevant gazes than both AC (M 21.40, SD 30.05) and TD (M 7.73, SD 7.88) (F (2, 24) = 3.07, p =0.065).

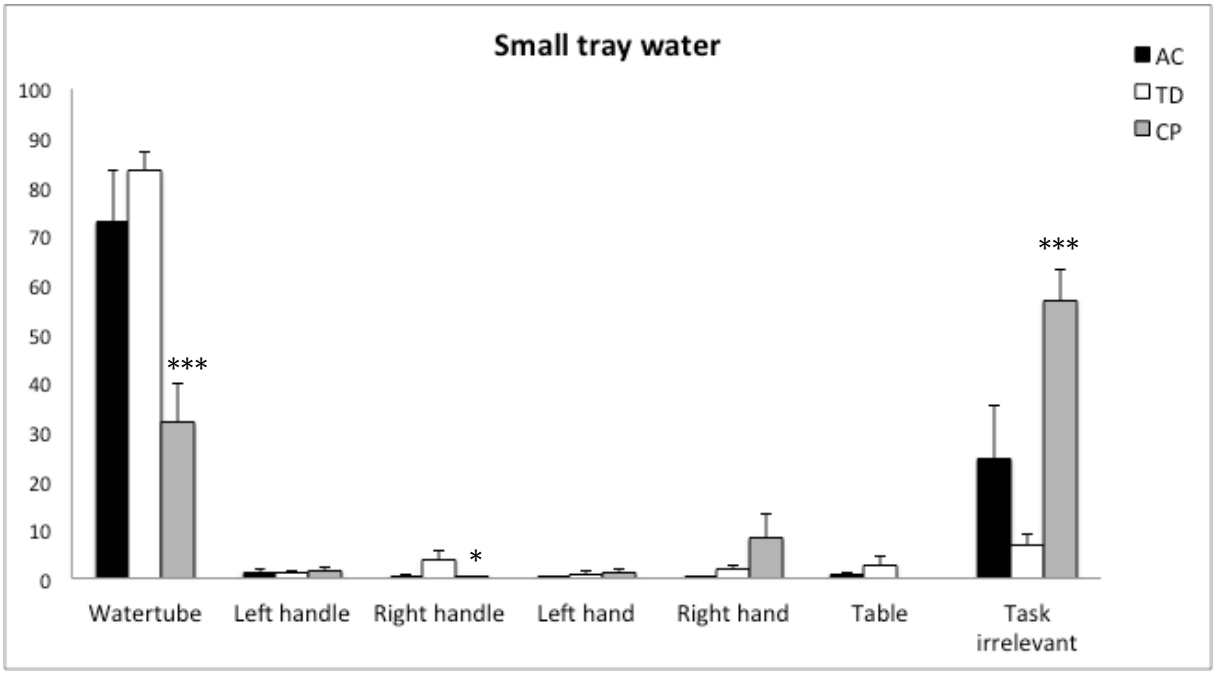



**Figure 12. Results tray task.** Condition (4): handle size: small, water tube: open. Bars show percentage fixated on the different variables shown on the X-axis. Error bars show standard error. Black bars: adult control (n=10). White bars: typically developing children (n=10). Grey bars: children with CP (n=9). Asterisks on top of bars indicate significance (*p<0.05; **p<0.01; ***p<0.001). Compared to both AC (M 72.82, SD 32.79) and TD (M 83.27, SD 11.51), children with CP (M 32.09, SD 22.89) fixated less on the water tube (F (2, 25) = 11.10, p =<0.001). Children with CP (M 56.72 , SD 19.24) showed more task irrelevant gazes than both AC (M 24.50, SD 30.74) and TD (M 6.63, SD 6.70) (F (2, 25) = 10.71, p =<0.001).

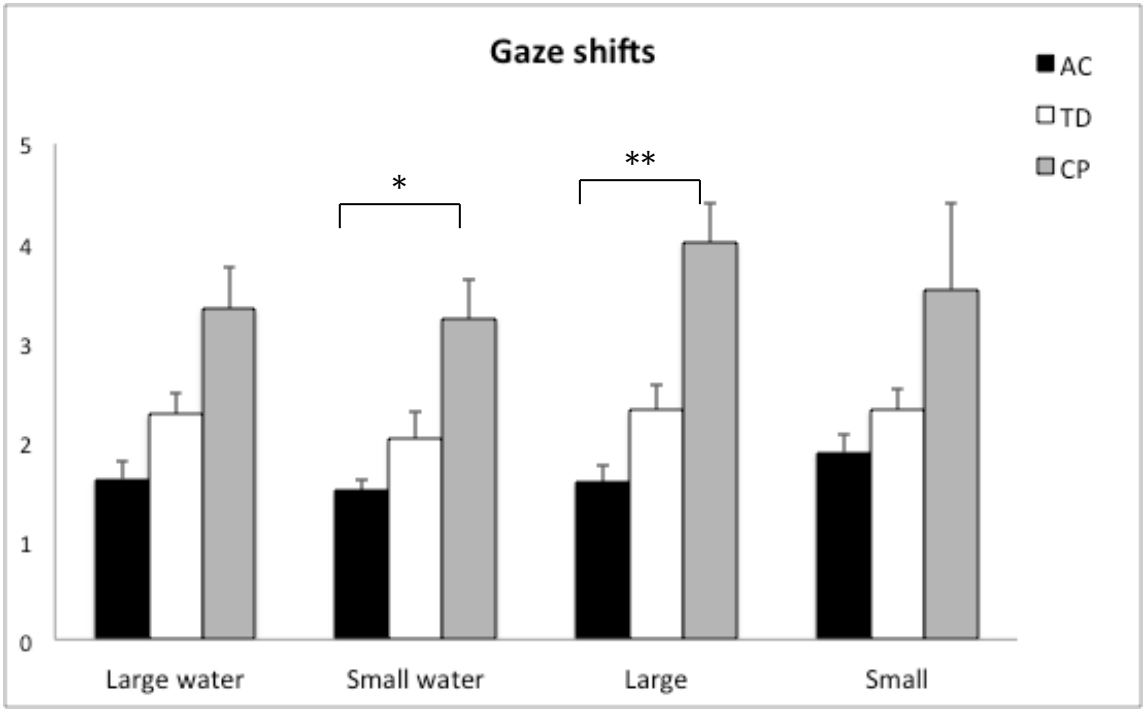



**Figure 13. Number of gaze shifts in tray task.** Bars show average amount of gaze shifts made in every condition (shown on x-axis). Error bars show standard error. Black bars: adult control (n=10). White bars: typically developing children (n=9). Grey bars: children with CP (n=10). Asterisks on top of bars indicate significance (*p<0.05; **p<0.01; ***p<0.001). Children with CP exhibited more gaze shifts than adult control participants in the large condition (F (2, 27) = 5.34, p = 0.011) and the small water condition (F (2, 25) = 4.37, p = 0.024)

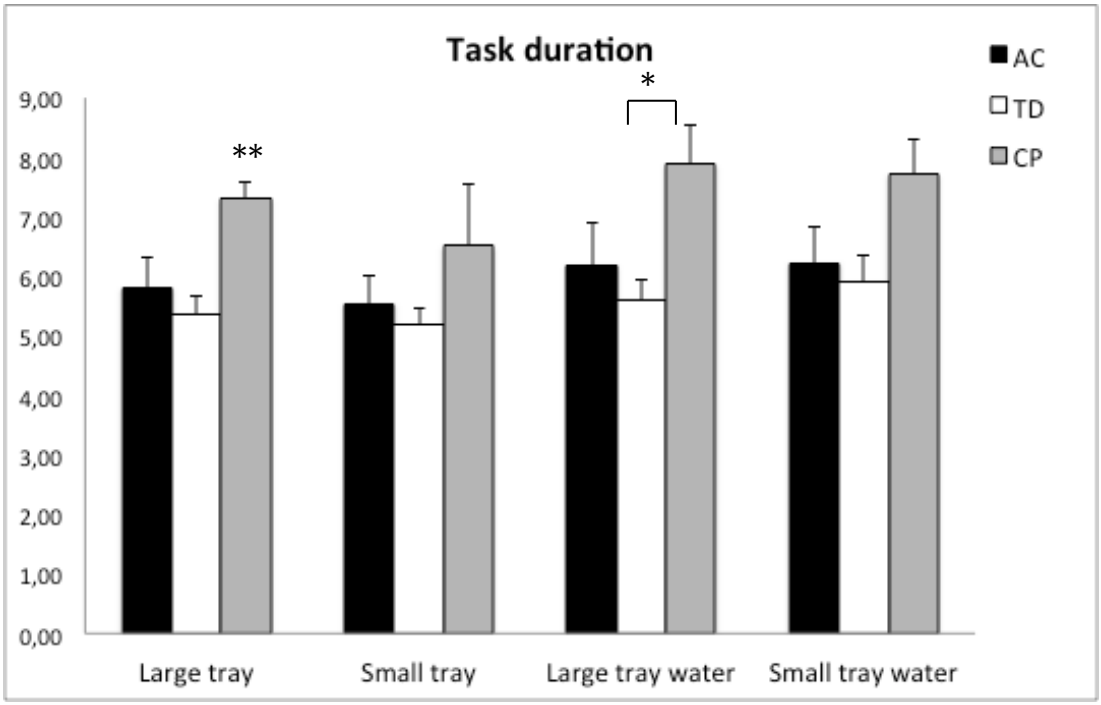



**Figure 14. Task duration tray task.** Bars show average task duration in seconds per condition (shown on x-axis). Error bars show standard error. Black bars: adult control (n=10). White bars: typically developing children (n=10). Grey bars: children with CP (n=11). Asterisks on top of bars indicate significance (*p<0.05; **p<0.01; ***p<0.001). Compared to both AC (M 5.81, SD 1.64) and TD (M 5.35, SD 0.99), children with CP (M 7.30, SD 0.92) were slower in the large (no water) condition (F (2, 27) = 7.05, p = 0.003). In the large water condition, children with CP (M 7.89, SD 1.89) needed more time than TD children (M 5.60, SD 0.99) (F (2, 24) = 3.71, p = 0.039).

## Vision test

Results of the vision tests can be seen in Appendix 1. The vision test revealed no clear visual field defect in any of the participants. It must be noticed that all the children had difficulties staying focused during the test. Test results therefore may not be very reliable.

## General observations

The children with CP had more difficulties performing the task, indicated by longer task durations in both tasks (Figure 8 and 14). For the drawer task especially the conditions with right hand as drawer hand and the condition with the small switch (if right hand is task hand) seem to be harder (right-large: F (2, 26) = 6.61, p = 0.005; left-small: F (2, 28) = 10.24, p =<0.001; right-small: F (2, 27) = 5.59, p = 0.009). For the tray task the conditions with the large handles appeared to be harder due to difficulties with grasping the handle with the affected hand (large: F (2, 27) = 7.05, p = 0.003; large water: F (2, 24) = 3.71, p = 0.039).

Another observation was that children with CP made many more head movements. If movement started with the non-affected hand, the head was turned to the affected side. Hereby the non-involved hand remained out of the visual field of the subject. Although gaze was not per se directed to the involved hand, most of the time the visual field only included the involved hand. This type of movement was not seen in the control subjects. In the control subjects both hands remained in the visual field during the whole task.

## Discussion

The primary purpose of this study was to compare hand-eye coordination during goal-directed bimanual tasks of children with CP with that of age-matched typically developing children and healthy adults. The most striking finding is that compared to both adult controls and typically developing (TD) children, children with CP showed a higher percentage of task irrelevant fixations and a larger number of gaze shifts. Besides, children with CP experienced more difficulty performing the tasks, indicated by longer task durations.

### *Children with CP exhibit more task irrelevant fixations*

Compared to the TD children, children with CP exhibited more task irrelevant fixations. This contrasts with the behaviour of the control subjects. In line with previous research (Land & Hayhoe, 2001), control subjects directed gaze almost exclusively to the objects involved in the task and hardly ever fixated on their hands. The behaviour of the children with CP might be explained the fact that many of them have attentional impairments (Bax et al., 2005).

Furthermore, children with CP show more gaze shifts than control subjects, which can also be indicative for attentional impairments.

### *Children with CP fixate more on their affected hand*

Based on previous research by Steenbergen and Van der Kamp (2004) where they concluded that children with CP rely more on visual guidance of the moving hand during upper limb movements, I hypothesized that the children with CP would show more hand-directed fixations than controls. Although less than expected, children with CP showed more fixations directed to their affected hand. This was especially the case in the more difficult conditions (difficulty inferred from a longer task duration). This suggests that in easy tasks proprioceptive information is presumably adequate, but that this might not be the case in more difficult tasks.

### *Gaze-behaviour of CP children is not adapted based on hand use*

Contrary to the findings of Verrel et al. (2008), who concluded that individuals with CP adapted their eye movements when using the affected hand compared to the unaffected hand, we did not find different eye-movement behaviour depending on whether the affected or non-affected hand opened the drawer. A possible explanation is that in the study of Verrel et al. (2008) participants had to perform a unimanual task, whereas in the current study I tested bimanual performance. Possibly visual focus is more hand-directed if the task is only performed with one hand.

### *Children with CP make more head movements*

Compared to controls, children with CP made many more head movements. My observations for the children with CP were as follows: if the movement started with the non-affected hand, the head was turned towards the affected side. Consequently, the non-involved hand remained out of the visual field of the subject. Although gaze was not per se directed towards the involved hand, most of the time the visual field presumably only included the involved hand. This type of head movement was not seen in the control subjects. In the control subjects both hands remained in the visual field during the whole task.

Increased head movements in children with CP have been noticed in previous studies examining eye movement (e.g. Good et al., 2001). The observed head movements might be explained in several ways:

First, Saavadra et al. (2009), argue that increased head movements of children with CP during object reaching may be related to an inability to separate eye movements from head movements.

Second, Good et al. (2001), found that children with CVI often use peripheral vision to search for objects. They may turn their head before reaching for an object, thereby turning the head away from the side of vision loss. This might explain why the subjects from the current study turn their head towards the right side of the tray when reaching for the right handle.

Moreover Good et al. (2001) found that often these children bring objects closer to their eyes to magnify the object of interest. Since grasping of the right handle was more difficult for the children with CP, this feature of the task was more of interest than

the other features. Thus, by turning their head towards the right side of the task, they magnified the object of interest.

### *Head movements of children with CP might be indicative of hemianopia or hemineglect*

Although the vision tests in the current study did not reveal a presence of hemianopia in any of the subjects, the head movements might – nevertheless - be taken as an indication for the presence of a hemianopia or hemineglect (i.e. unilateral visual inattention). Similar to the motor impairment, a possible hemianopia or hemineglect would also occur contralateral to the damaged hemisphere. Therefore the affected side of the body would fall outside the intact visual field. A head movement towards the affected side would move the intact visual field such that the affected side of the body becomes visible again. Therefore, the observed head movements might be a compensatory mechanism (CM) for the children with CP.

### *Implications for therapy*

Although CI therapy and HABIT are proven to be efficacious in improving bimanual hand use (Dong et al., 2013; Gordon et al., 2007; Gordon et al., 2011), I believe current therapies can be expanded and improved upon by combining bimanual therapy with visual therapy. My findings suggest that children with CP not only use compensatory motor mechanisms to perform bimanual tasks, also visual coordination is different compared to typically developing children and healthy adults. I argue that these findings should be taken into account in the development of future therapies.

### *Limitations*

*Excessive head-movements*: Sometimes the videos were hard to analyze since many of the children moved their head a lot. Sometimes this even caused the cables to uncouple from the glasses. I think it is important to not try to reduce the amount of head movements, since this might also be part of the strategy children with CP use to perform a certain task. Therefore an eye-tracker with built-in head tracking seems to be most suitable for this kind of research. Furthermore, Saavati et al. (2009) argue that if eye and

head movements are indeed coupled, eye motility may be misjudged in previous studies that examined hand-eye coordination while fixating the head. For future research I strongly recommend using an eye-tracker combined with a head-motion tracker.

*Calibration difficulties:* When calibrating the hands and the task were clearly visible within the participants' field of view (recorded with the scene camera), but when performing the task some children bended over causing the hands to fall outside the field of view.

*Limited range of task difficulties:* Since hand-guided eye movements only seemed to occur in the more difficult conditions, I suggest designing an experiment with more variation in difficulty.

*Limited visual field assessment:* future research should include comprehensive visual field testing to investigate the differences between hand-eye coordination of children with CP with and without CVI. Unfortunately the test used in this experiment does not seem reliable, therefore it cannot be concluded whether children with CP had CVI or not. Thus, I cannot conclude whether bimanual performance of the children with CP depends on the presence of visual field defects.

### *Suggestions for future research*

In my opinion it is important to expand the current research to a more natural environment in which children have to perform bimanual activities they encounter in daily life. In a natural environment the actual strategies children with CP use can be observed. Moreover, an experimental setting can distract children and influence task performance.

To further investigate the head movements observed in children with CP it would be interesting to test activities that require head movements in healthy controls as well.

For now only the effect of visual impairment on motor performance is assessed. To investigate whether children with CP would benefit from visual therapy I suggest future research should include a task with changing visual task features. This allows to test whether bimanual performance can be manipulated by changing the visual input.

## Conclusion

Visuomotor research in cerebral palsy is still very scarce. Consequently, the current study was mainly explorative in nature. My findings suggest that children with CP not only use compensatory motor mechanisms to perform bimanual tasks, also visual coordination is different compared to typically developing children and healthy adults. I believe these results are relevant and thus argue that future research is necessary. Furthermore, these findings should also be taken into account in the development of future therapies.

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**Disclosure**

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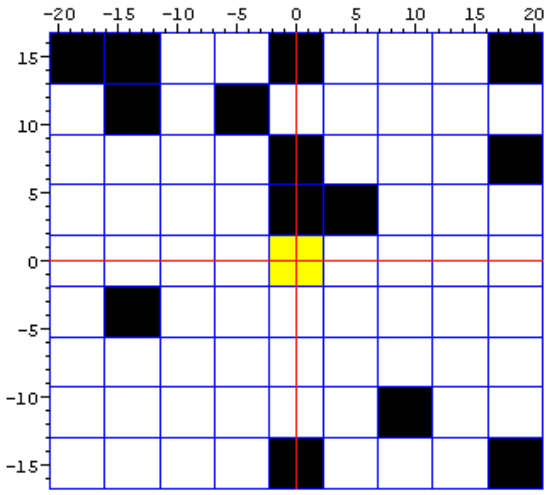
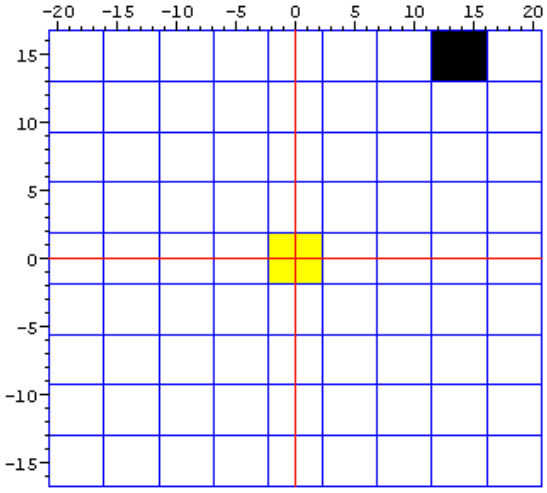
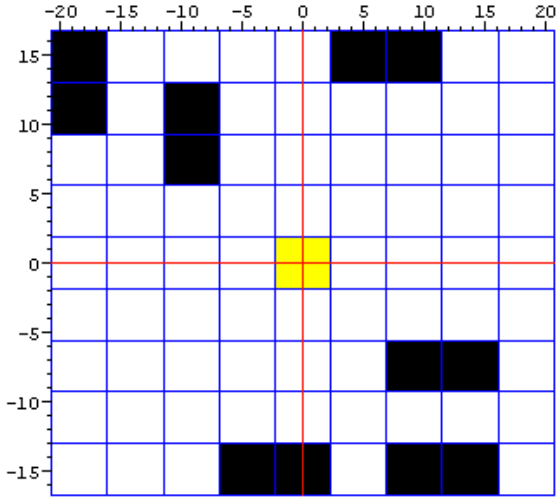
# Appendix 1: Results vision test



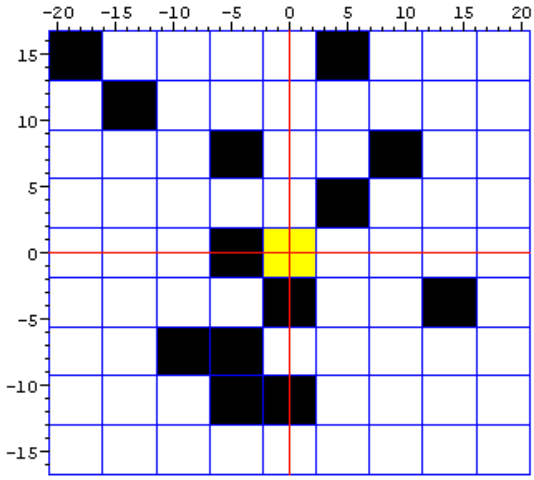

Vision test 1: CP062



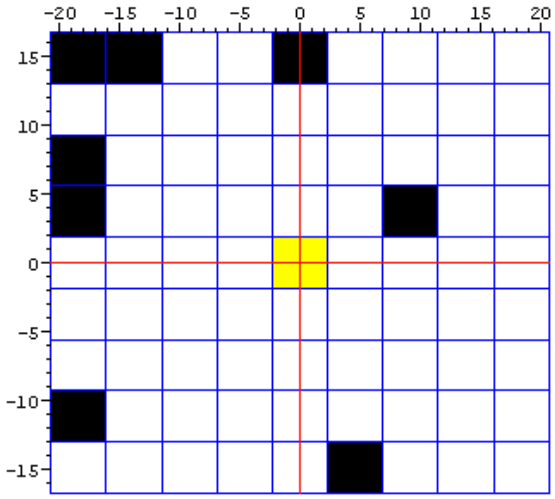

Vision test 2: CP069



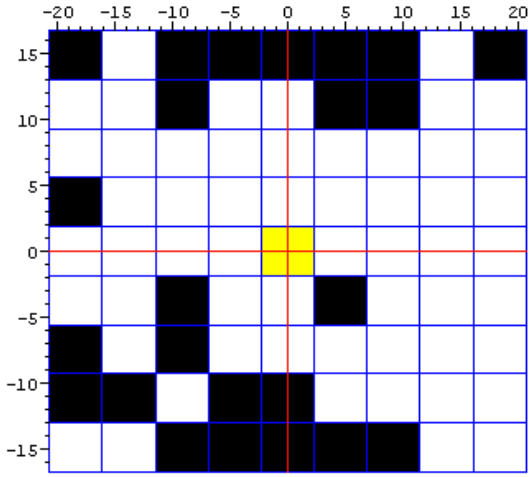

Vision test 3: CP063



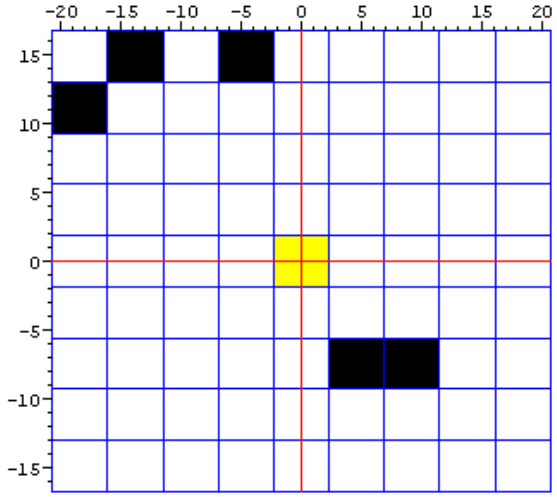

Vision test 4: CP065



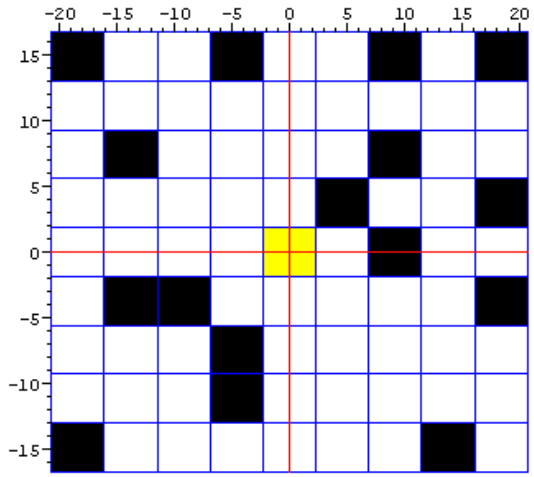

Vision test 5: CP061




Vision test 6: CP012b




Vision test 7: CP059




Vision test 8: CP060

# Appendix 2: How to use Pupil Pro

## Pupil Pro – Run from source (Python)

Since Mac OSx currently doesn't support binocular Pupil Pro, you need to run Linux Ubuntu alongside Macintosh in order to use it (otherwise you only record one camera instead of three).

### Install Linux Ubuntu on SD card

The safest way to install Ubuntu is to copy it on a SD card. The SD card should be **class 10** and needs to have **at least 16 GB**.

1. Download pupil_ubuntu_14.04.dmg from:
   https://drive.google.com/folderview?id=0Byap58sXjMVfU1ZiNkpfdDNSM28&usp=sharing
   a. Copy the file to your desktop.
2. Insert SD-card (NB: all contents will be erased!!)
3. Open terminal
4. Run: `diskutil list` to find out the name of the SD-card.

```
/dev/disk0
   #:                       TYPE NAME                    SIZE       IDENTIFIER
   0:      GUID_partition_scheme                        *500.1 GB   disk0
   1:                        EFI EFI                     209.7 MB   disk0s1
   2:          Apple_CoreStorage                         499.2 GB   disk0s2
   3:                 Apple_Boot Recovery HD             650.0 MB   disk0s3
/dev/disk1
   #:                       TYPE NAME                    SIZE       IDENTIFIER
   0:                  Apple_HFS Macintosh HD           *498.9 GB   disk1
                                 Logical Volume on disk0s2
                                 4292190A-BB74-4352-91D1-444838536451
                                 Unlocked Encrypted
/dev/disk2
   #:                       TYPE NAME                    SIZE       IDENTIFIER
   0:      GUID_partition_scheme                        *32.2 GB    disk2
   1:                        EFI EFI                     209.7 MB   disk2s1
   2:                  Apple_HFS PUPIL                   31.9 GB    disk2s2
```

(In this case, it is disk2).

5. Format the SD card; in terminal run: `sudo newfs_msdos -F 16 /dev/rdisk2`
   (!: make sure you type the correct name of the SD card at the end of the code)

*If terminal asks: 'Password', type in the password of your Mac.*

6. Unmount and write image:
   `diskutil unmountDisk /dev/disk2`
   `sudo dd if=~/Desktop/pupil_ubuntu_14.04.dmg of=/dev/rdisk2 bs=5m`
   ** Wait until done, this can take a few minutes**

## Booting from Linux

1. Insert the SD card into the computer you want to load Ubuntu with.
2. (Re)start your Mac while holding `alt`
3. You will be presented with a selection of boot options ***If not: follow the steps from the next paragraph: [No boot selections]! ***. Choose the one with the USB logo (might say Windows but it will boot into Ubuntu).
4. If asked for a user password it is: pupil_pupil

### *No boot selections*

1. If you are not presented with a selection of boot options, do the following:
2. Go to: http://refit.sourceforge.net
3. Download rEFIt 0.14 (Mac disk image)
4. Double click to unpack
5. Copy the 'efi' folder to the root level of your Mac OS X volume (Finder, Documents, Command–Up Arrow)
6. Open terminal:
   a. `cd /efi/refit`
   b. `./enable.sh`
7. Download refind-bin-0.8.4.zip from http://sourceforge.net/projects/refind/files/0.8.4/
8. Copy refind-bin-0.8.4 folder to efi folder
9. Remove refit folder from efi
10. Terminal:
    a. `cd /efi/refind-0.8.4.`
    b. `sudo ./install.sh`
11. Reboot: hold `alt`: You are now presented boot selections.

*** If it is still not possible to reboot from SD: install Ubuntu on a USB stick ***

## Getting access to the Internet

Ok, now you are booting from Linux, since we want to run Pupil Pro from source, we need to install some dependencies. But first we need to get access to the Internet.

1. Go to: System > Properties > Network Connections
2. Select Wireless > Add

3. Fill in the following fields:
    a. <Tab: Wireless>
    b. Connection name: **eduroam**
    c. SSID: **eduroam**
    d. Select: connect automatically
    e. <Tab: Wireless Security>
    f. Security: Select **WPA & WPA2 Enterprise**
    g. Authentication: Select **Protected EAP (PEAP)**
    h. CA Certificate: **AddTrust External Root (etc, SSL)**
    i. Inner authentication: Select **MSCHAPv2**
    j. Username: **p**123456**@rug.nl** or **s**123456@rug.nl
    k. Password: Your central RUG password
    l. **Apply > Close**

### *If eduroam doesn't connect directly*

1. Download the b43updated.zip file to a USB flash drive, then drag and drop the file to your Ubuntu desktop.
2. Right-click it and select Extract here.
3. Open the terminal and type:

```
sudo mkdir /lib/firmware/b43
sudo cp Desktop/b43_updated.zip/*  /lib/firmware/b43
sudo modprobe -rv b43
sudo modprobe -v b43
```

## Install dependencies

Open the terminal and copy the following commands:

```
sudo apt-get install python-opengl mesa-common-dev libglu1-mesa-dev
git python-setuptools libv4l-dev v4l-utils cmake python-zmq python-
dev python-pip libav-tools python-opencv python-scipy build-
essential libglew-dev nasm libavformat-dev libavcodec-dev
libavdevice-dev libavutil-dev libswscale-dev libavresample-dev pkg-
config
```

If terminal asks for update: `sudo apt-get update`
Copy previous commands again in the terminal to make sure every step is executed.

```
wget -O libjpeg-turbo-1.3.90.tar.gz
http://sourceforge.net/projects/libjpeg-
turbo/files/1.3.90%20%281.4%20beta1%29/libjpeg-turbo-
1.3.90.tar.gz/download
tar xvzf libjpeg-turbo-1.3.90.tar.gz
cd libjpeg-turbo-1.3.90
./configure --with-pic
```

```
sudo make install

sudo pip install numexpr
sudo pip install cython
sudo pip install psutil
sudo pip install av

sudo apt-get install libxrandr-dev libxi-dev libxcursor-dev
libxxf86vm-dev libxinerama-dev
cd ~/
git clone http://github.com/glfw/glfw
cd glfw/
git checkout tags/3.0.4
cmake -G "Unix Makefiles"  -DBUILD_SHARED_LIBS=TRUE
sudo make install
sudo ln -s /usr/local/lib/libglfw.so.3 /usr/lib/libglfw.so.3
cd ../
sudo rm -r glfw

cd ~/
git clone http://github.com/pupil-labs/pyv4l2
cd pyv4l2
sudo python setup.py install

cd ~/
git clone http://github.com/pupil-labs/pyglui --recursive
cd pyglui
sudo python setup.py install
```

### Download and run Pupil Source Code

1. Create a folder named Pupil (or whatever you like) in Documents (or whatever directory)
2. Open the terminal:

```
cd /<Pupil (enter full pathname here)>/
git clone https://github.com/pupil-labs/pupil.git
```

### Run Pupil Capture from source

Open the terminal:

1. `pupil_capture (for monocular use)`
2. `pupil_capture binocular (for binocular use)`

B43

```
sudo mkdir /lib/firmware/b43
sudo cp Desktop/b43_new/*  /lib/firmware/b43
sudo modprobe -r b43 && sudo modprobe b43
```

### Run Pupil Capture via the bundle (now binocular supported on MacOS)

Install latest bundle via Pupil Github

Open terminal:

```
cd /Applications/Pupil\ Capture.app/Contents/MacOS/
./pupil_capture binocular
```