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Cognitive and motor aspects of a coincidence-timing task in Cerebral Palsy children

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Abstract

Cerebral Palsy (CP) is a clinical syndrome characterized by anoxia of the immature brain of the foetus or children before two years of age and involving postural and motor deficits. CP children are less accurate than healthy ones when trying to accurately reach a target and have specific problems for mapping visual inputs about the target and proprioceptive feedback to control their arm movements (Smyth et Mason, 1998).

Considering these deficits, it is difficult for CP children to perform anticipation-coincidence tasks requiring temporal and/or spatial accuracy and the ability to appropriately take into account own motor capacities to reach the target at the good place in the right time.

The purpose of the present experiment was to further investigate CP children ability to perform anticipation-coincidence tasks, by dissociating the cognitive and motor aspects of the task. 15 CP children aged 6 to 14 years, 51 healthy children aged 6 to 13 years, and 13 healthy adults participated to the experiment.

Participants' task was to perform, as accurately as possible, a coincidence-timing in response to a specific sound of a musical sequence, in two different conditions. In the verbal condition, temporal estimation occurred through a simple verbal response whereas in the motor condition, temporal estimation was performed by reaching a target at a self-paced velocity.

In the verbal condition, CP children made similar temporal errors than their healthy counterpart. However, even though all participants underestimated stimulus occurrence, CP children also exhibited greater and more variable temporal errors when they provided a motor response for estimating stimulus occurrence. These data suggested that CP children were able to anticipate stimulus occurrence and to partially take into account their sensory-motor deficits to reach the target at this time occurrence.

Introduction

Cerebral palsy (CP) is a clinical syndrome characterized by anoxia of the immature brain of the foetus or children before two years of age (prenatal or perinatal period) inducing postural and motor deficits. It concerns approximately 2.5‰ of births in the world (Kriger, 2006). The identified postural and motor troubles (Van der Heide, Fock, Otten, Stremmelaar, & Hadders-Algra, 2005) are frequently associated to sensory, cognitive, and musculo-skeletal deficits (Bax et al., 2005) and result in muscular spasticity (Albright, 1996), dystonia (Kyllerman et al., 1982) and hypotonic behaviour.

Previous data showed that CP children were less accurate than healthy ones when trying to accurately reach a target (Van Thiel & Steenbergen, 2001). More specifically, the much increased spatial errors observed when using proprioception only (Smyth & Mason, 1998) suggested that CP children have some problems for mapping visual inputs about target localization and proprioceptive feedback to control their arm movements. Moreover, CP children seem to mainly use visual feedback for controlling reaching movements (Wann, 1991). CP children also report a proportion of hearing loss ranging from 4 to 13% (Reid, Modak, Berkovitz, & Redibrough, 2011).

Considering these deficits, it becomes difficult for CP children to appropriately perform anticipation-coincidence tasks requiring temporal and/or spatial accuracy both for the perception of visual inputs related to the target to reach and for the control of their arm (Brouwer, Brenner, & Smeets, 2002; Brouwer, Middelburg, Smeets, & Brenner, 2003; Eggert, Rivas, & Straube, 2005; Lee, Port, & Georgopoulos, 1997; Mrotek, & Soechting, 2007; Port, Lee, Dassonville, & Georgopoulos, 1997). Indeed, these tasks require both a good spatio-temporal estimation of the occurring event and the ability to appropriately take into account one's motor capacities to reach the target at the good place in the right time. In other

words, initiation of the motor response needs to be specified as a function of the estimated movement time necessary to perform the interception.

One frequent paradigm to investigate coincidence-timing performance is the occlusion paradigm in which a real or simulated object is presented during a short time and then masked during a variable period of time until interception (Lee, 1976; Savelsbergh, 1991).

Participants generally need to point toward where the interception should occur or to catch the moving object following the occlusion period. Results showed a rather systematic underestimation of the time to collision, suggesting that mental representation of the object displacement, even though at constant velocity, is rather imprecise (Freyd, & Finke, 1984; Hubbard, 1990). On the other hand, Gray and Thornton (2001) showed that the underestimation was reduced when temporal cues were provided during the occlusion period.

Many studies demonstrated that children exhibit greater difficulties than adults to coordinate their action with the displacement of an object to intercept or catch (Benguigui, Broderick, & Ripoll, 2004; Gagnon, Fleury, & Bard, 1990), or to cross a street with high traffic (Te Velde, Van der Kamp, Becher, Van Bennekom, & Savelsbergh, 2005), suggesting that children ability to correctly anticipate the future position of an object is still maturing (Schiff, & Oldack, 1990). For example, it has been shown that children aged 5-6 exhibit a very stable pattern of response in which movement duration remains the same whatever stimulus speed, whereas older children and adults are able to adapt their movement to the speed of the presented stimulus (Benguigui, & Ripoll, 1998; Benguigui et al., 2004; Gagnon et al., 1991).

To our knowledge very few studies investigated anticipation-coincidence in CP children. However, this behaviour may be of importance to improve the rehabilitation process and considering the numerous daily life situations in which anticipation-coincidence processes may be involved, such as playing music, catching a ball, avoiding a moving

obstacle, etc. It has been shown that CP children are able to develop specific adaptations to compensate for their sensory-motor deficits to provide a correct behavioural response when performing a behaviourally-realistic task requiring walking at various velocities for catching a stationary or moving ball (Ricken, Savelsberg, & Bennett, 2006, 2007).

The purpose of the present experiment was to further investigate the CP children ability to perform coincidence-timing tasks on the basis of an hearing input, by dissociating the cognitive (temporal estimation) from the motor components of the task (movement execution). To that purpose, a music sequence in which the motor response was almost absent (temporal estimation) or present (temporal estimation + movement execution) was used. It was hypothesized that temporal estimation in CP children should not be different with respect to healthy children and adults when simple motor response was involved. Conversely, it was expected that when the coincidence-timing task required more complex movement execution, coincidence-timing was altered with respect to healthy subjects.

Methods

Participants

11 CP children, aged 6 to 14 years (mean age 10.5 years), voluntarily participated to the experiment. In the absence of an authorized access to the individual medical data, the level of motor deficits was estimated through a four points scale submitted to parents, teachers, physiotherapists, and ergo-therapists (1 = low CP, 2 = moderate CP, 3 = severe CP, and 4 = highly severe CP). Three children were classified as low, 3 as moderate, 2 as severe and 3 as highly severe.

A population of 51 healthy children, aged 6 to 14 years (mean age 10.2 years), also participated to the study. All the healthy children had no specific musical practice and exhibited no known hearing, visual, or motor deficits. Finally, a group of 13 healthy adults (7 women and 6 men, mean age 25.5 years) also served as a control group. As required by the

local ethics committee, all participants gave their written informed consent and parents consent was also obtained for the children.

Apparatus and task

Participants' task was to perform, as accurately as possible, a coincidence-timing in response to a specific event of a musical sequence (drum sound). This task was performed in two different conditions. In the verbal condition, participants provided their temporal estimation through a simple verbal response (top). This condition allowed estimating to which extent CP children were able to cognitively anticipate the occurrence of the drum sound with limited motor constraints. In the motor condition, the temporal estimation was performed through a more complex motor response in which participants had to reach a target at a self-paced arm velocity. This condition allowed estimating to which extent CP children were able to take into account their sensory-motor deficits and as a consequence, to adapt their behaviour for anticipating the drum sound occurrence.

Seven musical sequences were first elaborated by a professional musician and three of them were finally selected. These three musical sequences were composed of seven notes played at a regular temporal pace with a vibraphone and ended with an eighth note which was the sound of a drum. These musical sequences were delivered at three different paces: Slow (1.10 Hz or 65 beatings per minute (bmp)); medium (1.40 Hz or 85 bmp); and fast (1.75 Hz or 105 bpm).

The musical sequences were listened through sound amplifiers in order to compensate for presumable hearing deficits (Pharoah, Cooke, Johnson, King, & Mutch, 1998). In the verbal condition, a tie microphone was connected to the computer to provide the response. In the motor condition, participants faced a 40 x 40 cm and 2 mm thin contact surface on which two targets representing red flowers (3 cm of diameter) and distant 25 cm from each other were designed. Position of the targets induced an abduction movement of the arm from left to

right (Figure 1). The first target was used to detect the beginning of the arm reaching movement. The second target was used to detect the end of the arm movement. Timing data were recorded directly with the Audacity software.

Insert Figure 1 about here

Procedure

Participants comfortably sat on a chair placed in front of a table. CP children either sat as the healthy participants or on their wheelchair, depending on their motor deficits. The two targets were placed in front of the participants. Before the experiment, participants performed few practice trials in the verbal condition, only. Participants first listened to a basic musical sequence in which there was just one note per time at the slow pace and were instructed to identify the drum sound within the musical sequence. Once identified, participants were instructed to say « top » in synchronisation with the drum sound. Once this first task was successful, the three experimental sequences of music were presented at the slow pace so that participants were informed of the existence of different melodies. Participants practiced 7 to 8 trials in average but additional practice trials were allowed whenever necessary.

In the verbal condition, participants held the microphone in their preferred hand, in front of their mouth. Once participants were ready, one of the three musical sequences was presented. They were instructed to say “top” as precisely as possible, in synchronisation with the drum sound, as in the practice trials. A 1 min rest was provided after each sequence of three trials at the same pace, and participants were informed about the following pace of the musical sequences, in order to avoid the effect of surprise. Six blocks of three trials were performed for a total of 18 trials (2 blocks x three paces x three musical sequences).

In the motor condition, participants put the index finger of their right hand (preferred hand) on the starting target. The pointing movement toward the second target required an abduction of the arm. Participants were instructed to reach the final target in synchronization with the drum sound, in a single movement executed at spontaneous and regular speed, that is, without temporarily suspending the movement for expecting the stimulus occurrence (Figure 1). As for the verbal task, six blocks of three trials were performed. The order of presentation of the three musical sequences was randomized within the blocks of three trials at a given pace. The order of presentation of the 12 blocks of trials (2 blocks x 2 experimental conditions x 3 paces) was counterbalanced across participants.

Four dependent variables were investigated: The absolute error of temporal estimation, that is, the time difference between the occurrence of the drum sound and the participants' verbal "top" or motor response, the variability of temporal estimations, movement time and movement time variability in the motor condition.

Results

A 3 groups x 2 conditions x 3 musical paces analysis of variance (ANOVA) with repeated measures on the last two factors was applied to each dependent variable. Newman-Keuls post-hoc tests were performed whenever necessary. P level was set at 0.05.

Absolute errors of temporal estimation

Analysis of the temporal estimation errors showed main effects of group, $F(2, 71) = 14,568, p < .001$, condition, $F(1,71) = 16,516, p < .001$, and musical pace, $F(2,142) = 10,997, p < .001$. There was also a significant interaction of group x condition, $F(2,71) = 5,1700, p < .01$, and group x musical pace, $F(4,142) = 7,3975, p < .001$. As illustrated in Figure 2, post-hoc Newman-Keuls showed that for the healthy children and adults temporal errors were similar whatever the condition, whereas for the CP children temporal estimation errors were higher in the motor than verbal condition. Post-hoc Newman-Keuls also showed that for the healthy

children and adults, temporal estimation errors were similar whatever the musical pace whereas for the CP children, these temporal errors were higher for the slow pace than for the medium and fast paces. The three-way interaction of group x condition x musical pace was also significant, $F(4,142) = 8,7895, p < .01$, and showed that the temporal estimation errors were higher for the CP children in the motor condition and at the slow pace.

Insert Figure 2 about here

Variability of temporal estimation

Analysis of the standard deviation of temporal estimation showed main effects of group, $F(2,71) = 17,426, p < .001$, condition, $F(1,71) = 13,849, p < .001$, and musical pace, $F(2,142) = 5,0986, p < .01$. Two-way interactions of group x condition, $F(2,71) = 4,6609, p < .01$, and group x musical pace, $F(4,142) = 3,9149, p < .01$, were also significant. Post-hoc Newman-Keuls showed that temporal variability was higher for the CP children than for the healthy children and adults (Figure 3) and that CP children exhibited a higher variability at the slow pace with respect to the other two groups who exhibited a similar temporal variability whatever the musical pace.

Movement time

Analysis of movement time showed main effects of group, $F(2, 71) = 6,6275, p < .01$, and musical pace, $F(2, 142) = 16,634, p < .001$. Post-hoc Newman-Keuls showed that CP children exhibited a longer movement time than healthy children and adults. In addition, movement time was longer at the slow than at the medium and fast musical paces.

Variability of movement time

Analysis of movement time standard deviation showed a main effect of group, $F(2,71) = 16,524, p < .001$. As expected, post-hoc Newman-Keuls showed that CP children exhibited

more variable motor responses than healthy children (Figure 3). Interestingly, temporal estimation variability was significantly smaller than movement time variability (± 487 ms vs. ± 205 ms, $p < .01$).

Insert Figure 3 about here

Discussion

The present experiment aimed at investigating coincidence-timing ability of CP children in response to an auditory stimulus occurring at the end of a musical sequence. Participants were submitted to two verbal and motor responses and three different musical paces. In the verbal condition, results showed that CP children made similar temporal errors than their healthy counterpart. These data clearly suggested that CP children were perfectly able to anticipate the occurrence of a sound stimulus and associate it to a verbal response. In the motor condition, however, CP children exhibited greater and more variable temporal errors than healthy participants, even though all participants underestimated the time occurrence of the drum, that is, were delayed. Meanwhile, healthy participants made similar temporal errors, whatever the verbal or motor response to provide, showing that these participants perfectly integrated the characteristics of their movement for synchronizing their response with the occurrence of the auditory stimulus. Interestingly, the observed temporal underestimation was below or similar to the threshold of sound discrimination established around 100 ms (Leipp, & Salapy, 1978), suggesting that for the participants the coincidence-timing performance was perceived as successful.

More specifically, results of the present study showed that movement time was longer in CP children than in healthy children and adults. This longer movement time may not only result from CP children sensory-motor deficits, but could also highlight an adaptation for

performing the coincidence-timing task. As illustrated by movement time variability, CP children were more variable than healthy ones. Interestingly, however, movement time variability was much higher than temporal estimation variability, suggesting that during movement execution CP children partially compensated for their lack of motor programming by continuously updating their motor command to the requirements of the task (Ricken et al., 2006; Ju, You, & Cherng, 2010; Mak, 2010).

In the Ricken et al.'s study (2006), for example, CP children were not only capable of adapting their motor behaviour to the spatio-temporal characteristics of the moving object but they were also more precise and with movements of larger amplitude than when reaching an immobile target without temporal and spatial constraints. In other words, our data emphasized the importance of an external constraint for increasing the efficiency of motor coordination of CP children (Van der Weel, & Van der Meer, 1991; Volman, Wijnroks, & Vermeer, 2002; Ricken et al., 2007). It remains, however, that their capacity to adapt and modify their motor command was not sufficient to fully compensate for their motor deficits: The higher variability of temporal estimations in CP children suggested that their movement remained partially random and uncontrolled (Sanger, Kaiser, Placek, 2005; Sanger, 2006).

Whatever the group, the present results also showed that participants' movement time was longer for the slowest tempo, than for the other two ones, suggesting that CP children and healthy ones were able to adapt their behaviour to stimulus velocity as adults (Schiff et Oldak, 1990; Gagnon et al., 1988; Prime, & Harris, 2010). Previous results showed that healthy subjects under-estimated the arrival time of a slow moving stimulus and over-estimated the arrival time of an object moving at fast speed. These effects increased in children (Gagnon et al., 1988; Benguigui, & Ripoll, 1998; Benguigui et al., 2004). Other studies showed that CP children were perfectly able to adapt to stimulus velocity by varying movement time without

significantly changing the time of movement initiation (Ricken et al., 2006; Ricken et al., 2007), highlighting a good perception of the environment.

It remains, however, that temporal estimation errors were similar whatever the tempo in adults and healthy children whereas CP children made greater errors for the slowest musical tempo. Previous studies showed in children that the perception of fast tempi is mature before perception of slower ones, suggesting an immaturity of speed stimulus representation when speed stimulus is slow (Gagnon et al., 1988). In the present experiment, this result suggested that sensory-motor deficits of CP children somewhat delayed the maturation process of speed representation. The significant three way interaction of group x condition x pace also suggested that at a slow pace inducing a slower movement, CP children had more difficulties to perform the coincident-timing because the movement was less spontaneous and more controlled.

As expected, results showed that CP children were less temporally accurate than healthy ones when pointing with their arm, confirming previous results suggesting the presence of uncontrolled movements during execution rather than programming deficits (Sanger et al. 2005; Ricken et al., 2006; Sanger, 2006). However, recent studies hypothesized that motor programming also is altered in CP children without clearly localizing the site of this presumed deficit (Te Velde et al., 2005; Mutsaerts, Steenbergen, & Bekkering, 2006; Mutsaerts, Steenbergen, & Bekkering, 2007; Steenbergen, & Gordon, 2006; Crajé, Aarts, Nijhuis-Van Der Sanden, & Steenbergen, 2010; Crajé, et al., 2010b).

To control human movements, both continuous and intermittent models of control acknowledge the necessity of internal models. The theory of multiple internal models proposes that a set of multiple pairs of corresponding forward and inverse models is selected to control a given motor behaviour, a greater responsibility being attributed to pairs of internal models exhibiting low prediction errors (Wolpert & Kawato, 1998). On the basis of subject's

experience, the pairs of internal models used for a given movement differ from each other. To control joint movements, a single pair of internal models would provide the system with a lower prediction than the one resulting from the weighting of multiple pairs. In other words, the number of pairs selected to control a movement depends on subject's sensory-motor experience.

In healthy participants, movement control may be mainly based on a continuous mode of control resulting from a selection of the appropriate pair of internal models among multiple pairs available. This would result in a correct prediction of coincidence-timing of the arm movement with the drum stimulus and would prevent the system from a new selection of pairs of internal models. Indeed, this new selection of internal models would de facto imply a discontinuity in the control process, i.e., the presence of more or less controlled sub-movements.

Conversely, CP children would rather use a mode of control which is frequently disrupted because the known presence of uncontrolled spastic movements (Albright, 1996) implied to continuously adapt the movement to unexpected changes. In other words, CP children would be forced to use a somewhat intermittent mode of control. Therefore, the only way to control the arm was to successively use various sets of internal models probably resulting in an increased number of sub-movements to take into account the uncontrolled children spasticity. In addition, the reported sensory-motor deficits may induce both a decreased variety and quality of internal models. Potential reasons for the impoverishment of the CP children repertoire of internal models are discussed below. Within this context of impoverished repertoire, CP children no longer had the specific set of internal models which perfectly fitted to the desired movement. Presumably, CP children have degraded internal representations of their body space. Consequently, inverse models and paired forward internal

models become impoverished, altering the capability of the central nervous system to finely mimic the direct relationship between motor commands and their consequences.

In conclusion, the present results showed that CP children were able to adapt their movement to temporal constraints. This suggested that the use of adequate motor tasks with specific constraints during the rehabilitation process may help them to improve their sensory-motor ability for interacting with their environment.

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References

- Albright, A.L. (1996). Baclofen in the treatment of cerebral palsy. *Journal of Child Neurology, 11*(2), 77-83.
- Bax, M., Goldstein, M., Rosenbaum, P., Leviton, A., Paneth, N., Dan, B., Jacobsson, B., & Damiano, D. (2005). Executive Committee for the Definition of Cerebral Palsy. *Developmental Medicine and Child Neurology, 47*, 571-6.
- Benguigui, N., & Ripoll, H. (1998). Effects of tennis practice on the coincidence timing accuracy of adults and children. *Research Quarterly for Exercise and Sport, 69*(3), 217-23.
- Benguigui, N., Broderick, M., & Ripoll, H. (2004). Age differences in estimating arrival-time. *Neuroscience Letters, 369*(3), 197-202.
- Brouwer, A.M., Brenner, E., & Smeets, J.B. (2002). Hitting moving objects: is target speed used in guiding the hand? *Experimental Brain Research, 143*(2), 198-211.
- Brouwer, A.M., Middelburg, T., Smeets, J.B., & Brenner, E. (2003). Hitting moving targets: a dissociation between the use of the target's speed and direction of motion. *Experimental Brain Research, 152*(3), 368-75.
- Crajé, C., Aarts, P., Nijhuis-Van Der Sanden, M., & Steenbergen, B. (2010). Action planning in typically and atypically developing children. *Research in Developmental Disabilities, 5*, 1039-1046.
- Crajé, C., Van Elk, M., Beeren, M., Van Schie, H-T., Bekkering, H., & Steenbergen, B. (2010). Compromised motor planning and motor imagery in right hemiparetic cerebral palsy. *Research in Developmental Disabilities, 6*, 1313-1322.
- Eggert, T., Rivas, F., & Straube, A. (2005). Predictive strategies in interception tasks: differences between eye and hand movements. *Experimental Brain Research, 160*(4), 433-49.
- Freyd, J., & Finke, R.A. (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10*, 126-132.

- Gagnon, M., Fleury, M., & Bard, C. (1988). Knowledge of results and spatio-temporal control in an anticipation-coincidence task in children 6 to 10 years of age. *Canadian Journal of Psychology, 42*(3), 347-63
- Gray, R., & Thornton, I.M. (1991). Exploring the link between time to collision and representational momentum. *Perception, 30*(8), 1007-22.
- Hubbard, T.L. (1990). Cognitive representations of linear motion: possible direction and gravity effects in judged displacements. *Memory & Cognition, 18*, 299-309.
- Ju, Y., You, J., & Cherng, R. (2010). Effect of task constraint on reaching performance in children with spastic diplegic cerebral palsy. *Research in Developmental Disabilities, 31*, 1076-1082.
- Krigger, K.W. (2006). Cerebral palsy: an overview. *American Family Physician, 73*, 91-100.
- Kyllerman, M., Bager, B., Bensch, J., Bille, B., Olow, I., & Voss, H. (1982). Dyskinetic cerebral palsy. I. Clinical categories, associated neurological abnormalities and incidences. *Acta Paediatrica Scandinavia, 71*(4), 543-50.
- Lee, D.N. (1976). A theory of visual control of braking based on information about time to Collision. *Perception, 5*, 437-459.
- Lee, D., Port, N.L., & Georgopoulos, A.P. (1997). Manual interception of moving targets. II. On-line control of overlapping submovements. *Experimental Brain Research, 116*(3), 421-33.
- Leipp, E., & Sapaly, J. (1978). Mode d'emploi du T.F.T., Tests de perception fréquentielle et temporelle. *Audiophonology, 3*, 31-37.
- Mak, M.K. (2010). Reaching and grasping a moving target is impaired in children with developmental coordination disorder. *Pediatric Physical Therapy, 22*, 384-91.
- Mrotek, LA, & Soechting, JF. (2007). Target interception: hand-eye coordination and strategies. *Journal of Neuroscience, 27*(27), 7297-309.

- Mutsaerts, M., Steenbergen, B., & Bekkering, H. (2006). Anticipatory planning deficits and task context effects in hemiparetic cerebral palsy. *Experimental Brain Research*, *172*, 151-62.
- Mutsaerts, M., Steenbergen, B., & Bekkering, H. (2007). Impaired motor imagery in right hemiparetic cerebral palsy. *Neuropsychologia*, *4*, 853-859.
- Pharoah, P.O., Cooke, T., Johnson, M.A., King, R., & Mutch, L. (1998). Epidemiology of cerebral palsy in England and Scotland, 1984-9. *Arch Dis Child Fetal Neonatal*, *9*(1), F21-5.
- Port, N.L., Lee, D., Dassonville, P., & Georgopoulos, A.P. (1997). Manual interception of moving targets. I. Performance and movement initiation. *Experimental Brain Research*, *116*(3), 406-20.
- Prime, S., & Harris, L. (2010). Predicting the position of moving audiovisual stimuli. *Experimental Brain Research*, *203*, 249–260.
- Reid, S.M., Modak, M.B., Berkowitz, R.G., & Reddihough, D.O.S. (2011). A population-based study and systematic review of hearing loss in children with cerebral palsy. *Developmental Medicine and Child Neurology*, *53*(11), 1038-1045.
- Ricken, A.X., Savelsbergh, G.J., & Bennett, S.J. (2006). External timing constraints facilitate performance of everyday interceptive actions in children with spastic hemiparetic cerebral palsy. *Neuroscience Letters*, *410*, 187-92.
- Ricken, A., Savelsbergh, G. J., & Bennett, S. J. (2007). Interception of moving objects while walking in children with spastic hemiparetic cerebral palsy. *Disability & Rehabilitation*, *29*, 69-77.
- Sanger, T.D. (2006). Arm trajectories in dyskinetic cerebral palsy have increased random variability. *Journal of Child Neurology*, *21*, 551-557.
- Sanger, T.D., Kaiser, J., & Placek, B. (2005). Reaching movements in childhood dystonia contain signal-dependent noise. *Journal of Child Neurology*, *20*(6), 489-96.

- Schiff, W., & Oldak, R. (1990). Accuracy of judging time to arrival: effects of modality, trajectory, and gender. *Journal of Experimental Psychology: Human Perception and Performance*, 16(2), 303-16.
- Smyth, M.M., & Mason, U.C. (1998). Use of proprioception in normal and clumsy children. *Developmental Medicine and Child Neurology*, 40(10), 672-81.
- Steenbergen, B., & Gordon, A.M. (2006). Activity limitation in hemiplegic cerebral palsy: evidence for disorders in motor planning. *Developmental Medicine and Child Neurology*, 48(9), 780-783.
- Te Velde A.F., Van der Kamp J., Becher J., Van Bennekom C., & Savelsbergh, G.J.P. (2005). Planning and control in a manual collision avoidance task by children with hemiparesis. *Motor Control*, 9, 417-438
- Van der Heide, J.C., Fock, J.M., Otten, B., Stremmelaar, E., & Hadders-Algra, M. (2005). Kinematic characteristics of postural control during reaching in preterm children with cerebral palsy. *Pediatric Research*, 58(3), 586-93.
- Van der Weel, F.R., Van der Meer, A., & Lee, D. (1991). Effect of task on movement control in cerebral palsy: Implications for assessment and therapy. *Developmental Medicine & Child Neurology*, 33, 419-426.
- Van Thiel, E., & Steenbergen, B. (2001). Shoulder and hand displacements during hitting, reaching, and grasping movements in hemiparetic cerebral palsy. *Motor Control*, 5(2), 166-82.
- Volman, M.J., Wijnroks, A., & Vermeer, A. (2002). Effect of task context on reaching performance in children with spastic hemiparesis. *Clinical Rehabilitation*, 16, 684-692.
- Wann, JP. (1991). The integrity of visual-proprioceptive mapping in cerebral palsy. *Neuropsychologia*, 29(11), 1095-106.

Figure captions

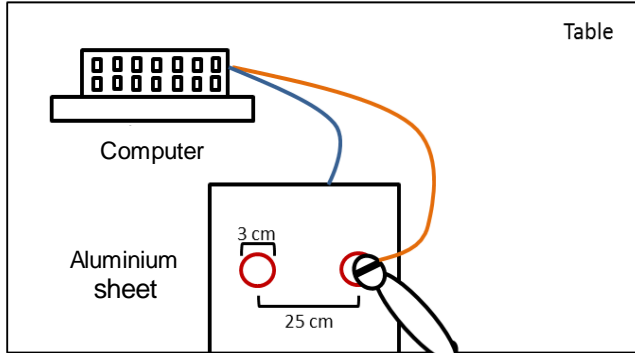
Figure 1: Schematic representation of the experimental device.

Figure 2: Mean temporal estimation errors in milliseconds, for the three groups and the two conditions of anticipation-coincidence response.

Figure 3: Mean standard deviation in milliseconds for the three groups and the two conditions of anticipation-coincidence response.

Figure 1

Experimenter



Aluminium sheet

3 cm

25 cm

Participant

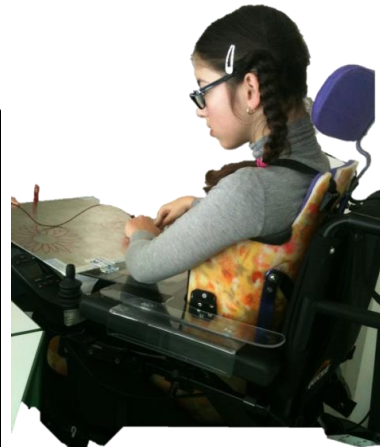


Figure 2

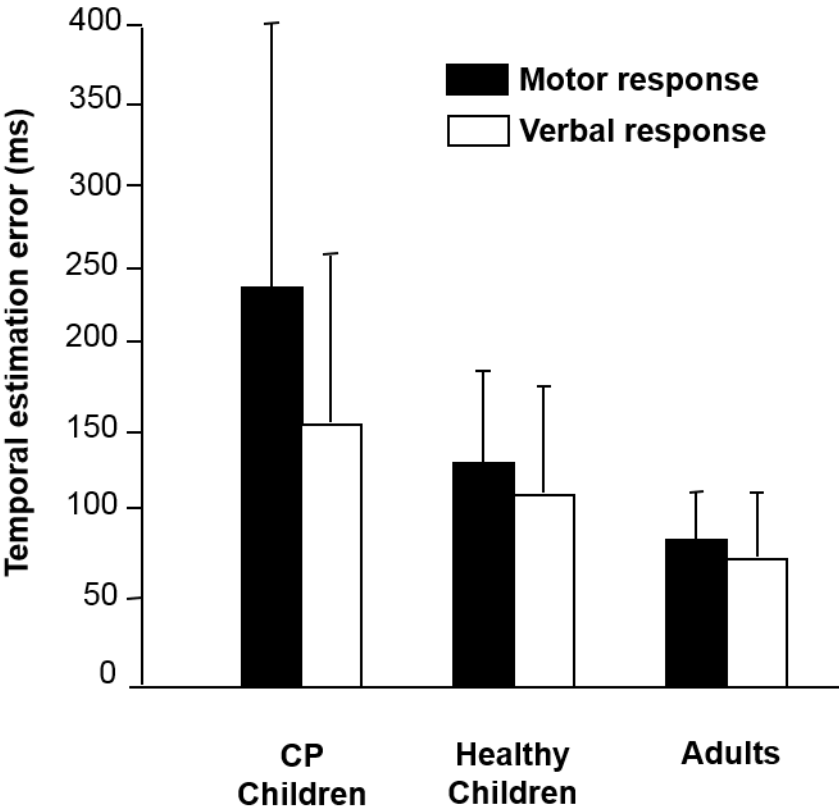


Figure 3

