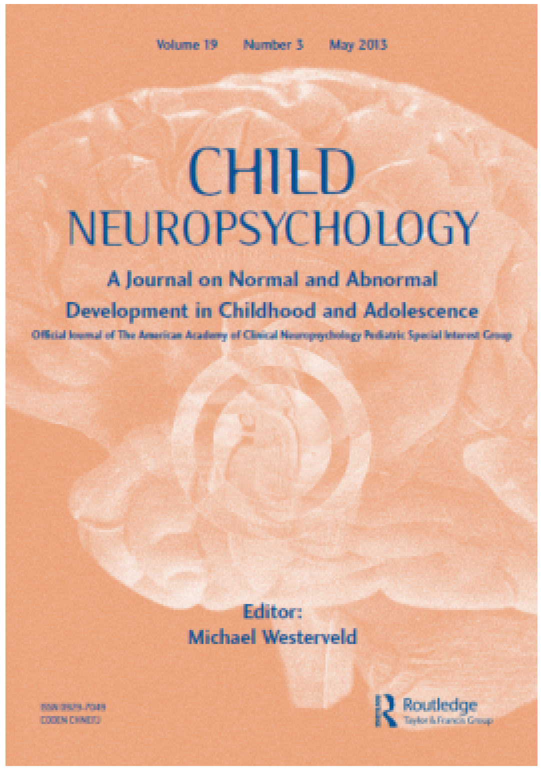

Inhibitory control and temporal perception in cerebral palsy

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1. Introduction

Cerebral palsy (CP) describes an amalgam of movement and posture disorders due to early brain injury when the central nervous system is maturing (Bax, Goldstein, Rosenbaum, Leviton & Paneth, 2005). The motor disturbances are often accompanied by other sensory, cognitive and behavioural difficulties, which produce a clear limitation of the functional activity of the person (Aisen et al., 2011; Rosenbaum et al., 2007; Young et al., 2010).

CP has traditionally been considered from a medico-clinical point of view, almost exclusive precedence being given to the motor pathology, the causes of the lesion or lines of rehabilitation, and scant attention being paid to the cognitive characteristics of these individuals, so little literature on this matter can be found (Sigurdardottir et al., 2008; Straub & Obrzut, 2009).

Recently, however, there has been a remarkable growth in interest in addressing the cognitive development of the individuals with cerebral palsy (Ballester-Plané et al., 2018; Bottcher, 2010; Bottcher et al., 2016; Sherwell et al., 2014; Stadskleiv, Jahnsen, Andersen, & von Tetzchner, 2018). Many of these studies agree that visuoperceptual, memory and language processes are those most often affected (Deramore Denver, Froude, Rosenbaum, Wilkes-Gillan, & Imms, 2016; Mei et al., 2016; Nordberg, Dahlgren & Miniscalco, 2015; Pueyo, Junqué, Vendrell, Narberhaus, & Segarra, 2009; Sigurdardottir et al., 2008; Stadskleiv, Batorowicz, Massaro, van Balkom, & von Tetzchner, 2018). Furthermore, several neuropsychological studies have pointed out that there are deficits related to executive functioning in CP (Di Lieto et al., 2017; Piovesana, Ross, Whittingham, Ware, & Boyd, 2015; Pirila, van der Meere, Rantanen, Jokiluoma & Eriksson, 2011; Stadskleiv et al., 2014; Stadskleiv, Jahnsen, Andersen, & von Tetzchner, 2017; Weierink, Vermeulen & Boyd, 2013; Whittingham, Bodimeade, Lloyd & Boyd, 2014) and, in particular, specific executive impairments in selective and sustained attention (Korkman et al., 2008; Lemay, & Lamarre, 2012), working memory (Baron, Kerns, Müller, Ahronovich , & Litman, 2012;; Jenks, de Moor, & Van Lieshout, 2009; Løhaugen et al.,2014; Peeters, Verhoeven & de Moor, 2009; Van Rooijen, Verhoeven, & Steenbergen, 2016), cognitive flexibility (Bodimeade, Whittingham, Lloyd, & Boyd, 2013; Laporta-Hoyos et al., 2017; Nadeau, Routhier, & Tessier, 2008) planning, goal setting and problem solving (Bodimeade et al., 2013; Roze et al.,2009; Skranes et al., 2008; Stadskleiv et al., 2014), and inhibitory control (Bottcher, Flachs,& Uldall, 2010; Caillies, Hody, & Calmus, 2012; Edgin et al., 2008; Li et al., 2014). Especially, in relation toabout inhibition, Christ, White, Brunstrom, and Abrams (2003) studied the effect of early central nervous system lesions on the development of inhibitory control in children with CP. They found, finding that these children had a significantly lower performance in inhibition tests than typically developing children, probably due to their white matter lesions associated with hypoxic-ischemic encephalopathy and to damage to frontostriatal connections (see also Straub & Obrzut, 2009, for a similar account).

Inhibition is considered one of the basic essential components of executive functions, together with mental flexibility and the processes of updating information in working memory (Miyake et al., 2000 Friedman, & Miyake, 2017). Inhibitory executive function allows relevant information to be suppressed, together with unwanted actions or emotions (Munakata, et al., 2011). Inhibitory mechanisms would, therefore, enable control of the individual's behaviour and mental functioning, as well as adequate management of his or her own emotions and motivations (Diamond, 2013).

Inhibitory processes are associated with high-level functions controlled by prefrontal areas, such as monitoring and control of response execution for goal attainment (Verbruggen & Logan, 2008), memory and verbal comprehension (Bäuml, Pastötter, & Hanslmayr, 2010; Cain, 2006; Carriedo et al.,, 2016), planning and problem solving capacity (Carlson, Moses & Claxton, 2004; Luna & Sweeney, 2004), decision making (Coutlee & Huettel, 2012; Van den Wildenberg & Crone, 2005), cognitive and behaviour control (Garavan, Ross, Murphy, Roche & Stein, 2002; Levy & Wagner, 2011) and emotional regulation (Hofmann, Schmeichel & Baddeley, 2012). ~~In addition~~Also, together with the executive functions of working memory and mental flexibility, inhibition is considered a good predictor of general intelligence in children (Brydges, Reid, Fox & Anderson, 2012; Michel & Anderson, 2009).

Some authors have also pointed out the importance of inhibition in cognitive development (Dempster & Corkill, 1999; Harnishfeger, 1995). According to various studies, inhibitory control emerges at early ages (Cuevas, Swingler, Bell, Marcovitch & Calkins, 2012; Garon, Bryson & Smith, 2008), with a significant development peak after 5 or 6 years (Baker, Friedman & Leslie, 2010; Bartgis, Thomas, Lefler & Hartung, 2008; Cragg & Nation, 2008; Diamond, 2006; Garon et al., 2008), full maturity not being reached until adolescence is over (Durston et al., 2002; Jaeger, 2013), or even until adulthood (Harnishfeger, 1995; Nielson, Langenecker & Garavan, 2002; Tamm, Menon & Reiss, 2002). Likewise, neuroanatomical development and expansion of the prefrontal areas involved in the development of inhibitory control also contribute towards consolidation of other higher cognitive functions like planning or decision making (Diamond, 2002; McCormack & Atance, 2011; Pennequin, Sorel, & Fontaine, 2010; Van den Wildenberg, & Crone, 2005).

On another note~~the other side~~, the human being's perception of time is crucial in humans for everyday activities~~;~~. A~~a~~ll stimuli and actions have temporal extent, and judgment of duration is essential for certain~~some~~ basic behaviors such as combining motor sequences to achieve a goal, and for more complex acts such as arriving on time for appointments, temporally structuring speech, or foreseeing future events (Allman, Teki, Griffiths, & Meck, 2014; Buhusi, & Meck, 2005; Matthews, & Meck, 2016).

Specific temporal processing impairments have been reported in children with learning problems such as dyscalculia or dyslexia (Cappelletti, Freeman, & Butterworth, 2011; Moll, Göbel, Gooch, Landerl, & Snowling, 2016; Plourde, Gamache, Laflamme, & Grondin, 2017), in children with attention-deficit hyperactive disorder (Mioni, Santon, Stablum, & Cornoldi, 2017; Smith, Taylor, Warner Rogers, Newman, & Rubia, 2002; Valko et al., 2010) and with autism (Isakson et al., 2018; Wallace, & Happé, 2008), the temporal perception difficulties of most of these children being attributable to deficits in executive functioning (Droit-Volet, 2013, 2016).

Development of the temporal perception ability, in parallel to the ontogenetic process of inhibitory function, also begins early (Brannon, Roussel, Meck & Woldorff, 2004; Droit-Volet, 2016; Provasi, Rattat & Droit-Volet, 2010), with a dramatic increase after the age of 7 years (Carelli, Forman & Mäntylä, 2008; Gautier & Droit-Volet, 2002a; Droit-Volet, 2013), and maximum development levels not being reached until late adolescence (Hwang, Velanova, & Luna, 2010; Neufang, Fink, Herpertz-Dahlmann, Willmes, & Konrad, 2008; Smith et al., 2011). Based on this evidence, some authors have stated that the gradual behavioural control developed during childhood and adolescence is related to the development of the temporal abilities (Barker et al., 2014; Droit-Volet, Wearden, & Zélanti, 2015; Vicario, 2013), and that, in turn, the individual differences observed in the temporal processing capacity depend on consolidation of executive functions (Carelli et al., 2008). This mutual interaction between attentional processes, like selective/focused attention or attentional control, and time perception abilities has been found not only in children (Droit-Volet, 2016; Droit-Volet, Delgado & Rattat, 2006), but also in adults (Block, Hancock, & Zakay, 2010). Thus, various authors have underlined the essential role played by the attentional capacity in the regulation of temporal experiences and in the ability to estimate interval duration (Block, & Gruber, 2014; Brown & Boltz, 2002; Coull, Vidal, Nazarian & Macar, 2004; Triviño, Correa, Arnedo & Lupiáñez, 2010; Matthews, & Meck, 2016), and that both processes take part in behaviour regulation and organisation of voluntary responses in parallel to the prefrontal cortex maturation (Luna & Sweeney, 2004), similar cerebral activation patterns having been found in attentional control and time perception processes in the prefrontal cortex (Triviño et al., 2010), in corticostriatal circuits (Wittmann & Paulus, 2008) and ~~in~~ fronto-parietal connections (Coull et al., 2004), and it having been found that tasks involving inhibition processes and temporal estimation share frontostriatal circuits, as well as parieto-cerebellar connections (Neufang et al., 2008).

Other studies have emphasised the more specific influence of inhibitory and impulse control processes for preparation and temporal regulation of behaviour (Correa, Triviño, Pérez-Dueñas, Acosta & Lupiáñez, 2010; Los, 2013). ~~For example,~~ In children with typical development, Meaux and Chelonis (2005) observed that behavioural inhibition problems caused poor development of temporal perception; other authors have also related temporal estimation difficulties to poor resistance to distraction (Choe, 2013; Zelanti & Droit-Volet, 2011). Similarly, Rubia, Halari, Christakou and Taylor (2009) have attributed both time orientation and estimation difficulties to low impulse control in children with attention-deficit hyperactive disorder (see also Noreika, Falter,

& Rubia, 2013); Pavlína, Tomáš, Pavla, Hana and Martin (2018) found a relationship between inhibitory control deficit and motor timing impairments in children with autism; and Grinblat and Rosenblum (2016) described time perception difficulties associated with inhibition and executive control problems in children with learning disabilities.

To sum up, there is a considerable empirical evidence showing that: a) children and adolescents with CP have inhibitory control problems (Bottcher et al., 2010; Edgin et al., 2008; Li et al., 2014; Straub & Obrzut, 2009; White, & Christ, 2005); b) inhibition interacts with and stimulates the development of the temporal perception ability (Meaux & Chelonis, 2005; Zelanti & Droit-Volet, 2011); and c) that the two processes are related both in typical development and in samples with neurodevelopmental disorders, as attention-deficit hyperactivity disorder or autism, not only in terms of their role in the control of the behaviour, but also with regard to their underlying neurological substrate (Neufang et al., 2008; Vicario, 2013).

In this context, the main aim of this study was to examine whether children and adolescents with CP have inhibitory problems and whether this inhibitory control deficit interferes with their ability to make temporal judgments. Our first hypothesis was that children and adolescents with CP would have lower performance in temporal estimation tasks and inhibitory control tasks than typically developing children. About inhibitory control tasks, we expected that the differences between the CP group and the control group would be especially significant under conditions of maximum interference, i.e., in the response time of the incongruent conditions. Secondly, we hypothesised that inhibitory control abilities would be related to temporal processing capacities, based on the well-documented relationship between response inhibition/impulse control and temporal perception skills (Barkley, Edwards, Laneri, Fletcher, & Metevia, 2001;

Berlin, & Rolls, 2004; Berlin, Rolls, & Kischka, 2004; Rubia et al., 2009; Vicario, 2013; Wittmann, & Paulus, 2009; Wittmann, & Paulus, 2008), in such a way that adequate functioning in inhibitory control would predict better results in time perception.

2. Methods

2.1. Participants

A sample of 16 individuals (37.5% girls, 62.5% boys) with CP was chosen from the total population (n=87) of a private subsidized centre for children of a medium-high socioeconomic level, dedicated to the treatment and education of children and adolescents with CP. The criteria for selecting the CP sample were the following: (a) exhibiting a predominantly spastic form of CP, although mixed symptoms were admitted, as in three cases (two with ataxic components and one athetoid); (b) having a mental maturity index above 5 ½ years and below 10 years assessed using the *Colombia Mental Maturity Scale* (Burgemeister, Lorge & Blum,1983); (c) having a degree of motor impairment corresponding to levels I, II, III and IV of the *Gross Motor Function Classification System* (GMFCS, Palisano et al., 1997). Children with level V of motor impairment were excluded due to the severity of their motor and cognitive impairments and their predictable inability to perform the tasks of our study; (d) having effective verbal responses, such as naming pictures or clearly saying "yes" or "no; and (e) having adequate visual fixation and acceptable eye tracking responses, assessed with the *Gaze Viewer* calibrator (see the Materials section).

The mean chronological age of children with CP was 13.2 years (*SD*= 4.20), and the mean mental age was 7 ~~½~~.6 (*SD* = 1.4). According to their degree of physical impairment (GMFCS), 50% of the children were classified in levels II and III (mild-moderate), and the other 50% in level IV (serious).

The comparison group (N= 16; 43.75% girls, 56.25 % boys) was obtained from a private subsidized school of similar socioeconomic status to the experimental group. As in the case of the CP group, control group participants were evaluated with the *Columbia Maturity Scale* (Burgemeister, Blum & Lorge, 2004) in order to establish their mental maturity index, and, as in the case of CP group, only participants having a mental maturity index above 5 ½ years and below 10 years were selected.

The 16 children and adolescents with CP were matched one-to-one with other typically developing children (control group) by mental age, in a similar way as Dahlgren, Sandberg, and Larsson (2010) did with children with CP (see also Hooper et al., 2008); and Sullivan et al., (2007) investigating response inhibition with fragile X syndrome.

The mean chronological age of this control group was 7.2 years (*SD*= 1.36), and the mean mental age was not significantly different to that of the group with CP (*M* = 7 ½.6 years; *SD*= 1.4). The characteristics of the participants with CP and the control group can be seen in Table 1.

Table 1. CP and control groups. Participants of both groups paired according to their mental levels. CMMS: Columbia Scale (results for both groups)

CEREBRAL PALSY				CONTROL GROUP	
Sex	GMFCS Level	Age	CMMS Mental Age (years)	Sex	Age
M	III	14.4	10	F	9.6
M	III	17.5	10	F	9.10
M	IV	14.5	9.6	F	8.11

M	III	17.6	8.6	M	8.0
M	III	15.1	8.6	F	7.9
F	IV	9.6	8	F	8.5
M	II	7.2	7.6	M	6.11
M	II	17.4	7.6	M	7.6
M	IV	18.2	7.6	M	7.1
F	II	8.1	7	F	6.1
M	IV	10.8	7	M	5.11
M	II	15.1	6.6	M	6.9
F	IV	14.9	6	M	6.0
F	IV	12.1	6	M	5.6
F	IV	6.8	6	M	5.8
F	IV	6.1	6	F	5.8

2.2. Materials

All tasks used in this study were suitably adapted to children with movement problems. Before experimental application different tryouts were performed with children that did not participate in the experiment until it was assured that the children understood the tasks and that the number of trials was appropriate to avoid fatigue and abandonment of the activity, especially in the CP group.

The experimental tasks were presented on a computer screen (*HP Pavilion G6* 15.6") with the program *Microsoft Power Point*. *AVS-Editor* program was used to record all the children's responses while they carried out the tasks, except the antisaccade task for which the *Tobii PCEye* tracker (Kooiker, Pel, van der Steen-Kant, & van der Steen, 2016) was used, controlled by the *Gaze Viewer* software (Lariviere, 2015), which enabled fixation points, times of fixations, gaze direction and time between saccades to be recorded. ~~It provides an individual report on performance in visual fixation and gaze tracking using a simple task consisting of looking at and following a point moving on a computer screen.~~

Previously to the experimental tasks, each participant was evaluated with the *Gaze Viewer* calibrator, which provides an individual report on performance in visual fixation and gaze tracking using a simple task consisting of looking at and following a point moving on a computer screen. In three trials, the calibrator makes available information about the quality of the gaze: if the child has completely followed the visual stimulus that moved across the screen and maintained the gaze fixation at all points where the stimulus remained immobile, the result appears on a green background (optimal performance). If the child has been able to follow the moving stimulus, but with difficulty and has fixed his or her gaze on all the fixation points although he/she was unable to maintain his/her gaze on all the points, the result was displayed on a yellow background (quite good performance). When the child was unable to look at any of the fixation points, although he/she did follow the stimulus moving on the screen, the result was presented on a red background (unacceptable performance) (see Fig. 1). Only children whose performance in the three trials was optimal or quite good were admitted as study participants. Those who, in any of the three trials, obtained one or more unacceptable results were not selected. In the first phase of participants' selection, two children with CP were excluded for not passing this test; all children of typical development passed it easily.

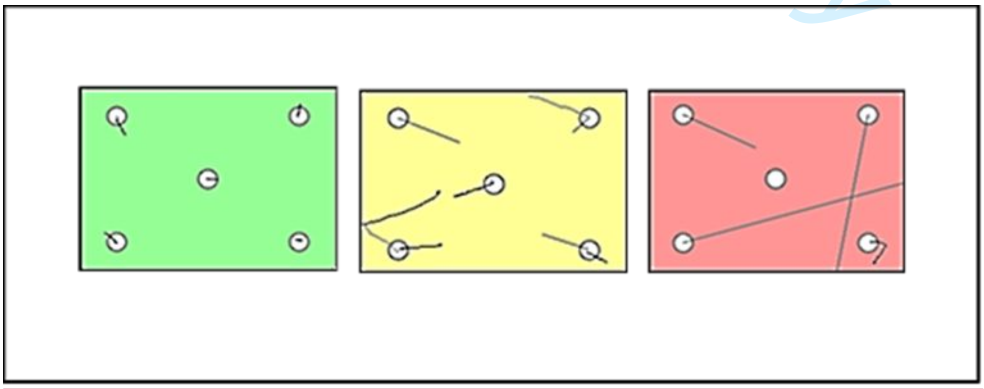

Fig. 1. Example of possible results of the *Gaze Viewer* calibrator. Only children whose calibration responses were shown in the rectangles on the left (green background) and on the center (yellow background) were admitted in our study. If the results of any of the three calibration trials were in the rectangle on the right (red background), the child was discarded as a participant.

2.2.1. Control measures.

The Gross Motor Function Classification System (Palisano et al., 1997). This was used to select the participants of the CP group. It evaluates voluntarily initiated movement with emphasis on sitting, transfers, and mobility. This scale ~~and~~ classifies people with CP in five levels of increasing order of severity according to gross motor symptomatology. Level I: children have acquired motor skills, with only speed, balance, or movement coordination slightly affected. Level II: children can walk indoors and outdoors, with limitations on stairs, long distances or crowded spaces, and show inability to jump or run. Level III: they can walk indoors or outdoors with assistive mobility devices and frequently orthoses, and with manually self-propelled wheelchairs. Level IV: children's sitting function usually needs to be supported, and their independent mobility is very limited, requiring an electrically powered wheelchair; level V: they show a total lack of independence even in basic antigravity postural control, total dependence for transport and no control of voluntary movement.

Columbia Mental Maturity Scale (Burgemeister et al., ~~1983~~2004). This was used to evaluate the mental age of all the participants, and to match the children of the control group with those of the group with CP according to the mental maturity index. This scale assesses the cognitive level achieved by children aged 3 years 6 months to 10 years and is especially suitable for the evaluation of children with motor impairments and verbal expression difficulties secondary to cerebral lesions (Sigurdardottir et al., 2008). The reliability of the Columbia Scale is high (.85) (Burgemeister et al., 19832004), and it correlates significantly with other intelligence tests such as the Raven's Color Progressive Matrices (.68, p<.05) (Facon, Facon-Bollengier, & Grubar, 2002). It is considered a valid tool for evaluating non-verbal intelligence (Breeman, Jaekel, Baumann, Bartmann, & Wolke, 2015), and it has also been used to match children with some disabilities with typically developing children by mental age in relation to language performance (Putnick, Bornstein, Eryigit-Madzwamuse, & Wolke,2017), working memory (Schuchardt, Gebhardt, & Mäehler, 2010), theory of mind (Calderon, et al., 2010), motor skills (Zelaznik, & Goffman, 2010) mental retardation in children and adolescents (Facon, et al., 2002), and it has been widely applied to determine intellectual functioning of children with cerebral palsy (e.g., Boldingh, Jacobs-van der Bruggen, Lankhorst, & Bouter, 2004; Mei et al., 2016; Yin Foo, Guppy, & Johnston, 2013).

This scale consists of sets of picture cards of increasing difficulty, for which the child must identify and point out which of the stimuli is different from the others. The number of correct answers was converted into the mental maturity index, a standardized score provided by the scale.

Object Search Task. This task was given to control the effect of processing speed on the performance of the experimental tasks to rule out the possibility that differences between the two groups could be due to the fact that children with CP have higher response times (Murray et al., 2014; Shank, Kaufman, Leffard & Warschausky, 2010). This task was an adaptation of the symbol search test of the Wechsler Intelligence Scale, WISC-IV (Wechsler et al., 2004). For the adaptation, we replaced the symbols of the WISC-IV with drawings of day-to-day objects to increase the familiarity of the stimuli and visual discrimination. Participants had to decide, under pressure of time, whether the object presented on the left was repeated or not among three images presented on the right. The child only had to answer "yes" (if the initial image was repeated) or "no" (if the initial image was not repeated). Children were asked to respond orally rather than in writing in order to make the task easier for the participants with CP. Each card appeared on screen for 2.25 s, after which the next card was shown automatically, together with a click to inform that a new item was being presented (see Fig. 2.). The reliability of this adapted task was .96. The dependent variable was the number of correct responses.

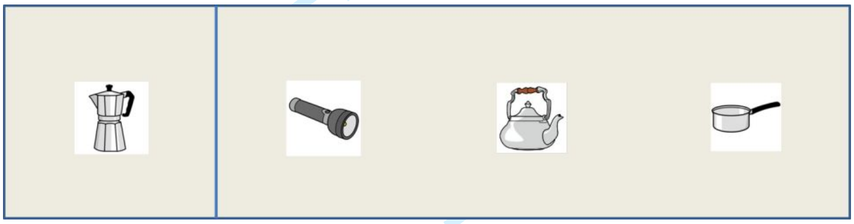

Fig. 2. Object Search Task trial example.

2.2.2. Temporal Estimation Tasks

We used two tasks within the prospective paradigm: Temporal Generalization Task, and Temporal Reproduction Tasks. In both tasks, participants were asked to make temporal duration judgements requiring conscious attention to the passage of time and executive control processes (Matthews, & Meck, 2016; Zakay & Block, 2004).

Temporal Generalisation Task. This was originally created to investigate the existence of temporal processing abilities in animals (Church & Gibbon, 1982), but it has been also used with humans, especially in studies of the development of the time perception ability (Droit-Volet, 2013). It consists of presenting a stimulus of standard duration followed by another stimulus, under different conditions: the same, longer or shorter duration as the standard. The participants only have to decide whether the duration of the second stimulus is the same as the standard one or not (Wearden & Lejeune, 2008).

We adapted the procedure of Droit-Volet, Clément & Wearden (2001). We presented one standard stimulus of 4s or 8s, compared with nine stimuli (randomly sorted) of 1, 2, 3, 4, 4, 4, 5, 6, and 7s respectively for the 4s standard stimulus, and 2, 4, 6, 8, 8, 8, 10, 12, and 14s respectively for the 8s standard stimulus. Thirty-six trials were presented in two blocks, each consisting of 18 trials (9 trials for the 4s standard stimulus, and 9 trials for the 8s standard) randomly presented.

The standard stimulus of 4s or 8s appeared in the middle of the screen, in the shape of a blue star that gradually grew until reaching a length of 12cm. The star was accompanied by white noise to encourage the participant's attention. Then, after 1s and a click signal, the standard stimulus disappeared and the stimulus to be compared — with the same characteristics as the standard stimulus, but yellow— appeared on the screen. The child had to say "yes" if he/she thought that the yellow star took the same time to grow as the blue one presented before, and "no" if he/she thought the two stars did not take the same time to grow (see Fig. 3). The dependent variable was the average of correct answers.

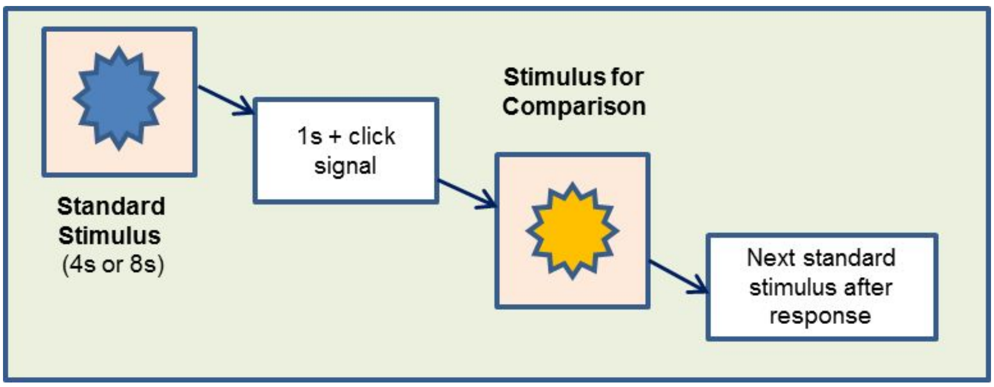

Fig. 3. Temporal generalisation trial example.

Temporal Reproduction Task. We adapted the procedure of Gautier and Droit-Volet (2002a) for this. This task requires the participant to give a response to a stimulus when he or she considers that the same time as the duration of a previously presented standard stimulus has elapsed (Wackermann & Ehm, 2006). In each trial, the image of a singing bird swaying slightly on a branch was presented. Each bird's tune was different, to prevent learning effects. The child was told that he/she should listen to the bird singing and pay attention to the time the song lasted. Then, after 2s with a response preparation slide, the image of the bird appeared again, but this time completely still on a green background, indicating to the child that he/she should begin to mentally reproduce the song time. When he/she thought that the same time of the previously presented bird song had passed, he/she had to say “now” (see Fig.4). Stimuli were presented in two blocks of trials. In each block, 16 randomly presented trials were included, 8 trials with 6s standard stimuli to be estimated, and 8 trials with 12s standard stimuli to be estimated. The dependent variable was the estimate of the duration, i.e., the average in ms of the difference between the real duration of the bird's song presented (standard stimulus) and the time estimated by the child.

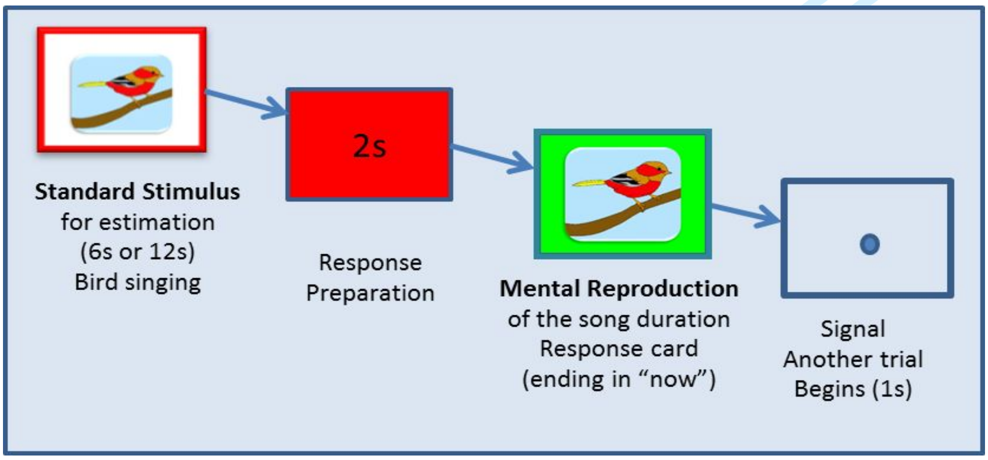

Fig. 4. Temporal reproduction trial example

2.2.3. Inhibition tasks.

Antisaccade Task. This task requires suppression of a saccade movement towards a peripheral stimulus and generation of an oculomotor movement in the opposite direction to the one in which the stimulus is presented (Munoz & Everling, 2004). We used a similar procedure to that of Christ et al. (2003), who also used this task with children with CP[1]. The task has two conditions: prosaccade and antisaccade. In both conditions, the order of the events was the same, but they differed in the response required to the participants. The task started with the appearance of a blue square at the beginning of each trial in the middle of the screen to help the child fix his or her eyes and focus his/her attention on the task (see Fig. 5). Two seconds after exposure to the blue square, a new gaze fixation point appeared on screen, with the blue square plus two identical 1.5 cm-sided cubes, motionless and white-colored, both placed 8 cm to the left and right of the blue square (fixation point). After 300 ms, the fixation point changed colour accompanied by a click, by way of a preparation signal. After 850 ms, one of the cubes lit up in yellow and began to turn for 1500 ms. After 300 ms, a signal (the central square changes color from blue to purple accompanied by a click for 850 ms) alerted the child that one of the cubes-lit up in yellow and began to turn for 1500 ms. The task had two conditions: prosaccade and antisaccade. Participants were instructed that iIn the prosaccade condition, participants were instructed that they had to look at the cube which was lit up and turning, and in the anti-saccade condition, to look in the opposite direction, i.e., at the cube which remained white and still.

[1] The only new thing we added to the method of Christ et al. (2003) was a blue square at the beginning of each trial in the middle of the screen as a fixation point, to help the child fix his or her eyes and focus his/her attention on the task (see Fig.5).

The prosaccade condition was administered before the antisaccade condition, to encourage the prepotent response of looking at the emerging stimulus. Each condition consisted of 30 trials, 15 with the yellow cube presented on the left and 15 on the right. The right/left position of the yellow cube was randomized. The dependent variable was the RT in ms to the correct responses in the antisaccade condition.

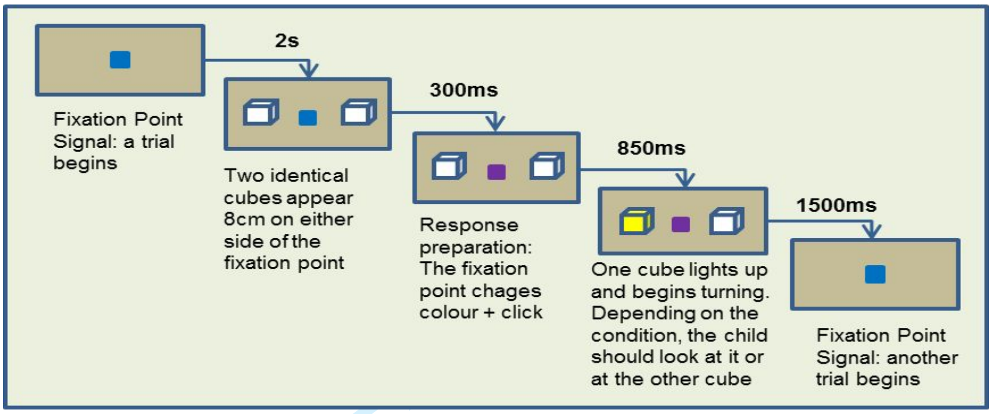

Fig. 5. Antisaccade task trial example

We recorded fixation points, fixation times, gaze direction, and time between saccades using the *Tobii Gaze Viewer*. Gaze fixations and gaze tracking were initially calibrated with Gaze Viewer Software as explained above. Anticipation (looking in a direction before the appearance of the required stimulus), omissions (not looking towards the required stimulus) and substitutions (looking towards the non-required stimulus) were classified as errors.

Day-Night Task (Gerstadt, Hong & Diamond, 1994). This task was created to study the development of inhibitory control in young children (McAuley, Christ & White, 2011) and it has recently been used to assess inhibitory capability in CP (Li et al., 2014). We followed the same procedure as Diamond, Kirkham & Amso (2002). In each of the 32 trials, a 14x10cm card was presented on the screen with a drawing of the Sun or the Moon. In the congruent condition (16 trials), the child had to respond "day" when the Sun card appeared, and "night" when the Moon card appeared. Conversely, in the incongruent condition (16 trials), the participant had to respond "night" to the image of the Sun, and "day" to the image of the Moon. The congruent condition was carried out first to consolidate the prepotent responses. A click accompanied every stimulus that appeared on the screen, so telling the child that the image had been changed (even if it was the same drawing as before) and he/she was told to answer. As soon as the verbal response had been given, the next stimulus was presented. The dependent variable was measured with the RT of the incongruent condition.

2.3. Procedure

The participants were individually assessed in a room suitable for the purpose. Application of all tasks lasted on average between 2 hours and 2 hours 30 minutes for both groups.except for some children with CP who needed more rest time between each block, condition or tasks.

Before all the experimental tasks, practice trials were carried out until it was sure the participant had fully understood the task. A five-minute break was given between each condition, and block and task, except for some children with CP who needed more rest time. Feedback was only given in the practice trials, and while the children were doing the tasks, they were encouraged to keep them motivated.

As stated above, for the antisaccade task, every participant was given an initial calibration to determine whether the gaze had a minimum quality for recording and analysis, and he/she was placed on a chin holder to prevent head movements contaminating the data.

The Columbia Mental Maturity Scale assessment and processing speed task were presented first and last, respectively. The temporal generalisation, temporal reproduction, day-night, and antisaccade tasks were counterbalanced.

3. Results

Table 2 shows the descriptive statistics of the two groups.

Table 2. Means and Standard Deviations (SD) in the two groups in all variables.

	Cerebral Palsy Group		Control Group	
	Mean	SD	Mean	SD
Reproduction**	4433	686	2351	566
Generalisation*	.48	.08	.68	.13
Day-Night (Incongruent)**	41748	9479	28285	3480
Day-Night (Congruent)**	32087	7153	23406	2910
Antisaccade (Incongruent)**	911	265	575	63
Antisaccade (Congruent)**	657	218	421	70
Mental Age (years)	7 ½;	1.4	7 ½;	1.4
Processing Speed*	.78	.13	.98	.02

* Proportion of correct responses.
** ~~TR in~~ Milliseconds

We first tested whether the children with CP had inhibitory and temporal perception impairments. For that purpose, different one-way ANCOVAs were carried out for each of the inhibition and temporal processing tasks, with the group as independent variable and mental age and processing speed as covariates. Additionally, we explored the relationship between inhibitory control and temporal processing tasks through correlation and regression analysis in both groups.

3.1. ANCOVA analysis

3.1.1. Temporal processing

In relation to the Temporal Reproduction task, the effect of the two covariates were significant: F (1, 28) = 5.04; p=.033; ηp^2 = .15 for processing speed, and F (1, 28) = 20.91; p<.001; ηp^2 = .43 for mental age. There was also a significant group effect, F (1, 28) = 54.74; p <.001; ηp^2 = .66, after controlling for the effect of processing speed and mental age, with the average deviation time being greater in the CP group than in the control group (see Table 2). In the case of the Temporal Generalization task, only the mental age covariate was significant (F (1, 28) = 28.80; p <.001; ηp^2 = .51). We also found a significant group effect, F (1, 28) = 21.97; p <.001; ηp^2 = .44, after controlling for the effect of mental age, with lower correct responses in the CP group than in the control group (see Table 2).

3.1.2. Inhibitory Control

In relation to the Antisaccade task, the ANCOVAs showed a significant effect of the two covariates only for the correct responses of the incongruent (antisaccade) condition: F (1, 28) = 4.75; p = .038; ηp^2 = .14 for processing speed, and F (1, 28) = 6.09; p = .02; ηp^2 = .18 for mental age. There were no significant differences between groups in the correct responses of any condition, congruent (prosaccade) and incongruent (antisaccade), but a significant group effect was observed on the RTs both in the incongruent (antisaccade) condition (F (1, 28) = 10.67; p = .003; ηp^2 = .27), and in the congruent (prosaccade) condition (F (1, 28) = 5.37; p=.028; ηp^2= .16), after controlling for the effect of processing speed and mental age, with higher RTs in the CP group (see Table 2).

With regard to the Day-Night task, only the covariate mental age showed a significant effect on the RTs of both conditions: incongruent (F (1, 28) = 15.14; p =.001; ηp^2 = .35) and congruent (F (1, 28) = 6.30; p =.018; ηp^2 = .18). There were no significant differences between groups in the correct responses of any condition, congruent and incongruent, but a significant group effect was observed on the RT both in the incongruent condition (F (1, 28) = 15.57; p <.001; ηp^2 = .36), and in the congruent condition (F (1, 28) = 11.35; p =.002; ηp^2= .29), after controlling for the effect of mental age, the RTs in the CP group being greater than in the control group in the two conditions (see Table 2).

To summarize, as predicted, the results showed significant differences between groups in the RTs in the incongruent condition of both inhibitory tasks after controlling for the effect of processing speed and mental age.

However, unexpectedly, significant differences in the congruent conditions were also found. This could be due to the possible existence in the CP group of articulatory fluidity difficulties (Nordberg et al., 2015) as well as oculomotor control impairments (Fazzi et al., 2012) which could affect both conditions, incongruent and congruent. To control the possible effect of articulatory fluidity and gaze agility, following the procedure of Christ et al. (2003), we did the ANCOVAs again, introducing the inhibition variable scores of the congruent conditions as covariates. If the higher response time in the incongruent conditions in the CP group were due to articulatory and oculomotor difficulties, then, introducing the baseline (response time in congruent conditions) as covariate should make disappear the differences between the group with CP and the typically developing group. However, if the differences in response time in the incongruent conditions were due to inhibitory difficulties, after introducing the scores of congruent conditions as covariates, these differences between groups should be maintained.

The results indicated that the new covariate had a significant effect on both tasks: day-night (F (1, 29) = 37.47; p <.001, ηp^2 = .56) and antisaccade (F (1, 29) = 20.08; p <.001; ηp^2 = .41). When the RT of the congruent conditions was controlled, a significant effect of group was also observed in the incongruent condition of both tasks: day-night (F (1, 29) = 5.07; p =.032; ηp^2 = .15) and antisaccade (F (1, 29) = 5.53; p =.026; ηp^2 = .16) showing that CP group had more inhibitory difficulties than control group.

3.2. Relation between inhibitory control and temporal processing

To explore the relationship between inhibition and temporal processing, we first carried out partial correlations using processing speed as control variable. ~~Pearson correlations for each group~~ (see Table 3).

~~Table 3. Correlations in each group~~

~~Cerebral Palsy Group~~					
	~~Reproduction~~	~~Generalisation~~	~~Day-Night~~	~~Antisaccade~~	~~Processing Speed~~
~~Generalisation~~	~~-.62*~~				
~~Day-Night~~	~~-.62**~~	~~-.66**~~			
~~Antisaccade~~	~~.13~~	~~.14~~	~~-.19~~		
~~Processing Speed~~	~~-.73**~~	~~.49~~	~~-.37~~	~~.06~~	
~~Mental Age~~	~~.83**~~	~~.66**~~	~~-.70**~~	~~.05~~	~~.65**~~

~~Control Group~~					
	~~Reproduction~~	~~Generalisation~~	~~Day-Night~~	~~Antisaccade~~	~~Processing Speed~~
~~Generalisation~~	~~-.41~~				
~~Day-Night~~	~~.60*~~	~~-.77**~~			
~~Antisaccade~~	~~.29~~	~~-.41~~	~~.20~~		
~~Processing Speed~~	~~.04~~	~~.14~~	~~.07~~	~~-.13~~	~~-.21~~
~~Mental Age~~	~~-.60*~~	~~.81**~~	~~-.72**~~	~~-.21~~	~~-.19~~

~~** *p*< .01 * *p*< .05~~

Table 3. Partial correlations controlling for processing speed.

CP Group				
	Reproduction	Generalisation	Day-Night	Antisaccade
Generalisation	-.47*			
Day-Night	.55*	-.60**		
Antisaccade	-.13	.13	-.18	
Mental Age	-.68**	.55*	-.66**	.02
Control Group				
	Reproduction	Generalisation	Day-Night	Antisaccade
Generalisation	-.43			
Day-Night	.60**	-.79**		
Antisaccade	.30	-.40	.22	
Mental Age	-.60**	.86**	-.73**	-.25

** *p*< .01 * *p*< .05

The correlational analysis showed a significant correlation between the day-night task and the temporal tasks in the CP group (*r*= .55~~62~~ with reproduction and *r*= -.60~~66~~ with generalization) and in the control group (*r*= .60 with reproduction and *r*= -.79~~77~~ with generalization) when the effect of the processing speed variable was controlled. However, the antisaccade variable did not show any significant relation to the temporal variables, and therefore, it was not included in subsequent analysis.

Mental age had a high and significant correlation with the two temporal variables both in the CP group (r = -.68~~83~~ in reproduction and r= .55~~66~~ in generalization) and in the control group (r= -.60 in reproduction and r= .86~~81~~ in generalization).[2]

Next, because our second objective was to investigate whether inhibition capacity influences temporal processing, we carried out several stepwise regression analyses following the forward method, for each of the dependent variables, the temporal reproduction, and temporal generalization tasks, for each group separately. As the first predictor we used the processing speed variable to control its effect, and then, as the second predictor, the Day-Night task, the only inhibitory measurement that had a significant correlation in each group of participants.

~~The results of the regression analysis showed that the Day-Night task on its own was a significant predictor of the temporal variables in both CP and typically developing children (see Table 4). Regarding the reproduction task, the Day-Night task explained a considerable proportion of the variance in the two groups (R^2= 39 and R^2= 37 in CP and control group respectively), and, in the case of the generalisation task, this response inhibition measure explained even a larger proportion of variance (44% in the CP group; 59% in the control group).~~

~~Table 4. Regression analysis results for each group with the Day-Night as predictor~~	
	~~Cerebral Palsy Group~~

2 Note that these correlations reflect relationships among mental age and temporal measures within each group, not between group differences in mental age, which were controlled. This issue is considered in the Discussion section.

	Reproduction			Generalisation		
	B	SE	β	B	SE	β
Day-Night	.045	.015	.623	-6.115E-6	.000	-.661
R^2	.39 (p =.010)			.44 (p =.005)		
	Control Group					
	Reproduction			Generalisation		
	B	SE	β	B	SE	β
Day-Night	.098	.035	.605	-2.992E-5	.000	-.768
R^2	.37 (p =.013)			.59 (p =.001)		

For the temporal generalisation task, regression analysis allowed just one significant model in both groups of participants, the Day-Night task being the only significant predictor both in the control (R^2= .59, p = .001, β = -.77) and in the CP (R^2= .44, p = .005, β = -.66) groups. The same pattern was obtained for the control group in the case of the temporal reproduction task, with the Day-Night as the only significant predictor (R^2= .36, p = .01, β = .60).

However, for the temporal reproduction task, regression analysis on the CP group allowed two models. In the first model, processing speed explained 54% of the variance (R^2= .54, p = .001, β = -.73); the introduction of Day Night task increased the explained variance by 14% (ΔR^2=.14, p = .03, β = .40).

Table 4. Result of the regression analysis for each group.

Cerebral Palsy group

	Temporal Reproduction			Temporal Generalisation			
	B	*SE*	*β*		*B*	*SE*	*β*
Step 1				*Step 1*			
Constant	7404.47	740.18		Constant	.74	.08	
P. Speed	-3772.18	927.42	-.74**	Day-Night	-.01	.00	-.66**
Step 2							
Constant	5568.73	994.67					
P. Speed	-2997.03	862.70	-.58**				
Day-Night	.03	.01	.40*				
R^2 = .54 (*p* = .001) ΔR^2 = .14 (*p* = .03)				R^2 = .44 (*p* = .001)			

Control Group

	Temporal Reproduction			Temporal Generalisation			
	B	*SE*	*β*		*B*	*SE*	*β*
Step 1				*Step 1*			
Constant	-430.79	985.94		Constant	1.53	.19	
Day-Night	.10	.03	.60*	Day-Night	-.03	.00	-.77**
R^2= .36 (*p* = .01)				R^2=.59 (*p* = .001-)			

P. Speed: Processing Speed. *SE*: Standard Deviation of *B*.
***p* < .01; **p* < .05

4. Discussion

This study was carried out with two aims: to find out if there were inhibitory control and temporal perception impairments in children with CP, and to investigate the relationship between the executive function of inhibitory control and temporal processing. We hypothesized that children and adolescents with CP would have lower performance in inhibitory control tasks (Bottcher, 2010; Christ et al., 2003; Kolk, & Talvik, 2000; Li et al., 2014; Pirila et al., 2011; Schatz, Craft, White, Park, & Figiel, 2001; Straub & Obrzut, 2009) and temporal estimation tasks than typically developing children. Moreover, we expected that the differences between the children with CP and typically developing children in inhibitory tasks would be especially significant under conditions of maximum interference, i.e., in the response time of the incongruent conditions. Secondly, we hypothesised that inhibitory control abilities would be related to temporal processing capacities (Brown, & Perreault, 2017; Choe, 2013; Correa et al., 2010; Los, 2013; Rubia et al., 2009), so that adequate functioning in inhibitory control would predict better results in time perception.

With regard to the first hypothesis, we found that, as expected, children and adolescents with CP showed significantly worse performance both in temporal estimation and inhibitory control tasks than typically developing children, even after controlling for the effect of mental age, and processing speed., as well as factors related to motor problems inherent to cerebral palsy.

The response inhibition difficulties that we found in children with CP corroborate other previous results (Bodimeade et al., 2013; Bottcher et al., 2010; Christ et al., 2003; Li et al., 2014; White, & Christ, 2005). Moreover, and importantly, our study showed that children with CP also have a deficit in estimating event duration, an aspect that, to the best of our knowledge, has never been investigated before.

About the second hypothesis, we found, as expected, that these response inhibition deficits are related to worse performance in temporal abilities in children with mental ages 5½-10 years, irrespectively of whether they had CP or not. These results support with children with CP the outcomes of previous studies that showed mutual interaction between executive control and time perception abilities in typically developed children (Droit-Volet, 2011; ; Droit-Volet, 2016; Droit-Volet et al., 2006;

Droit-Volet et al., 2015; Gautier, & Droit-Volet, 2002b; Meaux & Chelonis, 2005; Zelanti & Droit-Volet, 2011; Vicario, 2013) and in adults (Block et al., 2010; Brown, Johnson, Sohl, & Dumas, 2015; Brown, & Perreault, 2017; Mäntylä, Carelli, Forman, 2007; Ogden, Samuels, Simmons, Wearden, & Montgomery, 2017; Reynolds, & Schiffbauer, 2004; Wittman, & Paulus, 2008), at both behavioural and neurological levels (Berlin, Rolls, & Kischka et al., 2004; Neufang et al, 2008; Wittmann et al., 2011).

However, not all the inhibitory tasks used in this study worked in the same way. Only the Day-Night task had a significant predictive value over the two temporal perception tasks, while the Antisaccade task did not show any significant relationship with the temporal tasks. One possible explanation for these results is what is called "task impurity" attributed to executive tasks (Miyake & Friedman, 2012); in other words, the possibility that both tasks could measure not only response inhibition but also other processes that could be non-executive or require more than one executive function (Van der Sluis, de Jong, & van der Leij, 2007). Furthermore, in the group with CP, processing speed explained the highest proportion of variance of the reproduction task, but not in the generalisation task. It could indicate that, despite the effort made to control the processing speed, it is undeniable that children with CP have longer reaction times and slower processing speed than typical development children. Thus, it is possible that these problems would cause disadvantages when performing temporal tasks, especially in those whose dependent variable was time, as it was the case of the temporal reproduction task. This is an important issue that must be taken into account in future research on temporal skills in cerebral palsy.

Additionally, in our study, regression analysis showed that the relationship found between inhibitory control and temporal processing was analogous in both groups—typically developing children and the CP group—the proportion of explained variance being higher for the generalization task (44% in the CP group; 59% in the control group) than for the reproduction task (14~~39~~% in the CP group; 36~~7~~ % in the control group)[3]. This different contribution to the two temporal tasks could be due, as Droit-Volet suggests (2016; see also Droit-Volet et al., 2015), to the fact that each of the time judgment tasks is influenced by dissimilar cognitive abilities, so that reproduction task demands less attentional resources because it only requires temporal estimation, whereas the generalisation task also demands a process of decision making about whether or not a stimulus lasts as long duration as the previously presented one. Thus, the generalisation task would require a higher cognitive load, adding other processes to the temporal estimation activity itself, which would imply an additional inhibitory effort (Brown et al., 2015).

~~Likewise, not all the inhibitory tasks used in this study worked in the same way. Only the Day-Night task had a significant predictive value over the two temporal perception tasks, while the Antisaccade task did not show any significant relationship with the temporal tasks. One possible explanation for these results is what is called "task impurity" attributed to executive tasks (Miyake & Friedman, 2012); in other words, the possibility that both tasks could not only measure response inhibition but also other processes that could be non-executive or require more than one executive function (Van der Sluis, de Jong, & van der Leij, 2007).~~

[3] The proportion of explained variance for the reproduction task in the CP group was .54, but the increment of R^2 after introducing the inhibitory variable was .14.

Even so, and despite the disparities between tasks, the results showed that response inhibition predicted temporal estimation abilities mostly in the same way in children with CP and typically developing children. This may be due to the fact that in the mental age range used (5~~½~~.6 to 10 years) the ability to estimate durations still depends on the maturation of other cognitive functions (Droit-Volet, 2013; Hallez, & Droit-Volet, 2017), such as response inhibition, which at this age is in full process of development and consolidation (Diamond, 2006, 2013). That is to say, given that the participants of the two groups were matched by mental age, and that mental age correlates strongly with timing tasks (Mosing, Verweij, Madison, & Ullén, 2016; Holm, Ullén, & Madison, 2011) and inhibitory control (Duan, Wei, Wang, & Shi, 2010; Hooper et al., 2008), the partially acquired inhibition ability would have similar and proportional weight in the competence of temporal processing in both groups.~~, without forgetting, as we have previously indicated, that children and adolescents with CP presented significant problems in inhibition and temporal perception, compared to their typical development peers~~. However, further research would be necessary in order to replicate these pioneering results and to test whether this pattern would also be observed long after adolescence when inhibition abilities have been consolidated.

Moreover, the relation between mental age and temporal and inhibitory abilities deserves a deeper explanation. As we explained in the Methods section, to control the influence of mental age, the participants of both groups were matched by mental age to ensure equivalence of the two groups in this variable. However, this does not mean that mental age did not have some effect on inhibition or temporal estimation tasks. In fact, our results did show that mental age (as a measure of cognitive development) was significantly related both to temporal estimation abilities and to response inhibition in a similar way both in typically developing children and in the CP group, which could be reflecting the well-documented relationship between cognitive development and temporal estimation performance (Droit-Volet et al., 2015; Zelanti, & Droit-Volet, 2011; Vicario, 2013) and response inhibition abilities (Fischer, Biscaldi, & Gezeck,1997; Levin, et al., 1991; Luna, Garver, Urban, Lazar, & Sweeney, 2004; Munoz, Broughton, Goldring, & Armstrong, 1998; Ridderinkhof, Band, & Logan, 1999; Ridderinkhof, van der Molen, Band, & Bashore, 1997).

These results, although tentative, could have some important practical implications. Our results showed that CP children have deficits in the inhibitory control of responses. Given the influence of inhibitory control on academic performance, social participation, functional independence in everyday activities, and quality of life (Bottcher, 2010; Sakash, Broman, Rathouz, & Hustad, 2018; Laporta-Hoyos et al., 2017; Whittingham et al., 2014), it would be crucial to establish specialized programs for training inhibitory control of responses, to encourage both their cognitive and behavioral development (Bodimeade et al., 2013; Bottcher et al., 2010; Sørensen, Liverød, Lerdal, Vestrheim, & Skranes, 2016). Along with this, and taking into account the problems of temporal processing that we have found in children and adolescents with CP, these problems should be addressed in the clinical intervention. This intervention should be directed not only to the organization of responses in the environment over time or to the acquisition of temporal estimation skills, matters that have not yet been considered to our knowledge, but also with regard to the association of their inhibition capacity with timing abilities, crucial for self-control as well as for emotional and behavioral regulation in cerebral palsy (Parkes et al., 2008; Sigurdardottir et al., 2010; Weber et al., 2016). In this regard, train CP children in matters like delaying of gratification, producing of appropriate responses at the right time, or the organization of daily life activities (Barker et al., 2014; Bembenutty, & Karabenick, 2004; Wulfert, Block, Santa Ana, Rodriguez, & Colsman, 2002), issues that are essential for improving social adaptation and quality of life (Bodimeade et al., 2013; Bottcher et al., 2010; Brossard-Racine, et al., 2012; Whittingham, Sanders, McKinlay, & Boyd, 2014)., could be especially indicated.

Nevertheless, although the most important new result of our study was the link found between inhibitory control and temporal estimation abilities in children and adolescents with CP, given the small sample sizes, this study must be considered preliminary and its results tentative, and so should be confirmed in subsequent research. Future lines of research with larger sample sizes would address how inhibitory control evolves in children with cerebral palsy, and whether an age-related improvement of their response inhibition capacities also promotes a better acquisition of their temporal perception skills.

5. Conclusions

This study has revealed the existence of inhibition and temporal processing deficits in children and adolescents with CP, compared with typically developing children. It has also shown that the two functions are related and that this relationship is maintained in both groups, allowing us to state that adequate functioning of inhibitory control is associated to the development of temporal processing abilities. Even so, replication of this study with larger samples would be necessary.

More neuropsychological and neuroimaging research would be required to establish whether inhibition and temporal perception share anatomical structures, and if the brain lesions that commonly affect individuals with CP caused the deficits in both functions.

Taking into consideration the crucial role that inhibition exerts in the control of actions and emotions (Diamond, 2013, Munakata et al., 2011), our results indicate the need to train children and adolescents with CP in executive functioning (Piovesana et al., 2017), and specifically in inhibition and temporal processing in order to enhance their cognitive and emotional regulation.

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