

# Human-Computer Interaction for Users with Cerebral Palsy Based on Head Orientation. Can Cursor's Movement Be Modeled by Fitts' Law?

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## Abstract

This paper presents an experiment to validate a head-mounted inertial interface for human-computer interaction (HCI) developed for people with cerebral palsy (CP). The method is based on Fitts' law, an empirical model of human motor performance for aimed movements. Head motion is recorded in a series of goal-crossing tasks and a regression model of the movement time ( $MT$ ) is estimated for each user. Values of  $R^2$  above 0.9 are indicators of a strong correlation of those motion patterns with the linear model proposed by Fitts. The analysis of  $MT$  confirmed that head movements of non-disabled users follow Fitts' law and showed that 3 users with CP (MACS IV and V) had the same behavior. There was a weaker correlation ( $R^2=0.839$ ) for one individual with cervical dystonia and ballistic movements and no correlation for two users with cervical hypotonia and dyskinetic CP. Results show the

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impact of ballistic movements and poor postural control in computer interaction and provide the foundation for new interaction techniques to develop a universal computer interface for motor impaired users.

*Keywords:*

Fitts' law; Inertial sensor; Human-computer interaction; Cerebral palsy; Motor disorder; Head orientation

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## **1. Introduction**

Cerebral palsy (CP) is one of the most severe disabilities in childhood and makes heavy demands on health, educational, and social services as well as on families and children themselves. Bax et al. (2005) defined CP as 'a disorder of movement and posture due to a defect or lesion of the immature brain'. For practical purposes, it is usual to exclude from CP those disorders of posture and movement which are (1) of short duration, (2) due to progressive disease or (3) due solely to mental deficiency. The prevalence of CP is internationally 1.5-2.8 cases per 1000 births. In the United States 0.5 million infants are affected by CP (Winter et al. (2002)) and those figures are slightly higher in Europe (Johnson (2002)); the overall rate for the period from 1980 to 1990 was 2.08 per 1000 live births and there are nearly 17 million people with CP worldwide of all ethnicities and social status. The work 'Surveillance of cerebral palsy in Europe: a collaboration of cerebral palsy surveys and registers' presented a consensus that was reached on a definition of CP, description and classification in terms of nosology, topography and function (severity). SCPE (2000) divides the CP, according to a nosological classification, into three types: spastic, ataxic and dyskinetic.

Spastic CP is the most common form (70-80% of the individuals with CP are affected by spasticity) and is characterized by at least two of these signs: abnormal pattern of posture and/or movement, increased tone and pathological reflexes. It may be either bilateral or unilateral. Ataxic CP (6%) is characterized by both abnormal pattern of posture and/or movement and loss of orderly muscular coordination; movements are performed with abnormal force, rhythm and accuracy. Dyskinetic CP (6%) is dominated by both abnormal pattern of posture and/or movement; and involuntary, uncontrolled, recurring, occasionally stereotyped movements (SCPE (2000)).

CP can affect different parts of the body. We will refer as unilateral or bilateral CP if it affects one or two sides of the body, respectively, and quadriplegia or diplegia when both arms and legs or only legs are damaged. Manual ability is an issue in at least two thirds of children with CP and it affects activities such as eating, dressing, writing or playing. Severe motor disorders in combination with sensory and cognitive alterations result in great difficulties for these people to communicate and interact with their environment. Consequently, alternative channels to control devices such as tablets, PCs and others are needed in order to overcome some of these limitations and promote neural plasticity, specially during childhood.

Many authors have approached the development of alternative interfaces in response to the special needs of people motor with disorders. Those solutions are multi-platform (PC, tablets, smartphones) and multi-action-pointing (Tuisku et al. (2014)), dragging (Cockburn et al. (2012)), scanning (Biswas and Langdon (2013)) or scrolling (Zhao et al. (2014)). The interface translates voluntary actions, registered as physical gestures (Rempel

et al. (2014)), muscle activity (Chen and Wang (2013)), gaze and or head tracking (Špakov et al. (2014)), voice, etc. or other measurements such as evoked potentials (Schlögl et al. (2009)) into input commands. Davies et al. (2010a) systematically reviewed over thirty devices and technologies that enabled or enhanced computer access for individuals with CP, including pointing devices (Wu and Chen (2007)) and keyboard modifications (Lin et al. (2008)), adapted GUIs (Simpson et al. (2006)), filters and facilitation algorithms (Olds et al. (2008)) and speech and gesture recognition. While these solutions may enable computer access for this population, few of them had undergone systematic evaluation for CP. As Almanji et al. (2014) argued, the use of assistive technology for computer access encounters barriers that lead to the use of typical mice, track balls or touch screens for practical reasons. They proposed new metrics to describe the motor behavior of users with diplegia in order to develop new techniques that could facilitate pointing tasks, which is vital since Davies et al. (2010b) found that 65% of youths with CP that were MACS IV and V couldn't use standard mice nor keyboards. Motivated by Almanji's study, we aim to find the answer to the following questions:

1. Does a pointing device such as ENLAZA, presented by Raya et al. (2012) and based on head motion, follow Fitts' law (Fitts (1992)) when it is used by people without motor disabilities?
2. If the answer to (1) is affirmative, is ENLAZA also a valid interface (i.e. motor behavior can be modeled by Fitts) for people with CP? We will focus on those with diplegia and quadriplegia and manipulation skills classified as MACS IV and V.

In order to answer these questions, we will quantify how effectively these users are able to access the computer by means of modeling their movement times with Fitts' law. Even though Fitts' law describes, by definition, upper limb motor behavior, we believe that head motion during pointing tasks with a direct pointing device is of the same nature. Therefore, we hypothesize that Fitts' law fully applies in the movement times measured for non-disabled users. Although users with CP will most likely show poorer task performance, we are interested in analyzing how motor disorders interfere with the system's usability. While Davies et al. (2014) observed that Fitts' law did not apply in youths with CP, Almanji et al. (2014) specified that there was a correlation speed and accuracy, but not as strong as in typically developing youths. We expect to be able to confirm some of Almanji's findings. The analysis of data will provide us with information about which are the profiles of motor impairment that are best and worst modeled by Fitts' law in an heterogeneous group of users with CP. That can lead to changes in the calibration process or the development of new control strategies for the interface based on head movement.

## **2. Background**

### *2.1. Pointing models*

Fitts' law is an empirical model that explains trade-off characteristics between speed and accuracy for human movement during pointing tasks. The model was first developed for the optimization of worker efficiency during assembling tasks in production lines (Fitts (1992)). After Card et al. (1978), it has been widely applied in Human-Computer Interaction (HCI) and the

design and validation of graphical user interfaces (GUI).

Fitts' law models the human motor system as a communication channel with a certain bandwidth, measured in bits per second. Information is transmitted through the channel by performing a movement of a certain difficulty, measured in bits. Fitts defines a simple pointing task where the subject has to perform a movement of amplitude  $A$  to reach a target of size  $W$ . The model states that movement time ( $MT$ ) is a linear function of the index of difficulty ( $ID$ ).

$$MT = a + b * ID \quad (1)$$

Parameters  $a$  and  $b$  are named intercept and slope. The Shannon formulation used by MacKenzie (1989) represents the  $ID$  as:

$$ID = \log_2\left(\frac{A}{W} + 1\right) \quad (2)$$

The standard *ISO 9241-Part 9. Requirements for non keyboard input devices* defines the *Throughput*,  $TP$ , to quantify the performance in a reaching task with pointing devices. It is based on the time needed to complete the task and its difficulty and is considered a more robust parameter than the  $MT$  itself. The difficulty of the task is quantified by the index of difficulty,  $ID$ , which is based on  $A$  and  $W$ . The  $TP$  during a single task is:

$$TP = \frac{ID}{MT} \quad (3)$$

Wobbrock et al. (2011) extrapolated Fitts' model to a two-dimensional (2D) solution and compared two approaches for the estimation of the task *Throughput*: slope-inverse throughput,  $TP_{inv}$ , and mean-of-means throughput,  $TP_{avg}$ . They concluded that  $TP_{avg}$  agrees most across dimensionalities

and exhibits smaller variance among users.

$$TP_{inv} = \frac{1}{b} \quad (4)$$

$$TP_{avg} = \frac{ID_{avg}}{MT_{avg}} \quad (5)$$

Although each throughput calculation results in a bits/s measure, they consider different things. It is reasonable, then, to report all throughputs rather than adhere to one of them.

## 2.2. Pointing strategies

Wall and Harwin (2000) among others were critical of the classic *reciprocal tapping* because the subjects quickly learned to improve their performance during the repetitive action: what is “unrepresentative of most pointing tasks”. Soukoreff and Mackenzie (2004) achieved a standardization in the evaluation of pointing devices and Fitts’ law, but there are some scenarios and new ways of interaction that must be considered.

Quinn et al. (2013) simulated beginner and expert behavior with two pointing techniques (*random* task and *bi-directional tapping*). They described each trial as a 3-phase sequence (initiation, execution of movement and confirmation of cursor location) and found that the initiation phase was larger for random tasks. In a calibration stage *random* showed worse correlation with the linear model model than *bi-directional tapping* perhaps due to the initiation phase component, although both of them were considered good matches ( $R_{rnd}^2 = 0.96$ ,  $R_{tap}^2 = 0.99$ ). Cockburn et al. (2012) found that Steering law models *MT* better than Fitts’ law in *radial* selections.

Accot and Zhai (2002), Apitz and Guimbretière (2004) and Apitz et al. (2010) analyzed whether crossing boundaries could complement or replace

the traditional *enter object and select it* paradigm with a stylus and observed that “goal-crossing indeed follows a quantitative relation among movement time, movement distance and the constraint of the goal width” and “that relationship takes the same form as in Fitts’ law”. Goal-crossing *MTs* were shorter or no longer than pointing and selection under the same *ID*. Luo and Vogel (2014) extrapolated this analysis to direct touch input and confirmed Accot’s hypothesis.

### 2.3. Pointing devices

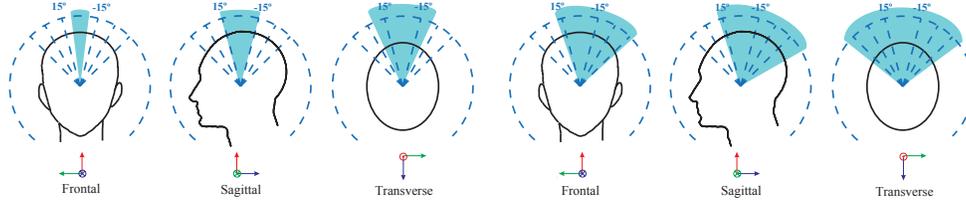
Fitts’ law is often used to evaluate new input devices beside mice. Felton et al. (2012) and Kim et al. (2013) applied it to a brain-computer interface (BCI); Kim et al. (2015), to a BCI-gaze-tracking hybrid interface. A linear relationship between *MT* and *ID* was found for both pure and hybrid BCI interfaces. Tuisku et al. (2012) and Alonso et al. (2013) evaluated gaze-tracking interfaces with Fitts’ law and found poor correlation with the model, which is in contradiction with Surakka et al. (2004) and others. Alonso pointed out that *MT* depended on the size of the target more than on the distance as eye movements are extremely fast. Scheme et al. (2013) and Kamavuako et al. (2014) described two interfaces based on superficial and intramuscular EMG to displace the computer cursor in one and two dimensions, respectively. Fitts’ evaluation showed that *MT* and *ID* had a strong correlation when the reaching tasks involved movements in one axis, and stronger with intramuscular EMG. Scheme and Englehart (2013) and Williams and Kirsch (2015) assessed 3D motion with superficial EMG but Fitts’ law did not apply as participants tend to use sequential command strategies for combined movements in different axis. Rudigkeit et al. (2015) (and Radwin et al. (1990) before

them) assessed the usability of a head-controlled interface with a standard two-dimensional Fitts' law test and obtained promising results even though no regression model was calculated. Only Felton *et al.* recruited users with motor disabilities for the experiments, but the nature of the disorder was not available.

### 3. The ENLAZA interface

Raya et al. (2012) proposed the ENLAZA interface, an adapted input device for users with severe motor disorders (specially CP) that cannot use traditional solutions such as mice, joysticks or trackballs to access the computer. ENLAZA allows users to control the cursor of the computer with movements of their heads and consists of a headset with a cap and an inertial measurement unit, IMU (Werium S.L., Spain) as depicted in Figs. 2(a) and 2(b). It integrates a tri-axial gyroscope, accelerometer and magnetometer. It uses Coriolis force principle to measure angular velocity and Hooke's law for acceleration. The magnetometer measures Earth's magnetic field. The IMU design is based on MEMS technology and is available in a small package (27x35x13 mm, 27 grams). It is able to measure  $\pm 2.0$  Gauss,  $\pm 3$  g and  $\pm 500^\circ/s$  in the three axes. The angular resolution of the device is  $0.05^\circ$ , a static accuracy less than one degree and a dynamic accuracy of about  $2^\circ$  RMS.

IMU orientation is estimated based on the data recorded by the accelerometer, gyroscope and magnetometer. The three Euler angles  $\alpha$ ,  $\beta$  and  $\gamma$  (in the frontal, sagittal and transverse planes) are calculated from the



(a) User without motor disabilities.

(b) User with cerebral palsy.

Figure 1: Representation of the head orientation in the frontal, sagittal and transverse planes. The Euler angles displayed are, from left to right,  $\alpha$ ,  $\beta$  and  $\gamma$ . Recordings correspond to a total of 16 reaching tasks with the ENLAZA interface.

rotation matrix:

$$\mathbf{R}_{GS} = \mathbf{R}_S \cdot (\mathbf{R}_G)^{-1} \quad (6)$$

$$\alpha = \text{atan}\left(-\frac{\mathbf{R}_{GS}(2,3)}{\mathbf{R}_{GS}(3,3)}\right)$$

$$\beta = \text{asin}(\mathbf{R}_{GS}(1,3)) \quad (7)$$

$$\gamma = \text{atan}\left(-\frac{\mathbf{R}_{GS}(1,2)}{\mathbf{R}_{GS}(1,1)}\right)$$

where  $\mathbf{R}_G$  is defined as the rotation matrix of the global reference system corresponding to the neutral position of the head (looking at the center of the screen) and  $\mathbf{R}_S$  as the rotation matrix that describes the orientation of the sensor at each frame. For the purpose of this study, the mouse pointer is controlled with an *absolute control*, meaning that there is a unique mapping between head orientation and location of the pointer. After a calibration process, all pixels in the screen are reachable for the user's head Range of Motion, *ROM*, described by Bible et al. (2010). Examples of different *ROM* can be observed in Figs. 1(a) and 1(b). During the calibration, a therapist adjusts the gain of the transfer function that translates the orientation of the head into a location of the pointer on the screen.

During the development phase, many cases of overshoots and undershoots were found in users with preserved good gross motor control but poor fine motor control. That caused a number of sub-movements around any target they tried to select. Raya et al. (2012) developed a Robust Kalman Filter (RKF) that facilitates fine motor control based on the characterization of involuntary movements found in users with cerebral palsy. The filter prevents the trajectory of the pointer from being affected by ballistic, athetoid, dystonic or other associated involuntary movements often found in this population and reduces drastically the sub-movements around the target .

Prior to this study, Raya et al. (2013) and Velasco et al. (2014) had used the inertial interface ENLAZA for the assessment of impairment. Two metrics were proposed: frequency of movement and *ROM* of user’s head. *ROM* is defined as the difference between the maximum and minimum Euler angles measured in one of the anatomical planes: frontal, sagittal or transverse (Euler angles  $\alpha$ ,  $\beta$  and  $\gamma$ ). Results showed significant differences in the measured *ROM* between healthy subjects and users with CP due to the motor control and posture disorders. Figs. 1(a) and 1(b) depict the three angles measured in one user of each study group. Head motion was analyzed in the frequency domain but no significant differences were found, indicating that the frequency components of the involuntary movements in CP overlap with those of the voluntary motion.

#### **4. Experiment**

We based our experiment on goal-crossing random tasks instead of the standard bi-directional tapping and selection proposed by Soukoreff and

Mackenzie (2004). While this may seem to be rather unorthodox, we believe that the motor and cognitive profile of our participants with CP required a different approach. The standard task would be unattractive and tedious for most of our users and we are confident that the works of Accot and Zhai (2002), Quinn et al. (2013) and others support our experiment. Users wore the ENLAZA device to control the cursor of the computer with movements of their heads. They were instructed to locate the mouse cursor over an static target as quickly as possible. All the participants had previous experience with the device.

#### *4.1. Goal-crossing random task*

A simple videogame (see Fig. 2) was developed using Visual C# for the framework .NET 4.0. Each work session with the videogame consisted in reaching 17 targets on the screen: one for practicing (and in order to set the exercise's starting point) and 16 for assessment. The target was a Pink Panther face inside a squared, transparent frame and there was high contrast between the pink target and the white background. Between 2 consecutive goal-crossing tasks, a brief scene corresponding to 1/17 the length of a video was played in order to give the participants both a reward and time to rest. A new target appeared on the screen in a randomized order when the video scene stopped. The user would reach the end of the video after completing the 17<sup>th</sup> task. No errors could be made and there was not any preset timeout.

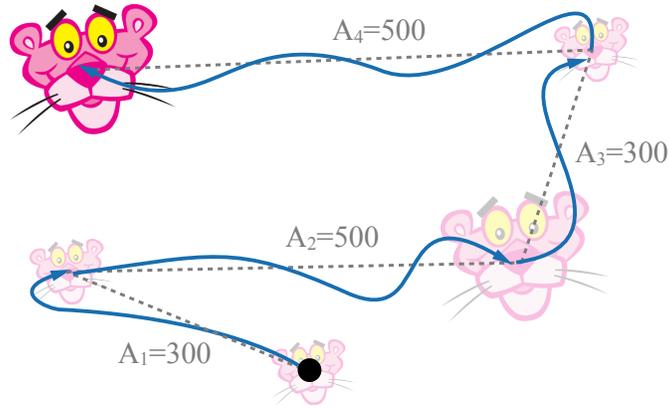
The location of the any new target was calculated as a function of the location of the cursor the very moment the video stopped. Two values of movement amplitude,  $A$ , were chosen; the target could be located at a distance of either 300 or 500 pixels from the position of cursor. Similarly, two



(a) IMU attached to the helmet.



(b) Participant from the CP group.



(c) Sequence of 4 random tasks with a goal-crossing strategy.

Figure 2: Experimental set up: the ENLAZA interface and representation of 4 random goal-crossing tasks in the *Pink Panther* videogame.

values of target size,  $W$ , were used: 100 or 200 pixels. Hence, there were 4 combinations of amplitude and width. In a session, the user had to perform four repetitions in a randomized order of those four  $(A, W)$  combinations, for a total of 16. Fig. 2(c) shows a series of 4 goal-crossing tasks in a randomized order: there are targets of two different widths,  $W$ , located at two possible values of amplitude,  $A$ . The dashed line represents the ideal trajectory while the solid line represents the actual path taken by the user. In this case, the

pairs  $(A, W)$  are:  $A_1=100$  px,  $W_1=300$  px;  $A_2=500$  px,  $W_2=200$  px;  $A_3=300$  px,  $W_3=100$  px;  $A_4=500$  px,  $W_4=200$  px. Note that the first target (marked with the black dot) is used as the exercise's starting point. The session was designed to not last more than 10 minutes in total, including goal-crossing task and the reproduction of the video. After each session the user could rest for five minutes.

#### *4.2. Participants*

A total of 15 users were recruited. Six users without disabilities, ND group, (age  $26.1\pm 4.2$ ) participated in the early experiments and completed  $3\pm 1$  training sessions before starting the study. Nine users with CP (age  $31.8\pm 9.2$ ) participated in second phase of the study at ASPACE Cantabria (Santander, Spain), a center specialized in CP and similar disorders. This study was approved by the Ethics Committee of ASPACE Cantabria and was in accordance with the Declaration of Helsinki on human research. Prior to the beginning of the tests, they had completed  $21\pm 7$  sessions with ENLAZA in two months and training games. Deficits in trunk control affect head stability as pointed out by Saavedra et al. (2010) and Saavedra and Woollacott (2015). Consequently, pelvic and torso support was provided for those participants with poor trunk postural control. Three of the participants left the study after a small number of sessions. Two of them had very poor motor control and difficulties to complete the task. Both continued using ENLAZA in less challenging activities. The third one was firstly included in the study but he was dropped out because he did not fully understand the proposed task due to his intellectual disability. Another participant had good performance but left ASPACE Cantabria before the end of the study.

Their tests are not included in the analysis. Table 1 depicts the classification of the users in terms of nosology and topology of the motor disorder. Table 1 also depicts their limitation in upper limb function. Some other descriptors that the therapists in ASPACE Cantabria considered relevant for the study can be observed in Table 2.

#### *4.3. Assessment of correlation with Fitts's law*

According to Fitts's law, the cursor's time of flight during a reaching task should be a logarithmic function of the target size and amplitude of movement, thus a linear function of the  $ID$ . A set of tests was defined to measure the Movement Time ( $MT$ ) during several goal-crossing tasks for predefined Indexes of Difficulty ( $ID$ ) and estimate the  $R^2$  value of the linear approximation of the  $MT-ID$  curves. As we mentioned earlier in the text, the tests are based on a series of tasks with 4 values of  $ID$ : 1.32, 1.8, 2 and 2.58 bits per second. A session with ENLAZA consisted in 4 repetitions of the task with each of the  $ID$  values enumerated in a randomized order. Each participant took part in 6 to 9 sessions depending on their availability during the study. In the end, an average value of  $MT$  for each of the 4 values of  $ID$  was used in the analysis. We define  $MT$  as the time the user needs to locate the cursor above the target. A linear regression is computed in order to fit a model to the data registered for individuals or groups. To measure the quality of the fit, the  $R^2$  or coefficient of determination was calculated from the residuals of the regression.

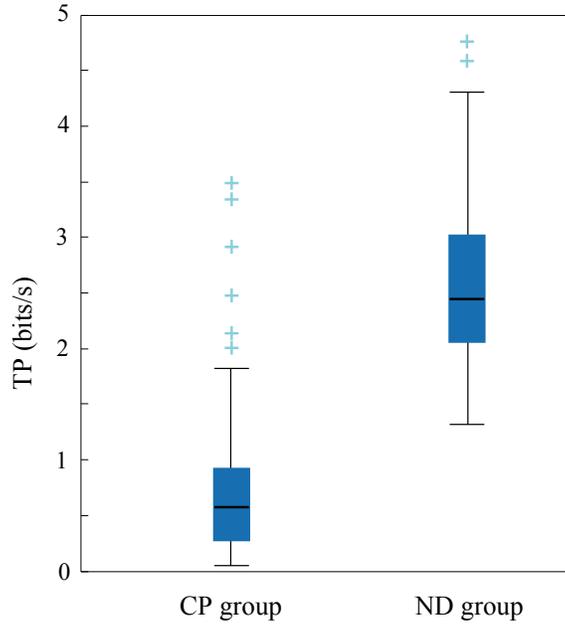


Figure 3: Measure of *Throughput* (TP) for the two groups. The box plots represent the values measured for each task during the work sessions of cerebral palsy group (CP) and users without motor disabilities (ND).

#### 4.4. Assessment of task performance

*Throughput* is the metric adopted to analyze task performance. Its value for each user will be estimated following three approaches,  $TP$  (as  $ID/MT$ ), mean-of-means throughput ( $TP_{avg}$ ) and slope-inverse throughput ( $TP_{inv}$ ). Please note that  $ID/MT$  is an estimation of the *Throughput* only in a certain reaching task,  $i$ .

## 5. Results

### 5.1. Correlation with Fitts' law

All  $MT/ID$  curves as well as the linear model estimated from the regression are plotted in Figs. 4 and 5. Linear regression of the experimental data resulted in the following equations (in seconds):

$$\begin{aligned} CP_{group} & : MT = -0.825 + 2.214 \cdot ID, \quad R^2 = 0.952 \\ ND_{group} & : MT = +0.474 + 0.137 \cdot ID, \quad R^2 = 0.924 \\ CP1 & : MT = -2.544 + 4.253 \cdot ID, \quad R^2 = 0.839 \\ CP2 & : MT = +0.094 + 1.004 \cdot ID, \quad R^2 = 0.980 \\ CP3 & : MT = +0.068 + 0.929 \cdot ID, \quad R^2 = 0.693 \\ CP4 & : MT = -2.412 + 3.939 \cdot ID, \quad R^2 = 0.785 \\ CP5 & : MT = +1.754 + 3.405 \cdot ID, \quad R^2 = 0.920 \\ CP6 & : MT = +1.387 + 2.241 \cdot ID, \quad R^2 = 0.918 \end{aligned} \tag{8}$$

Table 3 depicts movement times for each user and  $ID$  as well as the value of  $R^2$ . Despite the difference in the task performance, average motor performance of both groups was proven to fit the linear model proposed by Fitts's law, with  $R^2$  0.924 (ND) and 0.952 (CP). In terms of individual motor performance, the  $R^2$  calculated in 3 out of 6 participants with CP (CP2, CP5 and CP6) was above 0.9. In the case of CP1 (dystonia), it was slightly lower: 0.839. The lowest values of  $R^2$  corresponded to CP3 and CP4, both of them cases of cerebral palsy with cervical hypotonia.

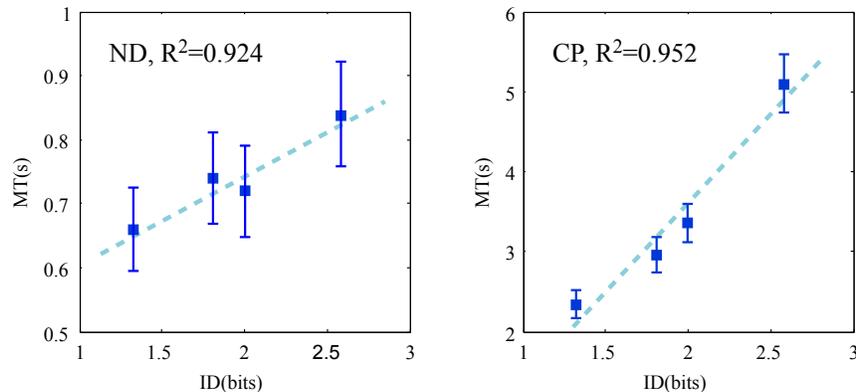


Figure 4: Representation of  $MT-ID$  curves measured in the experiments with the interface ENLAZA for both study groups: non-disabled users (ND) and users with cerebral palsy (CP). The value of  $R^2$  is an indicator of the good correlation with Fitts' law.

## 5.2. Task performance

As expected, non-disabled users (ND) were considerably faster and more efficient than those in the cerebral palsy (CP) group during the goal-crossing tasks proposed. The differences can be observed in Fig. 3. The  $MT$  registered was smaller (medians in ND and CP were 0.725 seconds and 3.290 seconds, respectively) and  $TP$  significantly larger in the ND group. The median values were 2.510 bits/s in the ND group and 0.572 bits/s among the users in the CP group ( $p < 0.01$ ). Table 4 depicts the results of the tests: the distribution of *Movement Time* and *Throughput* measured ( $MT$ ,  $TP$ ) as well as the mean-of-means throughput ( $TP_{avg}$ ). It can be observed that  $TP_{avg}$  is a good descriptor of the throughput since it is very similar to  $TP$  for all the users. There was no apparent relation between the performance of the task, described by  $TP_{avg}$ , and the goodness of the match with Fitts' law in terms of the calculated  $R^2$  for neither of the groups.

## 6. Discussion

Our goal in this study was to answer two questions concerning ENLAZA, a head mouse to access the computer specially developed as an adapted interface for people with severely affected manipulation skills. First, we were interested in capturing head movements of users without motor disabilities and evaluating whether those movements can be modeled by Fitts' law and there is a trade-off between speed and accuracy during pointing tasks. Secondly, provided that those head movements follow Fitts' law, we wondered if the linear model proposed by Fitts is also valid for users with severe motor and posture disorders such as those found in people with CP and diplegia or quadriplegia.

In the first phase of the experiments we measured the movement times of 6 users without motor disabilities and were able to estimate a good regression model of  $MT$  as a linear function of the index of difficulty for a series of random goal-crossing tasks. We observed that  $MT$  in the ND group (725ms) was not far from the values measured with standard mice by Luo and Vogel (2014), 716ms, or Aplitz et al. (2010), 500-600ms, for stylus. The second phase was also satisfactory as we achieved to estimate another linear model for 6 users with CP, even though they performed considerably poorer than the users without disabilities using the device. Davies et al. (2014) observed similar differences between typically developing youths (TDY) and youths with CP, MACS III and IV. Interestingly, they didn't find significant differences for  $ID$ s above 2 bits as we did and they concluded that Fitts' law is not valid for these kind of users. While our experiment and Davies' differ in several aspects (pointing device, pointing strategy, task, etc), the fact that

we use a RKF to filter some of the involuntary movements may be the key to explain why we found a strong correlation between *MT* and *ID*.

### *6.1. Experimental concerns and further work*

There are some limitations that are inherent to the population under study and the experiment itself. To begin with, the disability of the sample in our CP group (as CP itself) is rather heterogeneous in terms of muscular tone, postural control, involuntary movement and intellectual ability. Six users with CP is indeed a small number for any study, but the fact is that these limitations are shared with most of the publications reviewed and that points out the difficulties researchers find to recruit a large population of volunteers with CP and similar levels of severity. For instance, Davies et al. (2014) and Almanji et al. (2014) recruited 9 users MACS III and 3 MACS IV, but none MAC V; Saavedra et al. (2010), 3 users with CP GMFCS III. In addition, we had to deal with the daily routines of users with CP in AS-PACE Cantabria (with tightly scheduled occupational and physical therapy, lectures, transportation, lunch times, etc), that do not allow systematic testing. Instead, we were forced to plan shorter work sessions during a wider period of time that could be “squeezed” into their timetables. Finally, some aspects such as motivation or fatigue were not quantified although they may play an important role in the performance of the task. However, we found a consensus with the therapists in AS-PACE Cantabria and approached the subject by designing a protocol based on videogames in order to enhance user’s attention and minimize the effects of tedium that a traditional Fitts’ law study could cause in our users over the weeks of experimentation.

To gather a larger CP group to take part in a series of systematic tests

based on the traditional bi-directional tapping paradigm would be desirable for more robust statistical significance but that can only be achieved if we succeed to integrate this kind of exercises into these users' daily routines.

### *6.2. Explaining the impact of posture and motor control in goal-crossing tasks*

Three out of the six members of the CP group showed good correlation with Fitts' law (values of  $R^2$  greater than 0.9). We believe that low  $R^2$  may be a consequence of a poorer postural control, since the worst values of correlation were measured for users with decremented cervical tone and dyskinetic CP. Almanji et al. (2014) suggested that ballistic movements are common in CP and should be examined for computer interaction. Even though our RKF prevents most ballistic involuntary movements from affecting the trajectory of the cursor as Velasco et al. (2014) proved, the slightly lower value of  $R^2$  achieved by CP1 could be due to the residuals of his ballistic movements. More specific tests should be run with participants with hypotonic CP and or ballistic movements in order to establish whether their head movements follow Fitts's law. It would also be interesting to analyze different trajectory directions. That could give us some insight about how muscle weakness is affecting head movements and the interaction with ENLAZA.

### *6.3. Application of new input algorithms*

The strategy of interaction with ENLAZA, *absolute control*, is based on head posture and defines a direct relation between head orientation and cursor movement. The results of these experiments suggest that this strategy together with the RKF are a usable solution for most users with CP. However, we could implement new modes of control based on velocity rather than

orientation, as the one proposed by Rudigkeit et al. (2015). In parallel to Rudigkeit, we have developed a *relative control* based on the angular velocity measured by the gyroscopes. Preliminary results show that even if the user is leaning forward or backward due to muscle weakness, he or she will still be able to move the mouse pointer by small head movements. It is possible that those low values of  $R^2$  estimated in this study could be improved if those participants were using the relative control instead of the absolute control. In future studies, the relative control will be tested in users with cervical hypotonia. The aim of those studies will be to compare the task performance of the two possible control modes and to assess on the correlation with Fitts's law.

## 7. Conclusion

ENLAZA was developed as a universal interface for users with CP. While there have been efforts to analyze its usability (Raya et al. (2012), Raya et al. (2013) or Velasco et al. (2014)) none of this studies approached one of the most used paradigms in the HCI community; Fitts' law. Only two studies (Radwin et al. (1990) and Rudigkeit et al. (2015)) assessed head movements and Fitts' law but both of them counted with non-disabled users only. Our contribution was to fill that gap.

As expected, the movements of users without disabilities followed Fitts' law and we found good correlation for at least three users with CP (dystonic, spastic and mixed). We also found a weaker correlation for an user with dystonic CP and ballistic movements. Two users with dyskinetic CP and decremented muscular tone showed no correlation with Fitts' law. This

results encourages us to continue researching and developing new interaction techniques and facilitation algorithms towards the design of a universal interface for individuals with CP and other motion-impaired users.

## **Acknowledgments**

Authors would like to thank the members and staff in ASPACE Cantabria, specially Teresa González and Antonio Ruiz. This work was possible thank to ABC EU Project, CP WALKER Project, INTERPLAY Project and IVANPACE Project, which is funded by Obra Social de Caja Cantabria. A. Clemotte would also like to thank to Itaipu Binacional for its support.

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## **Vitae**

Miguel A. Velasco received the Telecommunication Engineering degree from Universidad de Zaragoza, Spain, in 2009 and the Master's degree in

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Rafael Raya received the Electronic and Automatic Engineering degree from the University of Córdoba, Spain, in 2006 and the M.S. and Ph.D. degrees from the University of Alcalá, Madrid, Spain, in 2008 and 2011, respectively. He was a Postdoctoral Fellow with the Harvard Medical School, Boston, USA, and with MOVE Institute (Vrije Amsterdam Universiteit, Amsterdam, The Netherlands). He is the author or coauthor of more than 40

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Dr Ramón Ceres, is Professor of Research at the Bioengineering Group of the Spanish National Council for Science Research (CSIC), received his Ph.D. at the Universidad Complutense of Madrid. He has led numerous R&D national and international projects, contributing to the creation of two spin off and other transfer technology processes. Is author of more than 250 publications centred on the field of research of the Assistive Technologies, particularly on sensors, interfaces and signal processing. He has worked in different positions, mainly in the rehabilitation field, being Founder President of Latin-American Association for Assistive Technologies AITADIS.

Eduardo Rocon was born in Vitoria, Brazil (1979). He graduated in Electrical Engineering at Universidade Federal do Espírito Santo (UFES) in 2001. From 1999 through 2000 he worked as a research associate at Laboratório de Automação Inteligente and successfully held a CNPq scholarship at UFES. Subsequently he moved to Spain to pursue a Ph.D. degree in Industrial Engineering at Universidad Politécnica de Madrid with Prof. Barrientos and Prof. Pons. His Ph.D. thesis (2006), for which he was awarded the Georges

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Table 1: User nosological, topographical and functional capacity classification.

User	Nosology	Topography	Function
CP1	Dystonic-Athetoid	Quadriplegia	Severe
CP2	Dystonic-Athetoid	Quadriplegia	Severe
CP3	Dyskinetic	Quadriplegia	Severe
CP4	Dyskinetic	Quadriplegia	Severe
CP5	Spastic	Quadriplegia	Severe
CP6	Mixed	Diplegia	Severe

Table 2: User description: relevant characteristics.

User	Cervical Tone	General Tone	Associated Movements	Intellectual ability
CP1	Dystonia	Dystonia	Ballistic movements	Normal
CP2	Hypertonia	Hypertonia	Athetoid movements	Normal
CP3	Hypotonia	Hypertonia	Dystonic movements	Normal
CP4	Hypotonia	Hypotonia	No movements associated	Mild disability
CP5	Hypertonia	Hypertonia	Athetoid movements	Medium disability
CP6	Hypotonia	Hypotonia	No movements associated	Medium disability

Table 3: Movement times and indexes of difficulty and  $R^2$  of the model.

User	ID (bits/s)				$R^2$
	1.32	1.80	2.00	2.58	
CP1	3.70s	5.17s	4.58s	9.18s	<b>0.839</b>
CP2	1.46s	1.92s	1.99s	2.74s	<b>0.980</b>
CP3	1.52s	1.72s	1.48s	2.72s	<b>0.693</b>
CP4	3.14s	3.24s	6.62s	7.70s	<b>0.785</b>
CP5	6.42s	7.22s	9.13s	10.52s	<b>0.920</b>
CP6	4.51s	5.57s	5.35s	7.41s	<b>0.918</b>
$CP_{group}$	2.34s	2.98s	3.35s	5.11s	<b>0.952</b>
$ND_{group}$	660ms	740ms	720ms	840ms	<b>0.924</b>

Table 4: Distribution of MT and TP and estimation of  $TP_{avg}$  and  $TP_{inv}$ .

User	MT(s)			TP(bits/s)			$TP_{avg}$	$TP_{inv}$
	25th Q.	50th Q.	75th Q.	25th Q.	50th Q.	75th Q.		
CP1	2.968	5.134	9.003	0.197	0.363	0.577	0.343	0.235
CP2	1.331	1.931	3.000	0.640	0.944	1.405	0.953	0.996
CP3	1.284	1.727	3.611	0.532	1.033	1.560	1.035	1.076
CP4	2.545	4.862	8.565	0.241	0.383	0.678	0.371	0.253
CP5	4.609	8.301	13.20	0.121	0.234	0.439	0.231	0.293
CP6	3.050	5.769	9.417	0.193	0.339	0.634	0.337	0.446
$CP_{group}$	1.801	3.290	7.022	0.278	0.572	1.004	0.559	0.451
$ND_{group}$	0.632	0.725	0.861	2.065	2.510	3.081	2.608	7.299

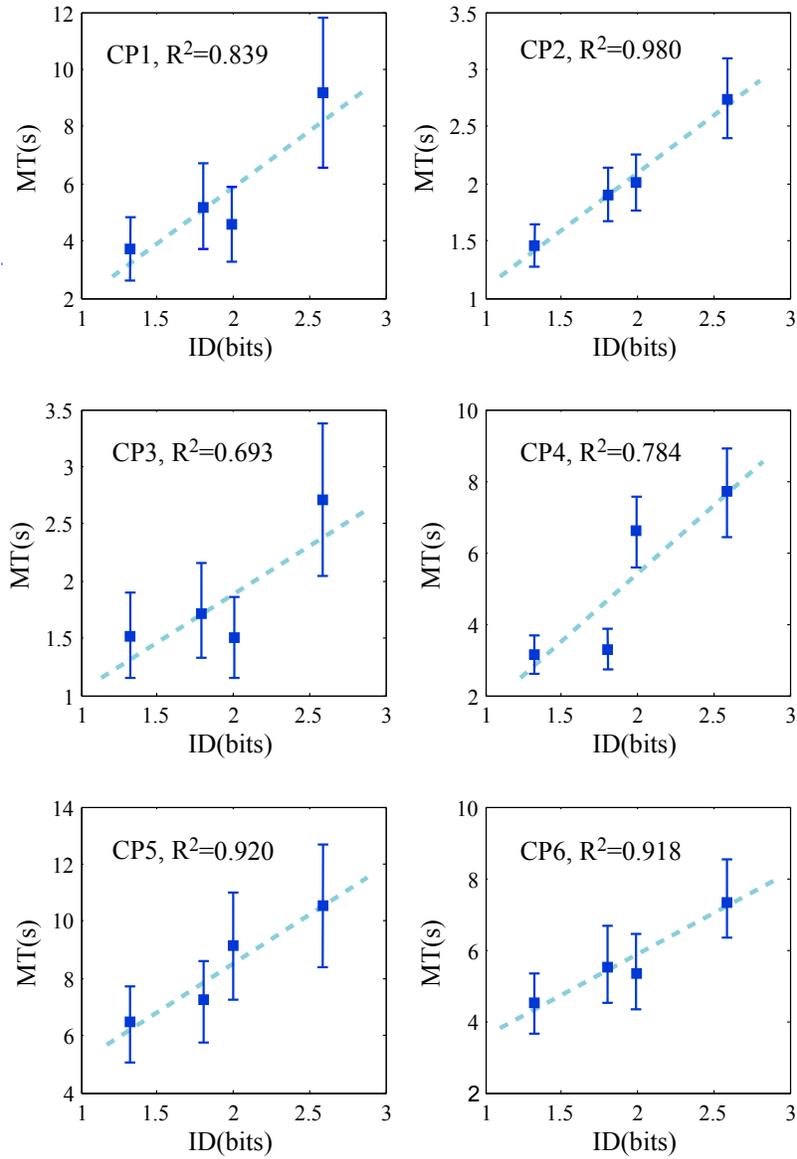


Figure 5: Representation of  $MT-ID$  curves measured in the experiments with the interface ENLAZA for the CP group. The value of  $R^2$  is an indicator of the good correlation with Fitts' law in 4 out of 6 users.