Speed-accuracy testing on the Apple iPad® provides a quantitative test of upper extremity motor performance in children with dystonia

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Abstract

The only currently available scales for quantitative measurement of the severity of childhood dystonia require human observer ratings and provide poor granularity in the scores for individual limbs. The recent availability of low-cost high-quality touchscreens suggests that these devices could be used for quantification of upper extremity severity. In this study we evaluated the use of an Apple iPad® for testing speed and accuracy in a simple pointing task. We compared the abilities or thirteen healthy adults, fifteen healthy children, and sixteen children with primary or secondary dystonia. The linear relation described by Fitts' Law held for all the groups. The movement time and the information transmitted were age and severity related. Our results provide evidence for the usability and validity of using Fitts' Law as a quantitative diagnostic tool in children with dystonia. Furthermore, testing on touch-screen tablets may help to guide the design of user interfaces to maximize communication rate for children who depend upon assistive communication devices.

Keywords

Dystonia; Fitts' Law; reaching; iPad®; human-computer interaction; transmission of information

Introduction

Childhood dystonia is defined as "a movement disorder in which involuntary sustained or intermittent muscle contractions cause twisting and repetitive movements, abnormal

postures, or both" (Sanger el al., 2003). Dystonia is particularly common in children with dyskinetic cerebral palsy (CP), which has an estimated prevalence of 25,000 children in the United States (Hagberg and Olow, 1975; Kyllerman et al., 1982; Kyllerman, 1982; Hagberg et al., 1989). Children with CP often must interact with the outside world through augmented and assistive communication (AAC) devices such as programmable touch screens. Thus, such children are dependent upon their sensory-motor abilities to activate the buttons on the screen.

The quantitative evaluation of dystonia is a critical aspect of clinical care, both during the first assessment and at follow-up visits, in order to evaluate medical treatment, physical therapy, and surgical interventions. Currently the sensory-motor abilities of patients with dystonia as well as severity are assessed by clinical scales, such as the Gross Motor Function Classification System (GMFCS) (Palisano et al., 1997), Burke-Fahn-Marsden dystonia rating scale (BFM) (Burke el al., 1985), the Barry-Albright Dystonia rating scale (BAD) (Barry et al., 1999) and the Unified Dystonia Rating Scale (UDRS) (Comella et al., 2003). The ease of use and immediate results are important features of these scales. However they are ordinal scales with a component of subjective interpretation, particularly for severity. Hence, adding a quantitative and objective test could be a very important adjunct for the sensory-motor assessment of childhood movement disorders, including dystonia.

In 1954 Paul Fitts (Fitts, 1954) proposed the first mathematical model to describe the trade-off between speed and accuracy. Derived from Shannon's information theory (Shannon and Weaver, 1949), Fitts hypothesized that the speed-accuracy relationship was due to a limitation of information transmission in the human motor system. He showed that movement time (MT) to reach a target increases with distance (D) and decreases as target size increases (W), such that $MT = a + b \log_2 (2D/W)$, wherein a and b are empirical constants for each subject, and $\log_2 (2D/W)$ represents the index of difficulty (ID) (Fitts, 1954; Fitts and Peterson, 1964). This relationship predicts that at a constant $2D/W$ ratio, MT will remain unchanged. Hence, MT is directly proportional to the ID, which may have the same value for different combinations of movement parameters D and W. The law has been validated in different experimental conditions, populations and devices (see Plamondon and Alimi, 1997 for a review). It has been shown that also children with congenital spastic hemiplegia obey Fitts' Law despite their limitations in fine motor control (Smits-Engelsman et al., 2007). Notwithstanding an increased signal dependent noise, Sanger and colleagues (2005) showed that children with dystonia could scale the movement speed with the target size as expected for the Fitts' speed-accuracy tradeoff.

Fitts' law was originally proposed as a test for the manual skill of factory workers, and it continues to be useful to measure the speed-accuracy abilities of healthy adults. Therefore, it seems that Fitts' Law might be a suitable test to evaluate the sensory-motor abilities in children with dystonia or other movement disorders, and a very useful diagnostic clinical aid for physicians.

Over the last thirty years, Fitts' law has been extremely successful in human computer interaction (HCI) to measure and characterize the performance of various input systems (for a review see Soukoreff and MacKenzie, 2004). The Fitts model has allowed comparing and

evaluating novel pointing devices through the Index of Performance (IP), expressed by the inverse of the linear equation slope ($1/b$) (Fitts and Peterson, 1964), such that the higher its value, the less MT is affected by increases in ID. Later, ISO 9241-9 (ISO, 2002; MacKenzie and Soukoreff, 2003) has introduced the Throughput (TP) in HCI design as a further metric in quantifying input system performance (see Methods for mathematical description). Fitts' law has recently been applied in optimizing the layout of AAC devices for children with CP using a mathematical model for information based on the relationship between movement time and buttons size (Sanger and Henderson, 2007).

The availability of the latest generation of touch screen tablets has changed the concept of using AAC devices in children with speech and motor impairments. These devices are extremely portable, easy to manage, and the screen layouts are relatively simple to program. Thus there is a need to analyze and compare the capability of these "input" devices for transmitting information from the user to the computer, and a need to optimize the communication rate for children.

This study tests two hypotheses: 1) Fitts' Law applies to targets on touch-screen tablets, in typical children and in children with movement disorders. 2) Fitts' index of performance (IP) can assess and compare the sensory-motor abilities between children with dystonia and control subjects.

Therefore, we designed an experiment using custom software on the Apple iPad® to test the Fitts' Law paradigm in healthy adults, healthy children, and children with dystonia. The Index of Performance and Throughput were compared between groups to measure the extent of information transmitted by using the iPad® and to test its efficiency as an assisted communication device for children with speech and motor impairments (Sanger and Henderson, 2007).

Methods

Participants

16 children with a clinical diagnosis of either primary or secondary dystonia affecting one or both hands (13.7 ± 4.2 SD years old), 15 healthy children (9.7 ± 2.5 SD years old) and 13 healthy adults (28.5 ± 2.8 SD years old) participated. The children with dystonia were recruited from the movement disorders clinic at Children's Hospital of Los Angeles (CHLA). Their characteristics are outlined in Table 1.

Participants were excluded if there was clinical evidence of spasticity or corticospinal injury in the upper extremities, including hyper-reflexia, a spastic catch, or weakness. The University of Southern California Institutional Review Board approved the study protocol. All healthy adults and children's parents gave informed written consent for participation, and all children gave written assent. Authorization for analysis, storage, and publication of protected health information was obtained from parents according to the Health Information Portability and Accountability Act (HIPAA).

Experimental setting

Each participant attended a single experimental session of approximately one hour. All dystonic participants were previously rated on the Barry-Albright Dystonia scale (BAD) (Barry et al., 1999).

Participants sat in a chair or their own wheelchair in front of a table whose surface height was adjusted at the midpoint between the hip and the Xiphoid process. They placed the hand that was not used for the task on their lap.

An iPad® (Apple Inc, Cupertino, CA, USA) was located on the table in portrait mode in front of the participants at a distance that ranged between 40 to 55 cm. An adjustable metal bookstand supported the iPad® to allow the participants a comfortable screen view. The size of the screen was 19.5×14.6 cm. Custom software was developed for the experimental task (XCode 3.2 development environment, iOS 4.2 operating system; Apple Inc, Cupertino, CA, USA).

Task

The subjects were required to touch targets on the iPad® screen with the index finger of their preferred (less-affected) arm. Two children with dystonia (P7 and P9) were asked to perform the task with their non-preferred arm since the preferred was not affected by dystonia (BAD score equal to 0, see Table 1). Subjects were asked to maintain their trunk posture upright without touching the table or the bookstand with their pointing arm. Each trial was initiated by touching a 4×4 cm "start" button centered on the screen. The experimental task consisted of 180 targets divided in 4 blocks: 45 targets each block with a one-minute interval between trials to avoid fatigue. Targets appeared at one of nine different locations on the screen, and subjects moved their finger sequentially from one target to the next. The targets were square with an image of three blue bubbles. Subjects were asked to touch and "burst the bubbles". Subsequent targets appeared in a sequential manner on the screen at a random interval between 0.7 and 1.2 s and disappeared at the instant when the next one appeared. The subject was required to maintain contact with the last target until the next target appeared without returning to the start button position (Fig.1A). In all, six target distances (D = 4.5, 6.6, 8.0, 9.1, 13.2, and 16.0 cm) and five target widths (W = 1, 2, 3 cm) were used, yielding 18 different target conditions with different Indices of Difficulty, ID = $\log_2 (2D/W)$ (Fitts, 1954), varying from 1.60 to 4.99 bits. This resulted in 10 trials for each target condition, namely for each ID. The locations of the targets were chosen to match the six experimental distances and the 18 target conditions (ID) were shown in a pseudo-random order throughout the 180 trials, which resulted in nine Cartesian coordinates displayed in a rectangular grid (see Fig.1B). Subjects were encouraged to maintain motion close to the plane of the iPad® without an excessive displacement in perpendicular direction. However, sliding the finger along the iPad to the next target was not permitted, and success required that the first contact with the finger on the screen be within the desired target.

The software was programmed to avoid target locations that could be hidden by the hand or forearm. A score, rewarded in number of bubbles, was visually provided at each touch, just above of the target, based on the movement time and actual ID; it was computed as follows:

Score (S) = (2.5 × *ID*)/*MT*, where *MT* is the Movement Time, *ID* is the index of difficulty and 2.5 a constant term in order to return a tangible and reasonable score of the performance. At the end of each block of 45 sequential targets, the iPad® displayed the Total Score (TS, [45 × S]) showing the "total number of bubbles" achieved. In order to ensure attempts at accuracy, a penalty of thirty bubbles was given for each missed target. The penalties were, in that case, subtracted from the TS at the end of each block. The actual instruction to the subjects was: "Touch and burst the bubbles as fast as you can to get the highest score, if you miss the target you will lose thirty bubbles". Different auditory feedback was played for a hit or a missed target. The entire experimental test required less than 30 minutes for each subject.

Data Analysis and Statistics

Custom software computed the Movement Time (*MT*) and the endpoint at the target for each movement. Later, the data were transferred to a desktop computer and analyzed using Matlab 7.10 software (Mathworks Inc., Natick, MA, USA). The *MT* was determined as the time interval between release of the index finger from the screen and the next contact with the screen. The location of the touch (and whether or not it fell within the target) was determined from the operating system pointer location.

In order to test Fitts' Law, linear regressions were performed by the method of least squares, and the correlation coefficient was used to indicate the goodness of the fit of *MT* as a function of *IDs*. The index of performance (*IP*) was calculated by 1/*b*, where *b* was the slope of the linear regression equations (Fitts and Petterson, 1964) and the Throughput (*TP*) was defined as following (MacKenzie and Soukoreff, 2003):

$$TP = \frac{1}{N} \sum_{i=1}^{N} ID_i / MT_i$$

Where *N=18* is the number of *ID* conditions.

The intercept *a* of the linear regression equations and the fraction of successful touches (*S* = successful touches / 180) were also calculated. A two-way ANOVA was performed to test the effects of the groups (three levels; Group) and the Index of Difficulty (eighteen levels, *ID*) on the *MT*. In addition one-way ANOVAs were performed to test differences between the three groups for the other dependent variables: intercept *a*, slope *b*, S, IP and TP. The Levene's test was used to test the homogeneity of variance and Tukey's HSD (Honestly Significant Difference) tests were run as post hoc comparisons. The Games-Howell post-hoc test was used in case the population variances were unequal. Means and standard deviations were computed for outcome variables. For each participant, we also identified 95% confidence intervals. We used a criterion of p<0.05 in tests of significance. The statistical analysis was performed using SPSS 16.0 (SPSS Inc, Chicago, IL, USA).

Results

No subject withdrew from the study and there were no complaints of fatigue or any adverse events.

The one-way ANOVA showed a significant effect of group on S (successful pointing fraction) [$F(2,43) = 7.358$, $p = 0.002$]. Post-hoc comparisons of the three groups indicated that children with dystonia ($\mu = 0.88 \pm 0.11$, 95% CI [0.82, 0.94]) had lower success than healthy children ($p = 0.031$, $\mu = 0.96 \pm 0.19$, 95% CI [0.95, 0.97]) or adults ($p = 0.019$, $\mu = 0.97 \pm 0.20$, 95% CI [0.95, 0.98]). Comparison of success between healthy children and adults was not statistically significant ($p > 0.05$). On average the control groups completed the test with an error rate no more than 5%, while children with dystonia had an average error rate of 12%.

The two-way ANOVA showed a significant effect for both Group and ID factors [$F(2,41) = 860.61$, P<0.001 and $F(17,697) = 26.90$, P<0.001, respectively], with no significant interaction [$F(34,697) = 1.01$, P=0.452]. Children with dystonia were on average ($\mu = 0.611 \pm 0.116$ s, 95% CI [0.561, 0.660]) slower than healthy children ($p < 0.001$, $\mu = 0.438 \pm 0.100$ s, 95% CI [0.387, 0.489]) or adults ($p < 0.001$, $\mu = 0.251 \pm 0.632$ s, 95% CI [0.196, 0.305]) (Fig.2). Between controls, adults were faster than healthy children ($p < 0.001$).

MT showed a significant linear regression on ID for children with dystonia ($r = 0.89$, 95% CI [0.49, 0.70], $F(1,17) = 63.694$, $p < 0.001$), healthy children ($r = 0.88$, 95% CI [0.54, 0.71], $F(1,17) = 52.971$, $p < 0.001$), and adults ($r = 0.93$, 95% CI [0.54, 0.71], $F(1,17) = 104.008$, $p < 0.001$), see Fig.2. The correlation coefficients were 0.56 ± 0.20, 0.63 ± 0.16 and 0.81 ± 0.06 for children with dystonia, healthy children, and adults respectively. Correlation coefficients were not significantly different if we instead fitted MT against the ID computed using the effective information capacity formulation of Shannon and Weaver (1949): $ID = \log_2 ((D/W)+1)$, as proposed by Soukoreff and MacKenzie (2004) ($r = 0.90$, 0.88 and 0.93). Moreover the MT showed a significant linear correlation with the BAD score in children with dystonia: $r = 0.329$, $F(1,15) = 8.368$, $p < 0.05$, 95% CI [0.024, 0.159] (Fig. 4).

There were significant differences in the coefficients of the regression of MT on ID, including both intercept "a" [$F(2,43) = 24.731$, $p < 0.001$] and slope "b" [$F(2,43) = 4.687$, $p = 0.015$]. Post hoc tests showed a significant higher intercept in children with dystonia ($\mu = 0.425 \pm 0.156$ s, 95% CI [0.342, 0.508]) compared to healthy children ($p = 0.010$, $\mu = 0.270 \pm 0.114$ s, 95% CI [0.206, 0.333]) and adults ($p < 0.001$, $\mu = 0.111 \pm 0.559$ s, 95% CI [0.077, 0.145]). Healthy children had a higher intercept than adults ($p < 0.001$). The slope "b" was significantly higher in children with dystonia ($\mu = 0.068 \pm 0.023$ s/bit, 95% CI [0.056, 0.081]) compared to adults ($p = 0.013$, $\mu = 0.042 \pm 0.011$ s/bit, 95% CI [0.036, 0.050]) but not when compared to healthy children. There was no significant difference of slope between healthy children and adults ($\mu = 0.051 \pm 0.030$ s/bit, 95% CI [0.35, 0.068]).

We calculated the index of performance (IP) and the Throughput (TP) to compare the touchscreen tablet with other input devices used to transmit information between humans and computers, as well as to investigate the suitability of using touchscreen tablets to assess

and compare dexterity between healthy population and subjects with movement disorders. One-way ANOVA revealed a significant effect of group on IP [$F_{(2,43)} = 6.253$, $p = 0.004$]. Post-hoc comparisons of the three groups indicated that children with dystonia ($\mu = 16.36 \pm 6.18$ bit/s, 95% CI [13.06, 19.64]) had lower IP than healthy children ($p = 0.027$, $\mu = 23.14 \pm 8.26$ bit/s, 95% CI [18.57, 27.72]) and adults ($p = 0.006$, $\mu = 24.91 \pm 6.32$ bit/s, 95% CI [21.10, 28.74]). Comparisons between healthy children and adults were not statistically significant ($p = 0.782$). There was also a significant effect of *TP* among groups [$F_{(2,43)} = 48.488$, $p < 0.001$]. Post-hoc comparisons of the three groups indicated that children with dystonia ($\mu = 5.56 \pm 1.26$ bit/s, 95% CI [4.89, 6.23]) had lower *TP* than healthy children ($p = 0.018$, $\mu = 7.88 \pm 2.03$ bit/s, 95% CI [6.76, 9.00]) and adults ($p < 0.001$, $\mu = 13.71 \pm 3.25$ bit/s, 95% CI [11.73, 15.67]). Adults had higher *TP* than healthy children ($P<0.001$) (Fig.3). The *TP* showed an inverse linear correlation with the BAD score in children with dystonia: $r = 0.278$, $F_{(1,15)} = 6.761$, $p < 0.05$, 95% CI [−1.691, −0.162] (Fig.4).

Discussion

In the last thirty years Fitts' Law had been validated using a large variety of input devices, including mouse, trackball, joystick and touchpad (see MacKenzie, 1992 and MacKenzie and Soukoreff, 2003 for reviews). Given the recent widespread availability of high quality touch-screen tablets, it is worthwhile to validate whether Fitts' Law using these inputs devices might result in a useful clinical tool to assess motor skills in patients with sensory-motor disabilities, such as dystonia. It may also be a helpful tool for the selection and programming of assistive communication devices.

In this study we tested two hypothesis: 1) Fitts' Law applies to targets on a touch-screen tablet in healthy subjects and in children with dystonia, and 2) Fitts' index of performance (IP) can be used to differentiate between children with dystonia and control subjects. Both hypotheses are supported by our results. The movement time to point at the targets scaled with the index of difficulty in the three groups. The correlation coefficients (0.93, 0.88, 0.89 for Adults, Children and Dystonic respectively) lie in a range of coefficients of Fitts' Law previously tested with different input devices (MacKenzie, 1992). Furthermore, there were significant differences between children with dystonia and both healthy children and healthy adults, with almost no overlap between the performance measures of individual subjects within the healthy and dystonic groups.

Fitts' Law has been validated for different age populations (Hay, 1981; Brogmus, 1991) and for children with motor-sensory disabilities (Sanger et al., 2005; Smits-Engelsman et al., 2007). In particular Hay (1981) found that as children develop, their movement speed increases. This has been explained as a maturation of the CNS (Sporns and Edelman, 1993; Schneiberg et al., 2002) that leads the motor system to process more quickly the information necessary for motor skills. In our results, adults performed faster than children. In children with sensory-motor impairments, Fitts' Law holds despite limitations of motor function, including increased signal-dependent noise and slower movements compared to typical age-matched children (Sanger el al., 2005).

Children with dystonia showed a significantly lower index of performance than healthy children and adults, resulting in lower information transfer rate. In other words, at the same index of difficulty children with dystonia perform the task more slowly. This agrees with the hypothesis that slower movement compensates for increased variability due to increased signal-dependent noise (Sanger et al., 2005; Sanger, 2006). Thus, dystonic children are constrained to reduce the velocity, namely the motor output, to contain the movement variability in order to accomplish accuracy-dependent tasks (Harris and Wolpert, 1998). This is further confirmed by relationships between movement time and throughput, and the BAD scale in children with dystonia. Ultimately, the limited amount of information transmitted through a pointing movement on the iPad® closely reflects the reduced communication rate, (measured as words or items produced per minute), in children with CP (Sanger and Hendenrson, 2007).

To summarize, we have shown that Fitts' Law applies to rapid pointing movements on a touch-screen tablet, and the Index of Performance can be used to differentiate between children with dystonia and healthy subjects. We hope that our results will be useful for the development of future quantitative measurement tools for children with movement disorders, and that they may also help to guide the design of touch-screen user interfaces to maximize communication rate for children who depend upon assistive communication devices.

Acknowledgments

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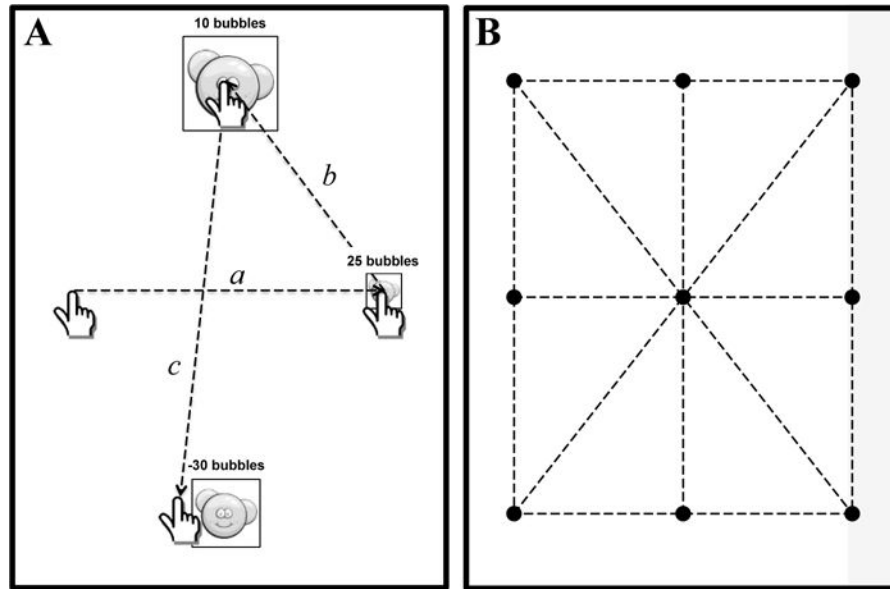
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Figure 1.
A) A representative sequence of three consecutive trials (a-b-c) with different target distance and target width. The score at each trial was based on the speed of the movement and the actual ID; note the values displayed in the figure were chosen only for demonstrative purpose. In case a target was missed, as the last move (c) in the figure shows, a penalty of 30 bubbles was deducted from the Total Score (TS, see Methods) at the end of the a block of 45 sequential targets. B) The nine locations of the targets on the screen (black circles) are shown; the dashed lines indicate the movement distances between targets.
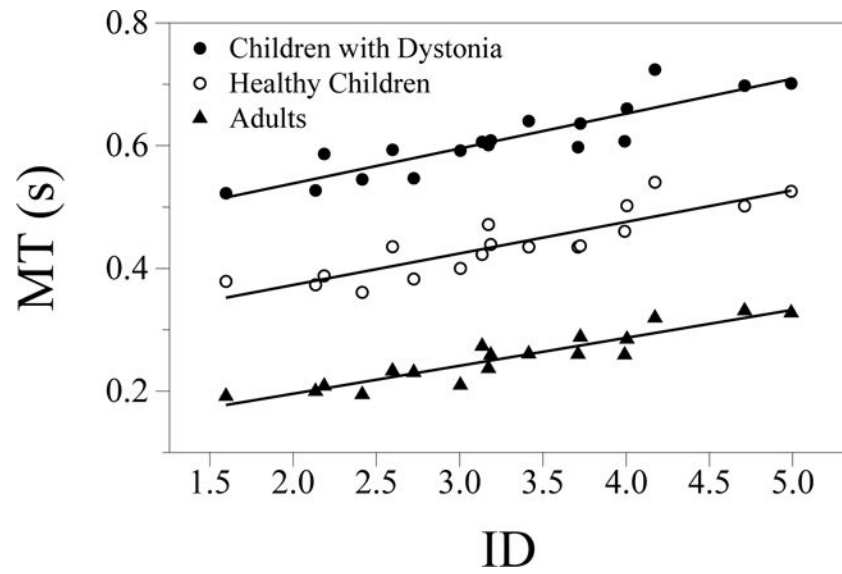
Figure 2.
Mean movement time (MT) for all subjects as a function of the index of difficulty (ID). The straight lines show the best fits by the least squares method for each group (● - Children with dystonia, ○ - Healthy Children and ▲ - Adults).
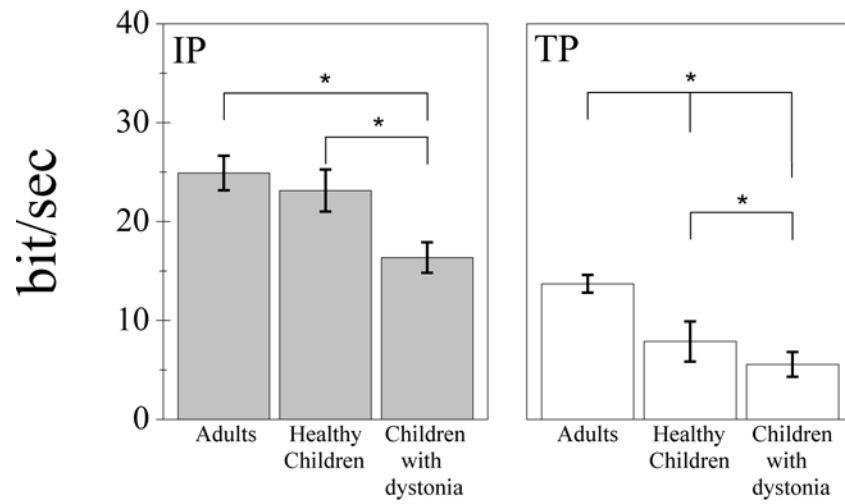
Figure 3.
Plot showing the means and standard errors of the Index of Performance (IP, left panel) and the Throughput (TP, right panel) for the three groups.
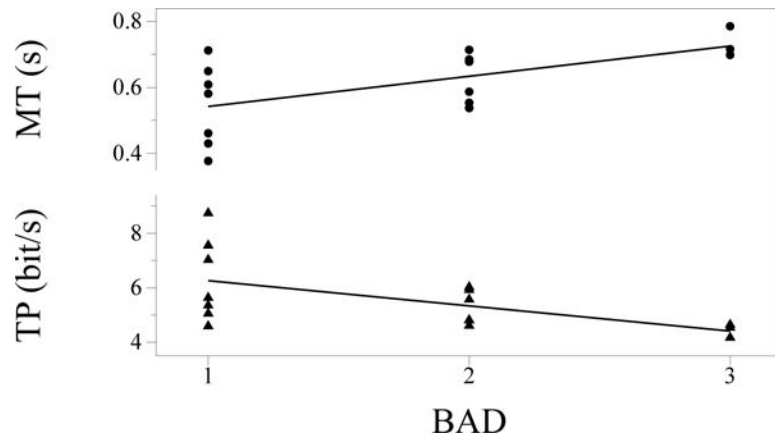
Figure 4.
Movement time (MT,top) and Throughput (TP, bottom) averaged across subjects as functions of the Barry Albright Dystonia (BAD) rating. Each data point represents one child with dystonia. The straight lines show the best fits by the least squares method.

Table 1

Characteristics of children with dystonia

Participant	Age	Gender	Diagnosis	Left arm BAD score	Right arm BAD score	Preferred arm	Arm used for the task
P1	14	F	Primary dystonia; DYT1-	2	3	Left	Left
P2	18	M	Secondary generalized dystonia; vitamin E deficiency	1	1	Right	Right
P3	18	M	Secondary generalized dystonia; cerebral palsy	3	3	Left	Left
P4	7	M	Secondary generalized dystonia; cerebral palsy	1	1	Left	Left
P5	16	F	Secondary generalized dystonia; Glutaric acid urea type 1	3	3	Left	Left
P6	18	M	Primary dystonia; DYT1+	1	1	Left	Left
P7	11	M	Primary dystonia; DYT1+	0	1	Left	Right
P8	11	M	Secondary generalized dystonia; cerebral palsy	1	1	Left	Left
P9	16	F	Secondary generalized dystonia; right hemiplegia	0	3	Left	Right
P10	9	M	Primary dystonia; DYT1+	2	2	Left	Left
P11	11	M	Primary dystonia; DYT1+	3	2	Right	Right
P12	19	F	Secondary generalized dystonia; cerebral palsy	2	2	Right	Right
P13	9	M	Secondary generalized dystonia; cerebral palsy	2	2	Right	Right
P14	18	F	Secondary generalized dystonia; cerebral palsy	3	1	Right	Right
P15	16	M	Dystonic tremor	2	1	Right	Right
P16	8	M	Secondary generalized dystonia; cerebral palsy	2	3	Left	Left

BAD, Barry–Albright Dystonia Scale