# Accuracy, Target Reentry and Fitts' Law Performance of Preschool Children Using Mice

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## Abstract

Several experiments by psychologists and human factors researchers have shown that when young children execute pointing tasks, they perform at levels below older children and adults. However, these experiments were not conducted with the purpose of providing guidelines for the design of graphical user interfaces. To address this need, we conducted a study to gain a better understanding of 4 and 5 year-old children's use of mice. We compared the performance of thirteen 4 year-olds, thirteen 5 year-olds and thirteen young adults in point-and-click tasks. As expected, we found age had a significant effect on accuracy, target reentry and Fitts' law's index of performance. We also found that target size had a significant effect on accuracy and target reentry. Measuring movement time at four different times (first entering target, last entering target, pressing button, releasing button) yielded the result that Fitts' law models children well only for the first time they enter the target. Another interesting result was that using the adjusted index of difficulty (*IDe*) in Fitts' law calculations yielded lower linear regression correlation coefficients than using the unadjusted index of difficulty (*ID*). These results provide valuable guidelines for the design of graphical user interfaces for young children, in particular when it comes to sizing visual targets. They also suggest designers should adopt strategies to accommodate users with varying levels of skill.

## 1. Introduction

"It's too small!" said one of the five year-olds using the software our team developed. She was having difficulty clicking on one of the icons. Her classmates in a kindergarten class were having similar problems with other icons. While we had not observed these problems in children aged seven and older, the kindergarteners were clearly in need of larger icons. They did not have difficulty with the size of the icons because of vision problems. Recognizing what the icons represented was not the problem either. The problem was that we had designed icons too small for them to select with a mouse comfortably given their still developing motor skills. After increasing the size of the icons, the problem went away.

In the past, Human-Computer Interaction (HCI) researchers have seldom used empirical evidence on young children's motor skills to influence their interface designs. Instead, they have relied on their experience, design partnerships, and on testing to ensure that their designs are appropriate.

While these are all important elements in the creation of good designs, empirical data on children's abilities with input devices can help avoid lengthier testing and offer some suggested guidelines to those researchers with little exposure to children. Some researchers have conducted studies to assess these abilities. However, these studies have been mainly aimed at comparing input devices, not at providing guidelines for the design of graphical user interfaces. This paper provides a thorough literature review of studies on children's motor skills and proficiency with input devices, and presents the results of a study we conducted to assess the abilities of four and five year-old children with mice. Our aim in conducting the study was to provide guidelines for graphical user interface design for these age groups.

The following sections of the paper:

- review children's information processing, motor skills, and input device use literature
- motivate, describe and analyze the results of the study we conducted
- discuss the relevance and the implications of the results of the study.

# 2. Literature Review

## 2.1. Information Processing Speed in Children

As children get older, they improve the rate at which they can process information. Thomas (1980) provides a summary of the research in this area. In the past few years, Kail (1991) has proposed a model for this improvement in terms of reaction time (shorter reaction times equal faster information processing speeds). Equation (1) illustrates Kail's model:

$$RTchild = (1 + be^{-c \cdot age})RTadult \qquad (1)$$

where for a particular task, *RTchild* is the predicted reaction time for children, *RTadult* is the measured reaction time for adults, *b* and *c* are empirically derived constants, and age is the age of the children. The ideal population used for determining *RTadult* is undergraduate students (eighteen to twenty-two years-old), as information processing rates are known to decline as adults age. Other researchers (Fry & Hale, 1996; Miller & Vernon, 1997) have evaluated Kail's model and found it to fit their experimental data. Figure 1 shows a plot of Kail's model with *RTadult* equal to 1, and the values for *b* and *c* reported in (Kail, 1991) ($b = 5.16$, $c = 0.21$). The values of these constants are still being evaluated, as both Miller and Vernon (1997) and Kail and Park (1992) have conducted further studies for this purpose.

Kail's exponential curve indicates information processing speed increases more rapidly in young children than it does in older children. This means that young children will show greater improvements in their performance in information processing tasks between grade levels than older children. It also means that the variability in information processing speed for children the same age will be greater for young children than for older children.

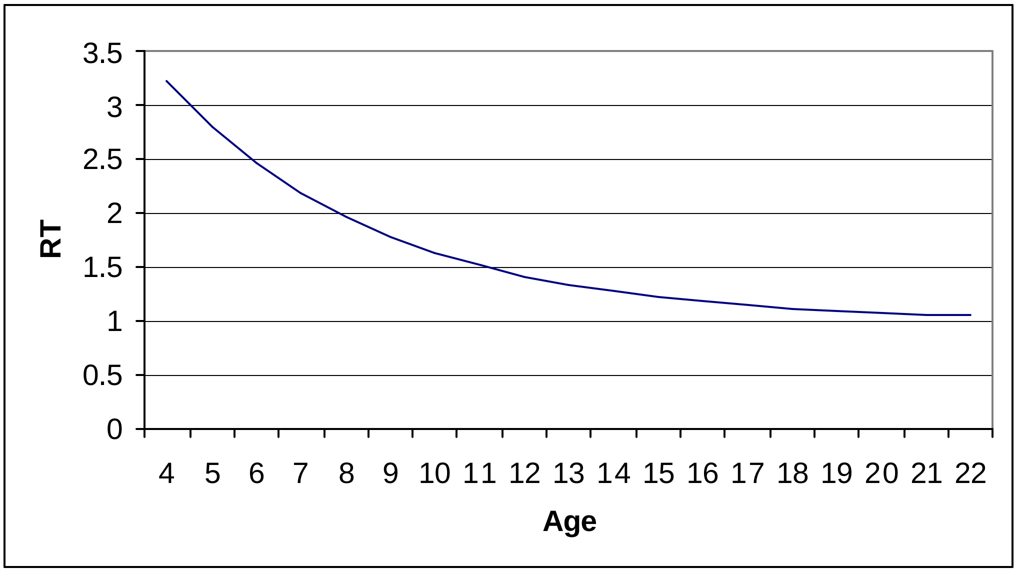


Figure 1: Plot of Kail's model with *RTadult* = 1, and the values for *b* and *c* reported in (Kail, 1991) (*b* = 5.16, *c* = 0.21).

While Kail reports children can greatly increase their performance in information processing tasks through practice, the same is true for adults (Kail, 1991). Kail believes there are no differences in the improvement children and adults can make through practice, and therefore practice does not have an impact on his model. He cites a study he conducted which confirmed his hypothesis (Kail, 1991).

Card, Moran and Newell's model of human performance Card, Moran and Newell (1983), widely cited in the HCI field, explains the relevance of Kail's model to children's motor skills. This model of human performance shows that the human motor system depends on processed information from the perceptual system. Research by Schellekens, Kalverboer and Scholten (1984) and Salmoni (1983) has shown that pointing movements, such as those needed to operate input devices are made up of a distance covering phase and a homing phase. Movement in the homing phase is not continuous, but a series of micro-movements followed by micro-corrections (Schellekens, Kalverboer & Sholten, 1984). People with quicker information processing rates will be able to make more micro-corrections in the same amount of time, which translate into smoother motion and better performance. Thomas, in his review, also mentions how information processing rates have an impact on children's movements Thomas (1980). Based on these models, young children's performance in pointing movements, such as those performed with input devices should be below that of older children and adults.

## 2.2. Fitts' Law

Fitts' law, a model that predicts pointing movement time based on target size and distance, was developed in the early 1950's by Paul M. Fitts, an experimental psychologist. Fitts' law models one-dimensional horizontal pointing movements. It states that pointing movement time is inversely proportional to the width of the target being pointed at and directly proportional to the distance from the center of the target to the starting point of the movement (theoretically, the target is of infinite height) (Fitts, 1954).

The equation that defines Fitts' law has undergone improvements since its inception (MacKenzie, 1992; Welford, 1968), and this is its currently most accepted form in the HCI community (Douglas, Kirkpatrick & MacKenzie, 1999; International Organization for Standardization 2000):

$$MT = a + b \log_2 (A/W + 1) \quad (2)$$

where $MT$ is movement time, $A$ is target amplitude (distance from the starting location to the center of the target), $W$ is the width of the target, and $a$ and $b$ are empirically determined constants. Other equations derived from Fitts' law are (3) and (4):

$$ID = \log_2 (A/W + 1) \quad (3)$$

$$IP = ID / MT \quad (4)$$

where $ID$ is the index of difficulty, and $IP$ is the index of performance. The index of difficulty expresses the difficulty of the pointing task (the same $ID$ may be obtained through different combinations of $A$ and $W$). The index of performance expresses the quality of the performance of participants pointing under the experimental conditions. It can be used to compare the performances of different groups of people under the same conditions (e.g. children vs. adults), or of people executing tasks under different conditions (e.g. using a mouse vs. a joystick). Sometimes the constant *b* is used to express similar concepts to *IP* as it corresponds to the slope of the function tying *ID* to *MT* (1/*b* is roughly equivalent to *IP*).

## 2.3. Fitts' Law Applied to Children

Psychology researchers have been studying how Fitts' law relates to children for almost 30 years. Through studies, they have shown that Fitts' law appropriately models children's pointing movements and confirmed that young children have a lower performance in these tasks than older children and adults (Kerr, 1975; Salmoni & McIlwain, 1979; Sugden, 1980; Wallace, Newell & Wade, 1978). They have also found that younger children show a greater variability in their performance (Kerr, 1975; Salmoni & McIlwain, 1979). Both these observations agree with Kail's model. Schellekens, Kalverboer and Scholten (1984), and Salmoni (1983) have also confirmed the existence of a distance covering phase and a homing phase in children's pointing movements. In addition, Schellekens, Kalverboer and Scholten (1984) found the differences in performance between young children and older children and adults occurred in the homing phase, suggesting information processing speeds contribute to the difference. Also of note are Kerr's findings of no gender differences, and no correlation between the skeletal age of children (assessed by X-rays) and their performance Kerr (1975).

Table 1 shows a summary of empirically obtained data from these studies. Since the data sets are so small, and the age of the adults in the studies is unknown, it is difficult to make any assertions as to whether they fit Kail's exponential curve.

| Study | Age | Empirically derived data |
|---|---|---|
| Kerr (1975) | 5 | $a$ = 564, $b$ = 139 (msec) |
| | 7 | $a$ = 227, $b$ = 123 (msec) |
| | 9 | $a$ = 142, $b$ = 108 (msec) |
| Wallace, Newell & Wade (1978) | 4, 5 | $b$ = 97.25 (msec) |
| | Adult | $b$ = 43 (msec) |
| Salmoni & McIlwain (1979) | 1st grade | $b$ = 137.9 (msec) |
| | 5th grade | $b$ = 99.0 (msec) |
| | 9th grade | $b$ = 95.6 (msec) |
| | University | $b$ = 110.1 (msec) |
| Sugden (1980) | 6 | $IP$ = 5.43 (bits/sec) |
| | 8 | $IP$ = 6.37 (bits/sec) |
| $ID$ = 5.585 | 10 | $IP$ = 7.53 (bits/sec) |
| | 12 | $IP$ = 8.44 (bits/sec) |

Table 1: Empirically derived data from four psychology studies of children's performance in Fitts' law tasks.

## 2.4. Fitts' Law Applied to Input Devices

While Fitts' law was developed for one-dimensional tasks, it has been applied successfully to two-dimensional tasks, including selecting items on a computer screen with an input device. Experiments by various researchers have shown very high correlation coefficients between pointing tasks using an input device and Fitts' law predictions, as summarized by MacKenzie (1992).

When applying Fitts' law's equation (2) to pointing tasks on a computer, its components map to useful information. The constant $a$, is usually associated with the action taken to select the target, such as clicking a mouse button. The constant $b$, on the other hand, is associated with the difficulty of using the particular input device for the type of task being performed. $IP$ is also used for this purpose and has been the choice for comparing the performance of input devices (MacKenzie, 1992).

In the HCI field, Fitts' law has been mostly used to evaluate and compare input devices. The first to use Fitts' law for this purpose were Card, English and Burr (1978).

Through their study, they compared the performance of a mouse, an isometric joystick, step keys, and text keys on the selection of text on a computer screen. The consequences of this study can still be felt today as most computer users have a mouse sitting next to their keyboards; the same device Card, English and Burr found to be superior.

Scott MacKenzie has been one of the most active HCI researchers with regards to Fitts' law since the early 1990's. Perhaps his most important contribution is the proposal of equation (2) (MacKenzie, 1991), currently the most accepted for use in Fitts' law experiments by the HCI community. He also made a significant contribution by studying how Fitts' law applies to two-dimensional tasks involving rectangular targets (MacKenzie & Buxton, 1992). He found that in such cases, the smallest of the rectangle's width and height should be used as the target width in Fitts' law (or alternatively a measure of width based on the approach angle). MacKenzie (1992) also proposed that HCI researchers follow Welford's advice (Welford, 1968) in using effective target width ($W_e$) for Fitts' law calculations based on the normal distribution of the coordinates of study participants' selections of targets.

Since conducting Fitts' law studies became the accepted way of evaluating input devices, the International Standards Organization (ISO) now provides specifications on how to carry out these studies in the ISO 9241 Part 9 standard (Douglas, Kirkpatrick & MacKenzie, 1999; International Organization for Standardization, 2000). The specifications include equation (2) and MacKenzie's proposal of following Welford's advice on using effective width in equations (2), (3) and (4).

## 2.5. Children and Input Devices

Many researchers have looked at children's use of input devices in the last decade (Crook, 1992; Inkpen, 2001; Joiner, Messer, Light & Littleton, 1998; Jones, 1991; King & Alloway, 1993; Strommen et al., 1996). They have found high correlations between study data and Fitts' model (Inkpen, 2001; Jones, 1991). They have also observed how children's performance with input devices increases with age (Crook, 1992; Joiner, Messer, Light & Littleton, 1998; Jones ,1991; King & Alloway, 1993), and how younger children show a higher variability in their performance (Joiner, Messer, Light & Littleton, 1998; Jones, 1991). Both these findings are compatible with Kail's predictions. Some researchers have also questioned the usefulness of Fitts' law when it comes to children (Joiner, Messer, Light & Littleton, 1998; Strommen et al., 1996).

Jones (1991) is not one of them. He has been the only one to study young children's Fitts' law performance with input devices. He conducted a study with six, eight and ten year-old children comparing the use of mouse, joystick and trackball input devices in continuous (going back and forth between targets) and discrete (one target at a time) tasks.

The study's tasks involved clicking on square and rectangular targets all at the same distance, at four fixed angles (up, down, left and right). When users missed a target, they had to repeat the task. They also had to repeat the task if they did not enter the square or rectangle through the side facing the original position of the cursor (this was an unusual requirement).

The study found children improved their performance with age, confirming the observations in the psychology studies and Kail's model's predictions. Table 2 summarizes the results for the continuous task with square targets. The ratios between the performances at each age are similar to those found in the psychology studies and to those predicted by Kail's model (see Table 3).

| **Age** | **Fitts' Constant b (msec)** |
|---|---|
| 6 | 735 |
| 8 | 578 |
| 10 | 510 |

Table 2: Empirically derived constant *b* for six, eight, and ten year-olds from Jones' study for a continuous task with square targets averaged over all input devices used Jones (1991).

| Source | Improvement in performance between ages | | |
|---|---|---|---|
| | 6 and 10 | 6 and 8 | 8 and 10 |
| Jones (1991) | 44% | 27% | 13% |
| Salmoni & McIlwain (1979) | 39% | n/a | n/a |
| Sugden (1980) | 39% | 17% | 18% |
| Kail (1991) | 51% | 26% | 20% |

Table 3: Comparison of improvement in performance with age between Jones' Fitts' law study (with input devices), two psychology studies, and predictions from Kail's model.

Jones' data also showed that younger children had more variability in their performance, as the standard deviation of children's movement time was consistently higher for younger children. This coincides with the observations of Kerr (1975), and Salmoni and McIlwain (1979), and the predictions of Kail's model.

As the study was conducted before MacKenzie showed how Fitts' law works with rectangular targets, Jones took the "depth" of the rectangle with respect to the user's original location to be the width of the target. This made Jones incorrectly conclude that Fitts' law did not apply to children when rectangular targets were involved. As far as comparing input devices, Jones did not find any of the devices to be clearly better than the others.

Another researcher who has looked into children and input devices is Kori Inkpen. Inkpen (2001) conducted a study comparing drag-and-drop versus point-and-click techniques with nine to thirteen year-old children using mice. While it was not the main goal of her study, Inkpen applied Fitts' law to her participants' use of the mouse. She found that the children's performance was comparable to those summarized by MacKenzie (1992). She did not look at differences in performance between ages.

Joiner, Messer, Light & Littleton (1998) conducted two studies comparing children's pointing and dragging. In the second study, children between the ages of five and twelve performed pointing and dragging tasks. The results were that the children's performance increased with age as the variability in their performance decreased, again in agreement with Kail's model. Joiner, Messer, Light & Littleton questioned the application of Fitts' law to children because according to them children are not capable of expert or errorless performance.

King and Alloway (King & Alloway, 1992; King & Alloway, 1993) conducted two studies comparing children's use of mouse, keyboard and joystick input devices while using an application designed for children. While the researchers did not use Fitts' law, they did keep track of time to complete the given task. King and Alloway's participants in the studies were four to eight years old. Children's performance improved with age, but the variability of performance within an age group was not reported. Confirming Kerr (1975)'s findings, no gender effects were found.

Crook (1992) conducted a study to find out if young children could use graphical user interfaces. His study concentrated on whether children could manipulate the tools usually found in such interfaces using a mouse. The participants were children aged three to eight years old, plus three teachers with no computer experience, and twelve adult expert users. In a point-and-click task, Crook reported a clear improvement with age (the numeric value of the variability of performance within an age group was not reported). But overall, the children did fairly well, with second and third graders achieving similar performance as two of the teachers. Given the small sample of teachers though, this finding may not be significant. The third teacher performed significantly better than the other two, at a level comparable to the expert users. This discrepancy could also be due to the age of the two poorly performing teachers (but we do not know because their age was not reported).

Strommen et al. (1996) studied three year-old children's use of mouse, trackball and joystick input devices. The study's task involved moving a cursor to click on targets appearing on different parts of the screen. The results showed gender differences, as boys were able to click on more targets than girls. This may be due to boys being more motivated towards this goal-oriented task than girls. The inconsistency with other studies

(Kerr, 1975; King & Alloway, 1992; King & Alloway, 1993) could also be explained by the fact that this study looked at younger children.

While the joystick ended up being the quickest device (with a slight advantage over the mouse), children entered and left the target more times when using the joystick than when using the mouse or the trackball. The result of the joystick being faster may be due to the fact that children could press the joystick's button before getting to a target, and as soon as the cursor touched the target, it would count as a click on the target. This type of button behavior is non-standard and should be avoided in future studies.

Instead of recommending the joystick, Strommen et al. recommend the use of the trackball, which the three year-olds found the easiest to use during the first session of the study, and had the least amount of target reentry. They also argue that the result of the joystick being quickest shows that speed (and by extension, *IP* in Fitts' model) does not necessarily equal ease of use when it comes to young children. They furthermore add that while efficiency may be a goal for adults using user interfaces, this may not be the case with three year-olds, for whom play might be more important, even in what appear to be goal-oriented tasks.

# 3. Study

## 3.1. Motivation

While the reviewed studies provide some trends in the evolution of children's abilities with input devices and some specific advice (e.g. point-and-click vs. drag-and-drop), they were not meant to provide specific guidelines for something as simple yet critical as the sizing of visual targets. In order to begin filling this gap, we conducted a study comparing the performance of 4 and 5 year olds with adults in the use of mice in pointing tasks. we decided to study preschoolers because that is where we expected to find the largest differences between age groups (according to Kail's model), and by extension, where data from a study would be most useful.

## 3.2. Research Questions

In order to obtain guidelines, we needed to learn how age impacts children's difficulty and efficiency in using mice in point-and-click tasks. The research questions we sought to answer through the study are the following:

- Do age, target size, or distance to target have a significant effect on accuracy (whether the participant presses and releases mouse inside target), or target reentry? What are the accuracy and target reentry rates for each combination of factors that do have a significant effect?
- Does Fitts' law model children's use of mice correctly when first entering the target, last entering the target, pressing the mouse button, or releasing the mouse button?
- Does age have a significant effect on Fitts' index of performance?
- Are there any patterns in participants' use of mouse buttons?

## 3.3. Participants

Thirteen four year-old children (6 girls and 7 boys, average age 4 years and 5 months), thirteen five year-old children (6 girls and 7 boys, average age 5 years and 6 months), and thirteen 19-22 year old adults (6 women, 7 men, average age 20 years and 6 months) participated in the study. The number of subjects is similar to that used in similar studies such as Crook (1992), Epps (1986), Jones (1991), King and Alloway (1993), MacKenzie and Buxton (1992), and Salmoni and McIlwain (1979). All participants were right-handed. The children were a racially and ethnically diverse group from a local pre-school located in the campus of the University of Maryland. The adults were a similarly diverse group of undergraduate and graduate students from the University of Maryland. We decided to include adults in the study because we believe data on children's performance is more valuable when compared with adult performance tested under the same conditions. Just like the ratio of adult performance using different input devices (e.g. using mice vs. trackballs) holds across different experimental conditions (MacKenzie, 1992), we expect that the ratio of adult to child performance with the same input device will also hold across experimental conditions. We only recruited adults in the ages of 18-22 because this adult age group should provide data on peak adult performance, as adult performance decreases with age (Kail, 1991).

The children had access to one computer in their classrooms (they had to sign up to use it). We asked parents how often their children used computers on a weekly basis and found that among four year-olds 11 of the participants used computers between 0 and 1 hours a week, while the remaining two children used computers between 1 and 5 hours a week. Five year-olds used computers more often, as four of them used computers between 0 and 1 hours a week, eight used computers between 1 and 5 hours a week, and one used computers between 5 and 10 hours a week. Among adults, one used computers between 0 and 5 hours a week, one used computers between 6 and 10 hours a week, three used computers between 11 and 20 hours a week, and eight used computers more than 20 hours a week.

## 3.4. Materials

I used a Pentium III 650MHz laptop with 128MB RAM running Microsoft Windows 98 at a resolution of 1024x768 pixels. As an input device, we used a Logitech USB Optical Mouse. The mouse produced a displacement of approximately 18 pixels for every millimeter of mouse motion (similar to what we obtained using the "medium" speed setting in Windows with no acceleration). We connected the laptop to a 21" monitor, yielding a control-display ratio of 0.15.

Tasks consisted of moving a cursor from a home area towards a target, and clicking on the target. The targets were red circles and always appeared to the right of the cursor's starting location in the home area. Tasks ended as soon as participants clicked, regardless of whether this occurred inside or outside the target circle. To start a new task, a researcher initiated a 1.5 second animation of a yellow square from the top of the screen towards a black square representing the participant's home area. When the yellow square covered the black square, a crosshair appeared in the middle of the yellow square. At this point, participants were allowed to move the mouse (moving earlier would cause the yellow square to restart its animation). Recording of elapsed time did not start until participants moved the crosshair.

To provide feedback to participants, on the bottom left of the screen, a blue bar showed the cumulative elapsed time, a pile of red circles showed the number of hits, and a pile of white circles showed the number of misses. Figure 2 shows a screenshot of the study software.

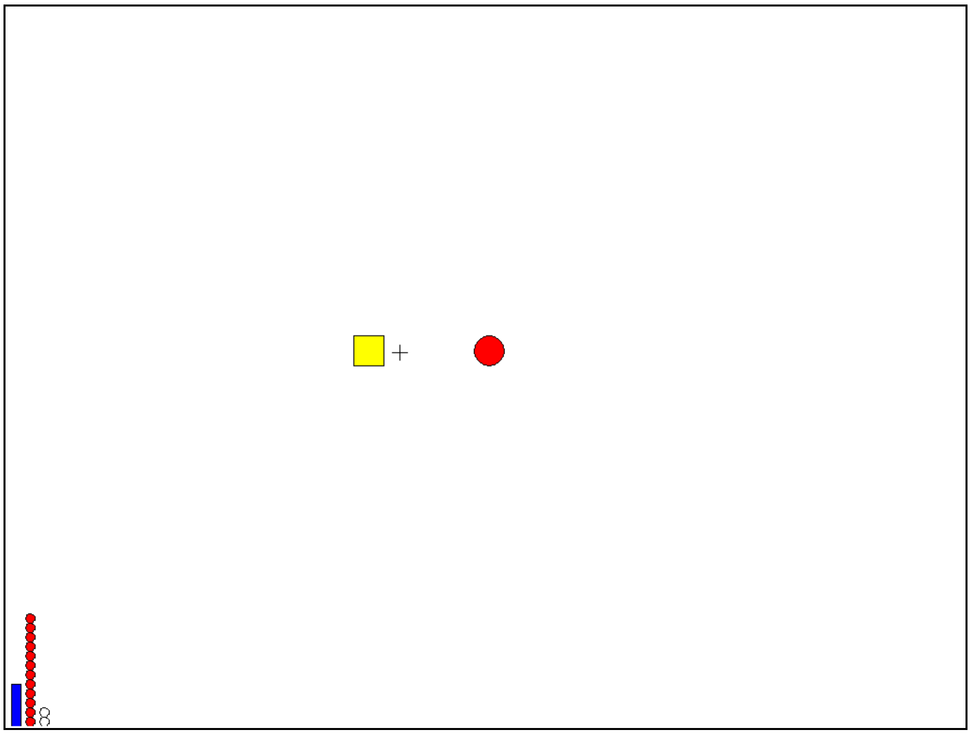

Figure 2: Screenshot of study software showing the yellow square representing the home area, the crosshair cursor, the target circle, and information on elapsed time and number of hits and misses on the bottom left.

I decided against having tasks one immediately after the other for three reasons:

- Children have difficulty clicking on mice
- I was not interested in measuring how quickly children would react to having a target appear somewhere else on the screen

- I wanted the participants to have a chance to move the mouse to a comfortable position.

I implemented the animation of the yellow square to avoid any mouse motion before the start of a task. We decided researchers should initiate the yellow square animation because of the difficulty young children have in clicking the mouse, and because we did not want them to be distracted by having to press something on the keyboard. With this setup, participants were still the ones initiating the task (by moving the mouse), yet we made sure that before initiating the task the participants: had not moved the mouse, knew where they had to click, and had the chance to move the mouse to a comfortable position. We decided to present targets at only one angle because determining the differences in performance by angle of approach was not one of the goals, and past research has not found large differences in performance at different angles of approach when using mice (e.g. MacKenzie and Buxton (1992) found diagonal motion took 4% longer than horizontal or vertical motion).

## 3.5. Procedure

The study was conducted in quiet rooms, one at the pre-school, and another at the HCIL. The room the children used was setup with chairs and a table of appropriate height for the children. During the study, participants sat down on a chair in front of a table that had the 21” monitor and the optical mouse on it. A researcher sat to the right of the table, holding the laptop.

Before the study started, a researcher explained to each participant that they had to click on red circles as quickly and as accurately as possible. The participants then proceeded to work on five practice tasks to make sure they understood how they had to proceed, and how to interpret what was shown on the screen.

Participants completed 5 blocks of 9 tasks each for a total of 45 tasks. They were encouraged to position the mouse comfortably between tasks.

## 3.6. Design

The target circles participants clicked on had one of three sizes (16, 32, or 64 pixels) and appeared at one of three distances (128, 256, or 512 pixels). The combinations between sizes and distances yielded the 9 tasks that made up a block. The study software presented these 9 tasks in random order, and repeated the same order for every block of testing. The dependent variables measured were: accuracy (whether participant pressed and released mouse button on target), target reentry, target reentry during click (between pressing and releasing the mouse button), and movement time (when first entering target, when last entering target, when pressing the mouse button, and when releasing the mouse button). The independent variables were: age level (between-subjects), target size (within-subjects), distance to target (within-subjects), and block number (within-subjects).

In measuring accuracy, target reentry, and target reentry during click, we heeded the advice of Strommen et al. (1996) in that when evaluating children's performance with input devices one should not concentrate only on how quickly they can complete tasks. However, we also wanted to learn how Fitts' law applied to 4 and 5 year-old children, and that is why we also measured movement time.

## 3.7. Results

### 3.7.1. Accuracy and Target Reentry

Through repeated measures ANOVAs, we found that target size and age level had a significant effect on accuracy, target reentry, and target reentry during click (see Table 4), while distance to target did not. Because of this, we decided to analyze accuracy, target reentry, and target reentry during click performance for every age group at each target size through repeated measures ANOVAs. Table 5 shows the results of my analysis, including significant differences according to Dunnett's T3 test for age differences (this test does not assume equal variances) and pairwise comparisons using Bonferroni's correction for target size differences. In addition, Figure 3, Figure 4, and Figure 5 illustrate the results from Table 5. As expected, the data shows clear improvements in performance with age and with larger target sizes. The standard deviation of performance also shows an overall decrease with age and the size of the targets, meaning that participants were more consistent as they aged and as targets got larger.

| Measurement | | F statistic | p value |
|---|---|---|---|
| **Target Size** (MANOVA Wilks' Lambda) | **Accuracy** | F(2, 35) = 34.924 | p < 0.001 |
| | **Target Reentry** | F(2, 35) = 28.409 | p < 0.001 |
| | **Target Reentry after Click** | F(2, 35) = 24.082 | p < 0.001 |
| **Age Level** (between subjects ANOVA) | **Accuracy** | F(2, 36) = 20.744 | p < 0.001 |
| | **Target Reentry** | F(2, 36) = 14.293 | p < 0.001 |
| | **Target Reentry after Click** | F(2, 36) = 27.039 | p < 0.001 |
| **Distance** (MANOVA Wilks' Lambda) | **Accuracy** | F(2, 35) = 0.158 | p = 0.854 |
| | **Target Reentry** | F(2, 35) = 0.484 | p = 0.621 |
| | **Target Reentry after Click** | F(2, 35) = 0.187 | p = 0.830 |
| **Block Number** (MANOVA Wilks' Lambda) | **Accuracy** | F(2, 35) = 1.260 | p = 0.305 |
| | **Target Reentry** | F(2, 35) = 1.971 | p = 0.122 |
| | **Target Reentry after Click** | F(2, 35) = 0.924 | p = 0.462 |

Table 4: Result of repeated measures ANOVAs, looking at significant differences based on target size, age level, and distance to target (amplitude).

| Measurement | Target Size | Age | Mean | Standard Deviation | Significant Differences (Age) | Significant Differences (Target Size) |
|---|---|---|---|---|---|---|
| Accuracy (percentage) | 16 | **4 yr** | 43 | 24 | 5$^{*}$, adult$^{***}$ | 32$^{***}$, 64$^{***}$ |
| | | **5 yr** | 74 | 25 | 4$^{*}$ | 64$^{*}$ |
| | | **adult** | 90 | 12 | 4$^{***}$ | |
| | 32 | **4 yr** | 77 | 11 | 5$^{**}$, adult$^{***}$ | 16$^{***}$, 64$^{**}$ |
| | | **5 yr** | 91 | 7.5 | 4$^{**}$ | 64$^{*}$ |
| | | **adult** | 96 | 5.8 | 4$^{***}$ | |
| | 64 | **4 yr** | 90 | 12 | | 16$^{***}$, 32$^{**}$ |
| | | **5 yr** | 97 | 5.2 | | 16$^{*}$, 32$^{*}$ |
| | | **adult** | 99 | 2.5 | | |
| Target Reentry | 16 | **4 yr** | 1.63 | 1.25 | adult$^{*}$ | 64$^{*}$ |
| | | **5 yr** | 1.38 | 0.64 | adult$^{***}$ | 32$^{*}$, 64$^{***}$ |
| | | **adult** | 0.38 | 0.20 | 4$^{*}$, 5$^{***}$ | 32$^{**}$, 64$^{**}$ |
| | 32 | **4 yr** | 1.11 | 0.65 | adult$^{***}$ | 64$^{*}$ |
| | | **5 yr** | 0.92 | 0.27 | adult$^{***}$ | 16$^{*}$, 64$^{***}$ |
| | | **adult** | 0.14 | 0.08 | 4$^{***}$, 5$^{***}$ | 16$^{**}$ |
| | 64 | **4 yr** | 0.63 | 0.39 | adult$^{**}$ | 16$^{*}$, 32$^{*}$ |
| | | **5 yr** | 0.39 | 0.15 | adult$^{***}$ | 16$^{***}$, 32$^{***}$ |
| | | **adult** | 0.11 | 0.09 | 4$^{**}$, 5$^{***}$ | 16$^{**}$ |
| Target Reentry During Click | 16 | **4 yr** | 1.12 | 0.66 | 5$^{**}$, adult$^{***}$ | 32$^{**}$, 64$^{***}$ |
| | | **5 yr** | 0.26 | 0.25 | 4$^{**}$ | 64$^{*}$ |
| | | **adult** | 0.12 | 0.18 | 4$^{***}$ | |
| | 32 | **4 yr** | 0.39 | 0.30 | 5$^{*}$, adult$^{**}$ | 16$^{**}$ |
| | | **5 yr** | 0.13 | 0.16 | 4$^{*}$ | |
| | | **adult** | 0.03 | 0.08 | 4$^{**}$ | |
| | 64 | **4 yr** | 0.15 | 0.26 | | 16$^{***}$ |
| | | **5 yr** | 0.03 | 0.11 | | 16$^{*}$ |
| | | **adult** | 0.01 | 0.03 | | |

$^{*}$ = $p < 0.05$, $^{**}$ = $p < 0.01$, $^{***}$ = $p < 0.001$

Table 5: Accuracy, target reentry, and target reentry during click for each age group and target size. The significant differences for age were obtained through Dunnett's T3 test. The significant differences for target size were obtained through pairwise comparisons using Bonferroni's correction.

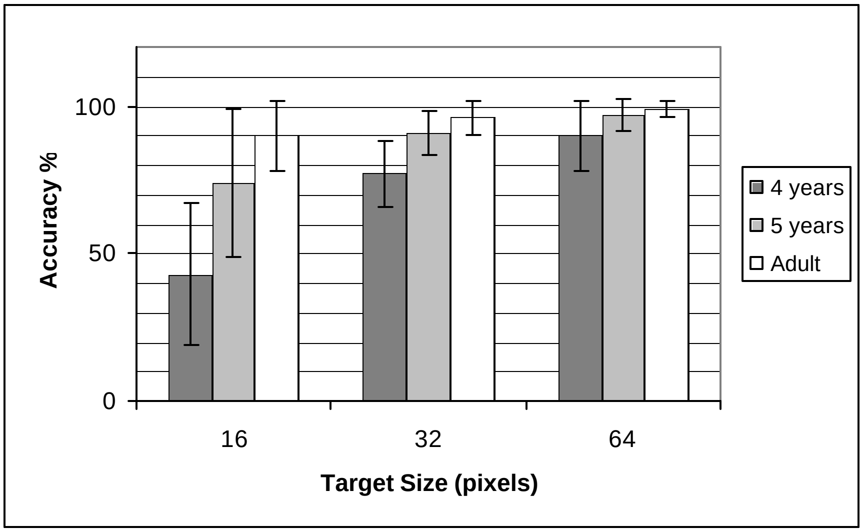


Figure 3: Average accuracy for participants clicking on targets by target size and age level. Error bars are two standard deviations long.

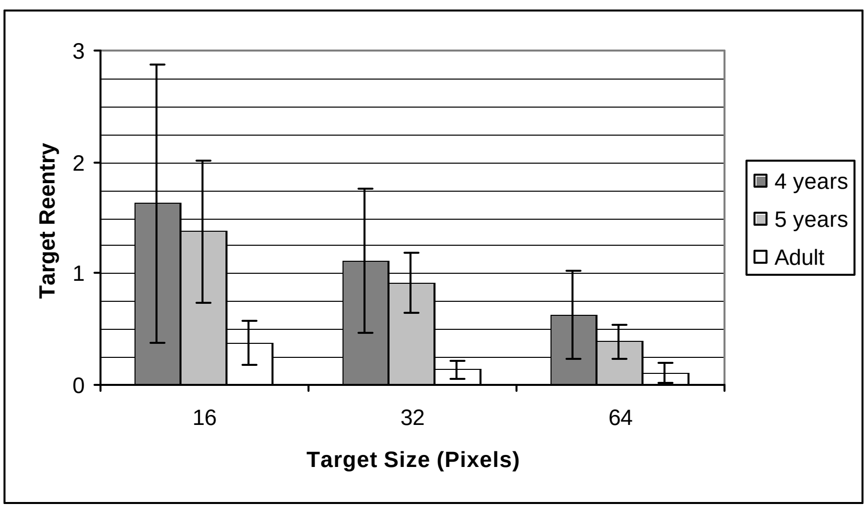


Figure 4: Average number of times participants reentered target (not counting the first time they entered a target) by target size and age level. Error bars are two standard deviations long.

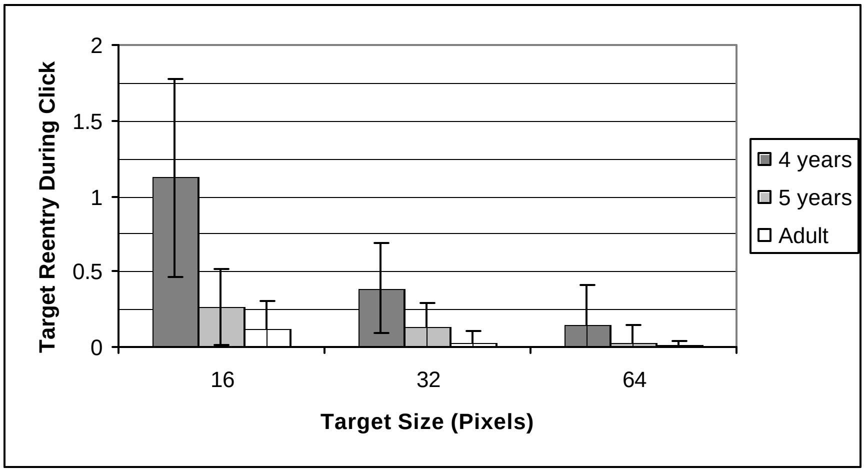


Figure 5: Average number of times participants entered a target while pressing the mouse button during a click by target size and age level. Error bars are two standard deviations long.

Perhaps the most interesting insight Table 5 provides is that to achieve the same level of accuracy as adults at 16 pixels, 5 year olds require 32 pixels, and 4 year olds 64 pixels (see Figure 3). Even at these increased sizes, the children will have a greater amount of target reentry and target reentry during click.

While developers should make decisions on sizing their visual targets based on the specific needs of their applications, the data on Table 5 suggests that 64 pixel targets offer significant advantages over 32 pixel targets for both 4 and 5 year olds in terms of accuracy and target reentry. For adults on the other hand, there are no advantages in going from 32 to 64 pixel targets. While these assertions are true given the experimental conditions, designers should be aware of the amount of displacement (in pixels) a mouse produces for every unit of distance it is moved by the user. For example, displacements smaller than the ones in this study should yield higher accuracy, and lower target reentry numbers and Fitts' law *IPs*. In spite of this caveat, we believe Table 5 provides very useful guidelines for designers and developers. In particular, designers may set accuracy and/or target reentry goals visual targets in their software and use Table 5 to find an optimal target size. In doing so, they should take into account the high variability of children's performance evidenced by the standard deviations in the results.

- Age and target size have a significant effect on accuracy and target reentry
- 64 pixel targets offer significant advantages over 32 pixel targets for both 4 and 5 year olds in terms of accuracy and target reentry

Figure 6: Summary of findings with respect to accuracy and target reentry.

### 3.7.2. Movement Time and Fitts' Law

I removed extreme outliers (using box plots) both in terms of movement time for all four different types of movement time recorded, and location of click for movement time to press and release the mouse button. The reason for removing outliers was that sometimes participants would get distracted during a task, or would accidentally click where they did not mean to click. The number of extreme outliers for the four movement times was below 4% (first entry 3.0%, last entry 3.5%, press 3.4%, and release 3.6%). After removing extreme outliers, we performed a linear regression with movement time as the Y variable and Fitts' *ID*, see Equation (3), as the X variable. we performed the regression for the four movement times for which we collected data. For the press and release regressions we calculated the index of difficulty using both $W_e$ (adjusted width as specified in Section 2.4, producing $ID_e$) and the actual width of the target (producing *ID*). Table 6, Table 7, and Table 8 show correlation coefficients ($R^2$) and Fitts' law's constants *a* and *b* (obtained from the regression, meant to calculate movement time in microseconds). Figure 7, Figure 8, Figure 9, and Figure 10 show the regression lines together with the data points for each of the times we measured, using *ID* instead of $ID_e$.

| Age | First entry | | | Last entry | | |
|---|---|---|---|---|---|---|
| | ***$R^2$*** | ***a*** | ***b*** | ***$R^2$*** | ***a*** | ***b*** |
| **4 years** | 0.94 | 386.4 | 447.6 | 0.82 | 379.3 | 711.9 |
| **5 years** | 0.96 | 167.0 | 280.1 | 0.85 | -31.13 | 483.1 |
| **Adult** | 0.91 | -43.13 | 151.5 | 0.97 | -34.81 | 169.1 |

Table 6: Fitts' law correlation coefficient and constants *a* and *b* for movement time on first entering and last entering the target.

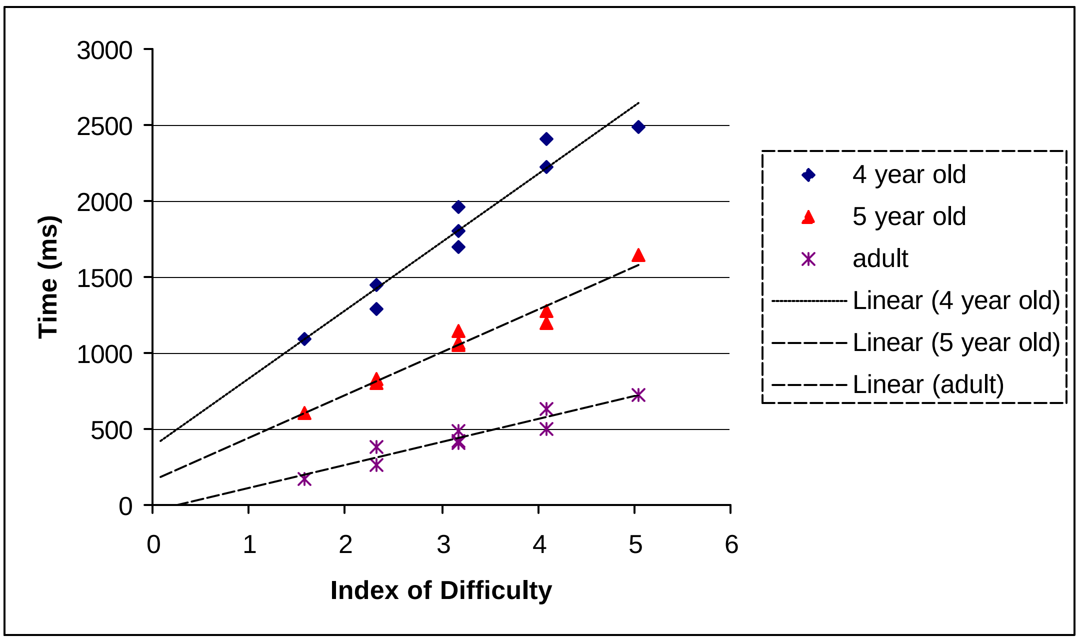


Figure 7: Plot of time to first enter target versus index of difficulty for 4, 5 year olds and adults, including regression lines.

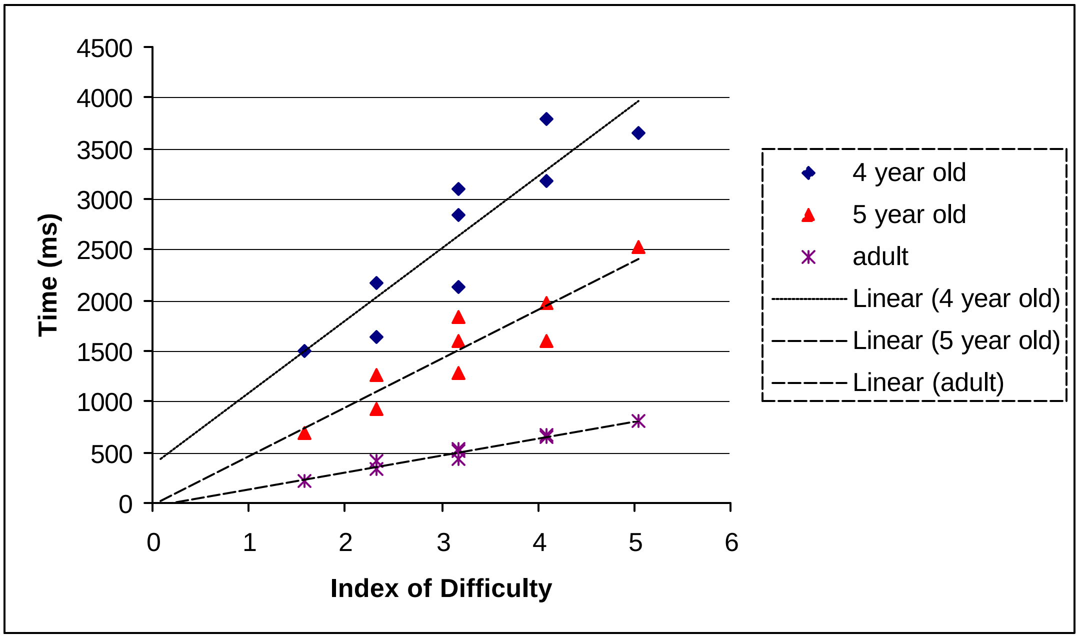


Figure 8: Plot of time of last entering target versus index of difficulty for 4, 5 year olds and adults, including regression lines.

| Age | Press | | | | | |
|---|---|---|---|---|---|---|
| | $ID_e$ | | | $ID$ | | |
| | $R^2$ | $a$ | $b$ | $R^2$ | $a$ | $b$ |
| **4 years** | 0.58 | 1564 | 687.3 | 0.78 | 1572 | 638.4 |
| **5 years** | 0.69 | 530.0 | 559.2 | 0.81 | 851.4 | 490.7 |
| **Adult** | 0.92 | 136.2 | 185.0 | 0.97 | 195.1 | 175.4 |

Table 7: Fitts' law correlation coefficient and constants *a* and *b* for movement time on pressing the mouse button.

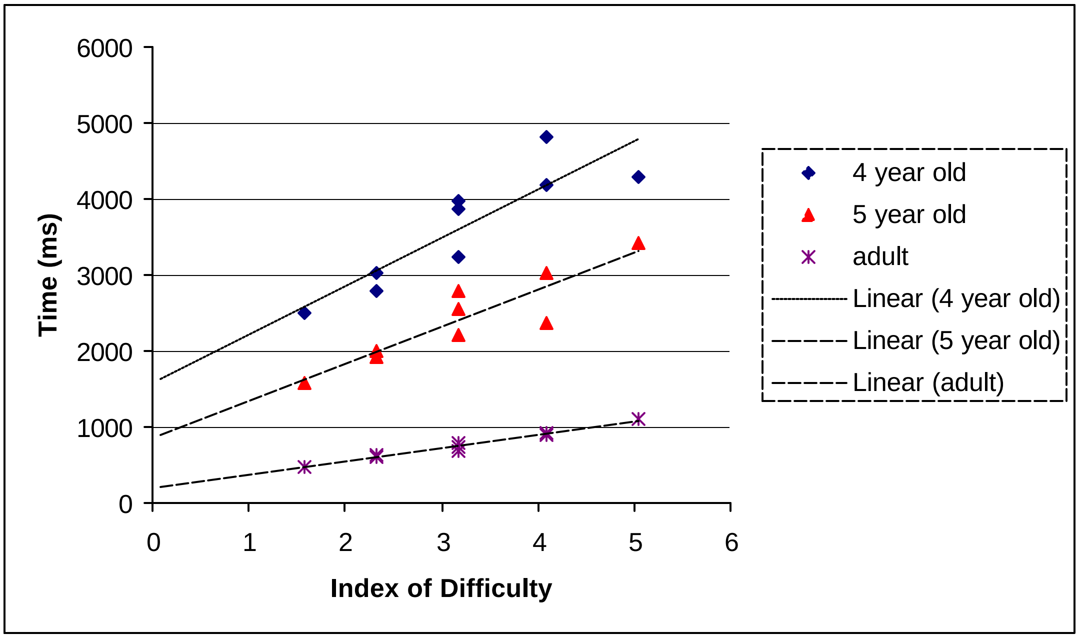


Figure 9: Plot of time to press mouse button versus index of difficulty for 4, 5 year olds and adults, including regression lines.

| | Release | | | | | |
|---|---|---|---|---|---|---|
| | ***$ID_e$*** | | | ***ID*** | | |
| **Age** | ***$R^2$*** | ***a*** | ***b*** | ***$R^2$*** | ***a*** | ***b*** |
| **4 years** | 0.44 | 2018 | 686.2 | 0.79 | 1819 | 648.5 |
| **5 years** | 0.50 | 1140 | 464.0 | 0.82 | 1105 | 490.0 |
| **Adult** | 0.92 | 263.0 | 180.0 | 0.97 | 310.0 | 176.0 |

Table 8: Fitts' law correlation coefficient and constants *a* and *b* for movement time on releasing the mouse button.

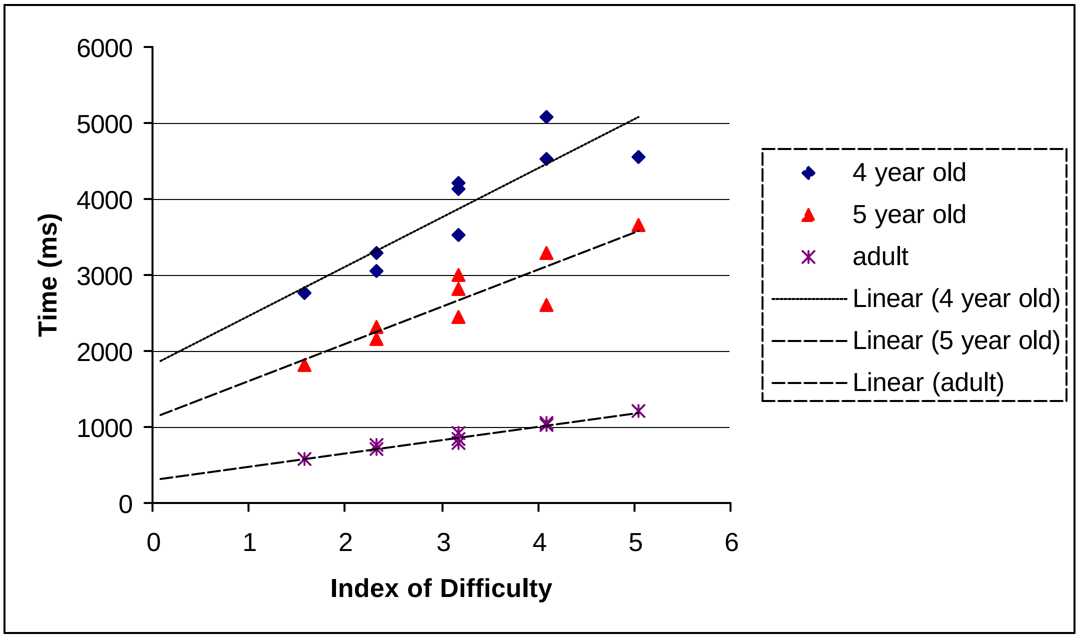


Figure 10: Plot of time to release mouse button versus index of difficulty for 4, 5 year olds and adults, including regression lines.

The data shows, as expected, very strong correlations for adults for all movement times and all methods of calculating the index of difficulty. Children, on the other hand, show very strong correlations on first entering the target, but not afterwards. This may be due to the fact that while adults follow a move to the target with an immediate click (as evidence by small target reentry numbers), children had a tendency to hover over the target once they got to it, to make sure they would click inside. The number of times they reentered targets is evidence of this behavior. Hence, for children, the task stopped being a Fitts' law task after they arrived at the target. Figure 11 sheds more light onto this issue by showing the composition of movement time for the three age groups. It shows the greater amount of time it took for children to press the mouse button after they got to the target. In addition, Figure 12 shows plots of typical paths taken by a 4 year old, a 5 year old, and an adult to click on a target. The path taken by the adult shows greater control of the input device and the type of motion expected in Fitts' law tasks. Figure 13, Figure 14, and Figure 15 support this observation by showing all paths taken by the different age groups for a particular task.

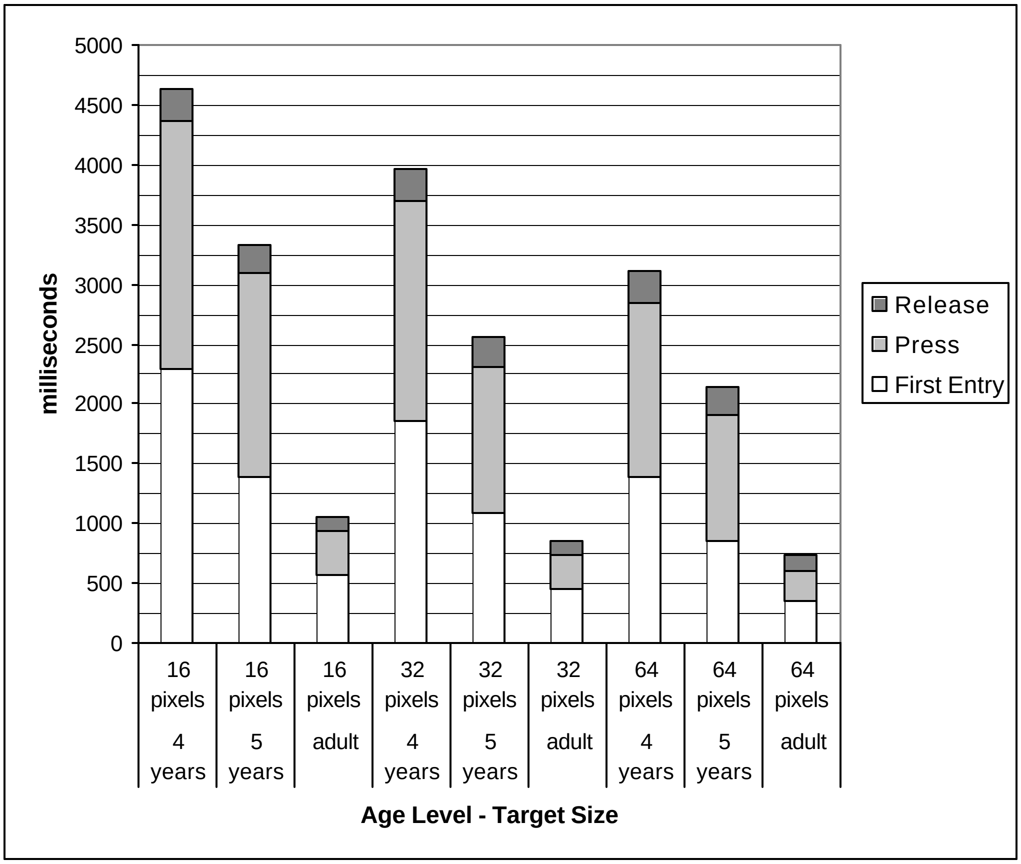


Figure 11: Average movement time for the three age levels at each target size decomposed by the time it took to first reach the target, the time it took to press the mouse button, and the time it took to release it.

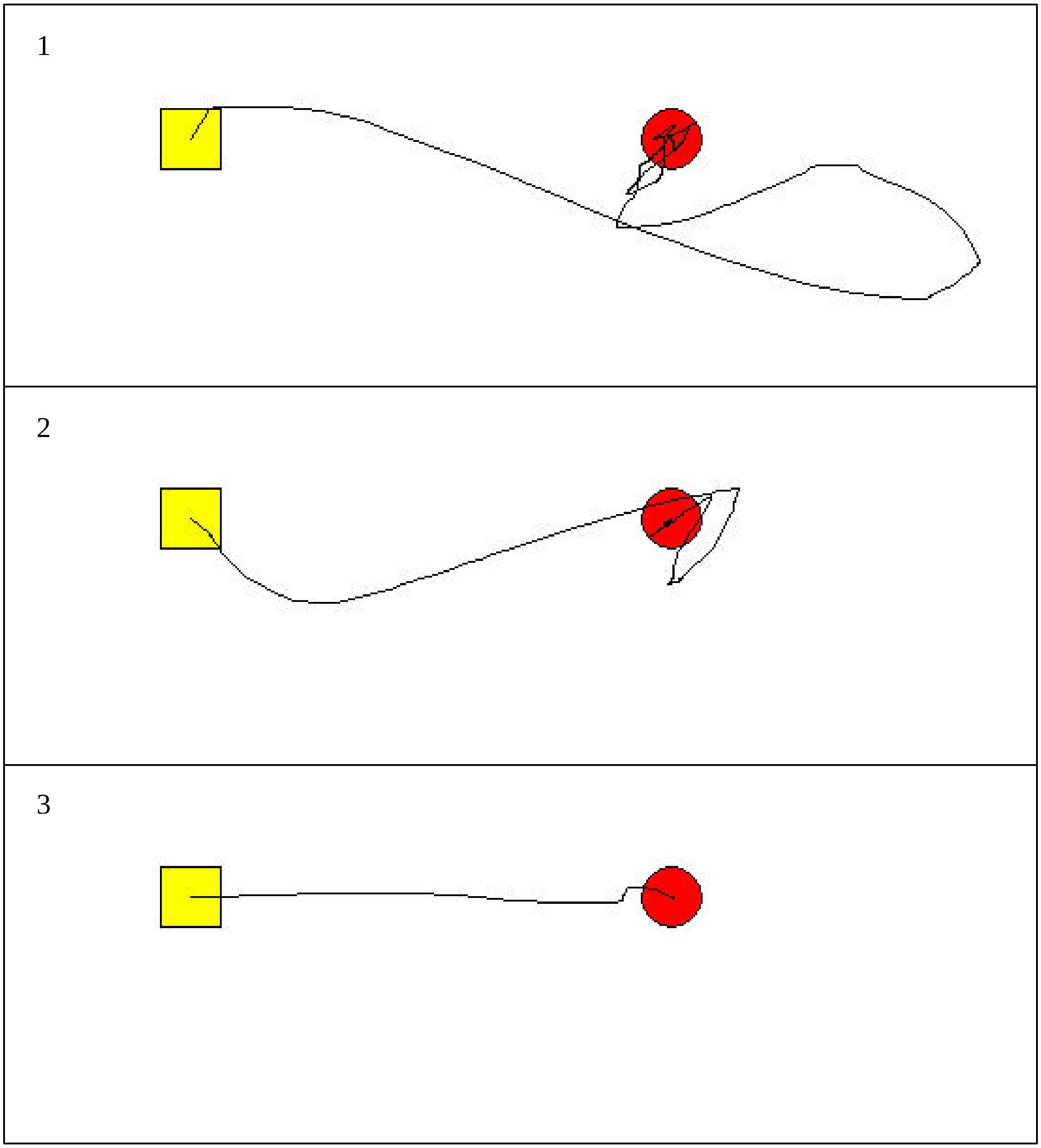


Figure 12: Plots of three participants' mouse motion towards a 32 pixel circular target 256 pixels away from the home position. Participant in (1) was a 4 year 6 month old female. Participant in (2) was a 5 year 8 month old female. Participant in (3) was a 21 year-old female.

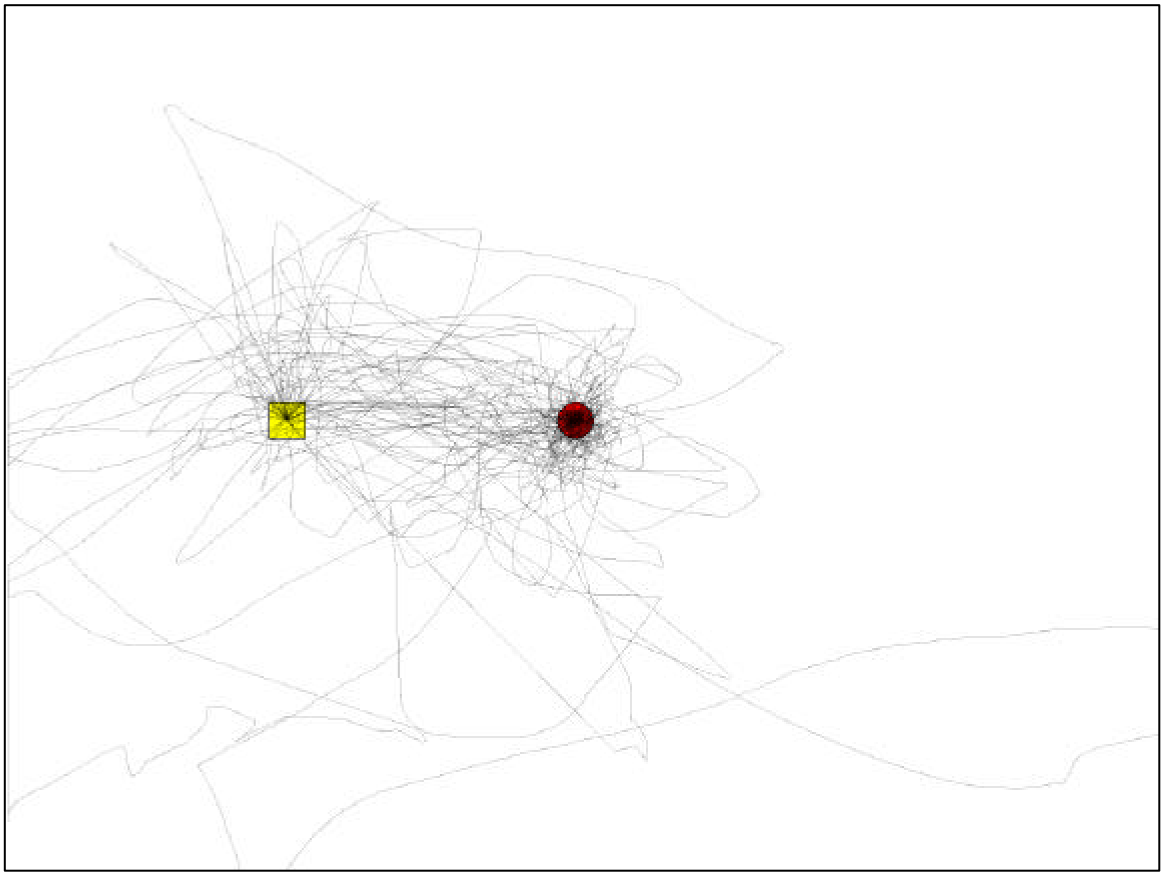

Figure 13: All paths taken by 4 year old participants to click on a 32 pixel target at a distance of 256 pixels.

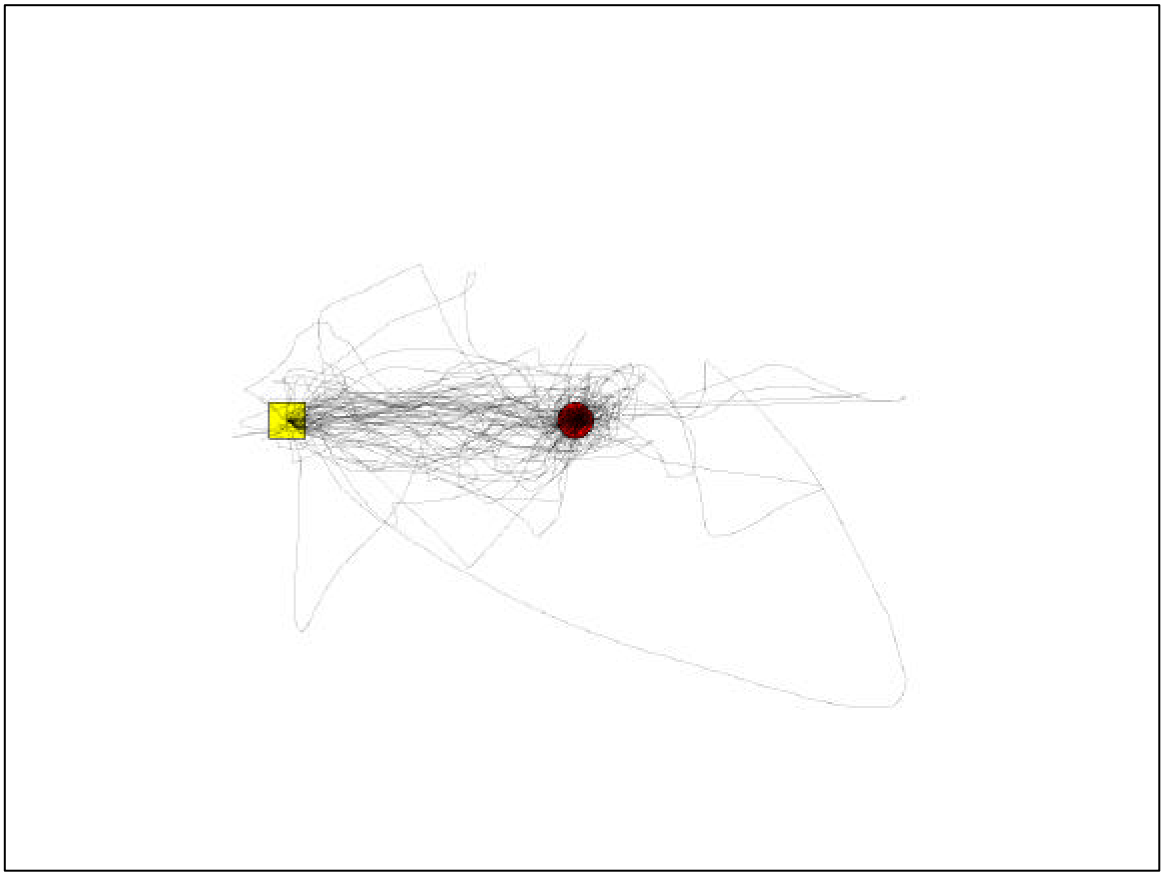

Figure 14: All paths taken by 5 year old participants to click on a 32 pixel target at a distance of 256 pixels.

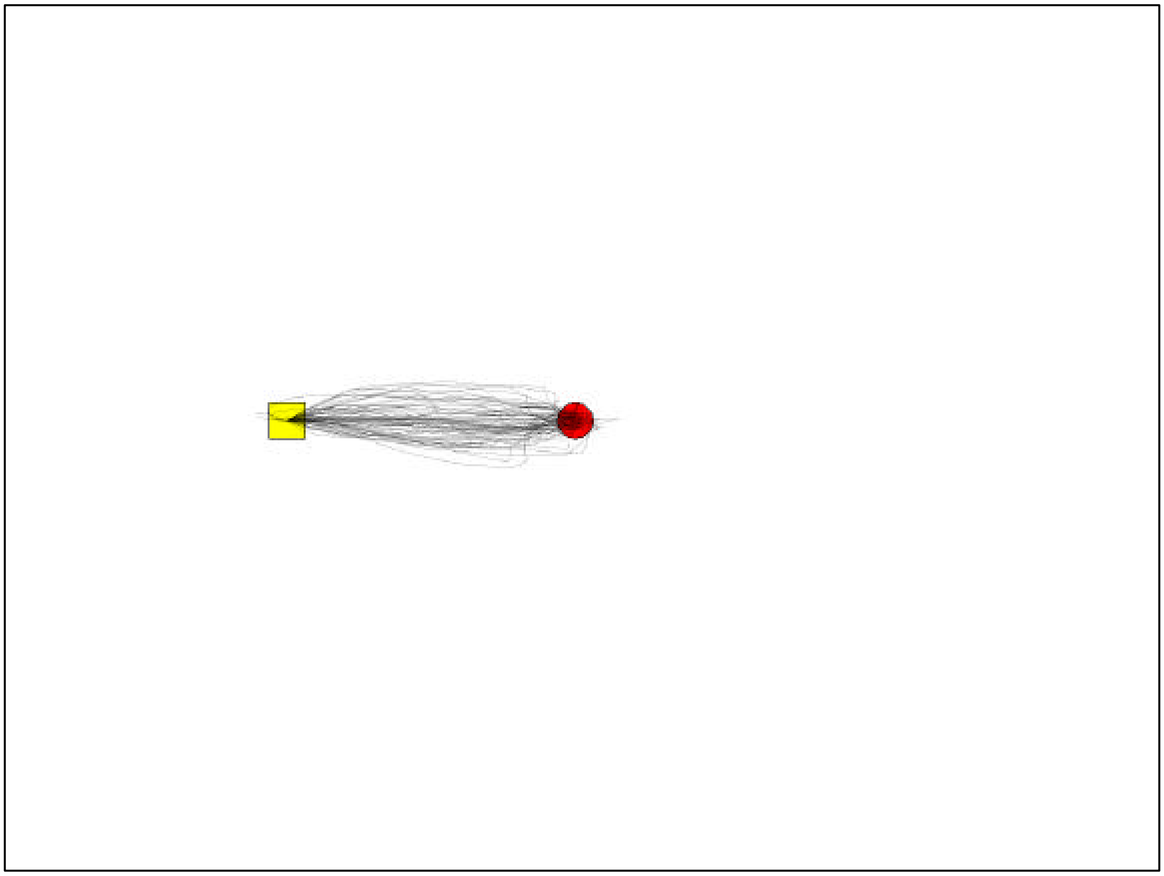

Figure 15: All paths taken by adult participants to click on a 32 pixel target at a distance of 256 pixels.

The figures suggest children made longer, less accurate movements with the mouse. This is consistent with a slower information processing speed that gives children the ability to adjust mouse motion less frequently. In spite of these issues, a correlation nearing 0.8 for both 4 and 5 year olds at the time of releasing the mouse is still high. Hence, using the Fitts' law constants obtained through this study may still prove useful for designers who want to estimate the time it would take children to click on a particular target.

Perhaps a greater surprise were the much lower correlation coefficients yielded when we used $ID_e$ instead of $ID$. While MacKenzie (1992) bases the reason for using $ID_e$ on information theory, the practical reason for adjusting the width of the targets is the idea that if participants are less accurate than expected, they likely performed the tasks too quickly (so the target width is adjusted to be bigger), while if they are more accurate than expected, they completed the tasks too slowly (so the target width is adjusted to be smaller). This may sometimes be true for adults, although it did not help in this case, but it does not fit what 4 and 5 year olds did. When clicking on small targets, the children's low accuracy caused $W_e$ to be larger than the real size of the targets even though children were not clicking on these targets "quicker" than they should as evidenced by the fact that correlation coefficients were much higher when using the actual target size. Figure 16 illustrates this by showing the paths a 4 year-old participant took to click on a 64 pixel target versus a 16 pixel target. When clicking on the 64 pixel target, the participant showed less hesitation yet managed to be accurate, while when clicking on the 16 pixel target, the participant hesitated more therefore taking more time, yet did not manage to click inside the target. This result suggests that in the future, researchers conducting similar studies with children should use both *ID* and $ID_e$ and compare the outcomes.

Less surprising are the numbers we obtained for Fitts' index of performance (*IP*). Table 9 shows *IP* calculated based on the time participants first entered the target (this is when correlations with Fitts' law were highest, as shown in Table 6, Table 7 and Table 8). The data shows a significant increase in performance with age and a decrease in the coefficient of variance (i.e. the standard deviation divided by the mean). The coefficient of variance tells us, for example, that a 4 year-old whose performance is one standard deviation greater than the mean would perform 30% better than the average child his/her age. On the other hand, an adult with a performance one standard deviation greater than the mean would perform 14% percent better than the average adult. This confirms that variability in performance decreases as children age.

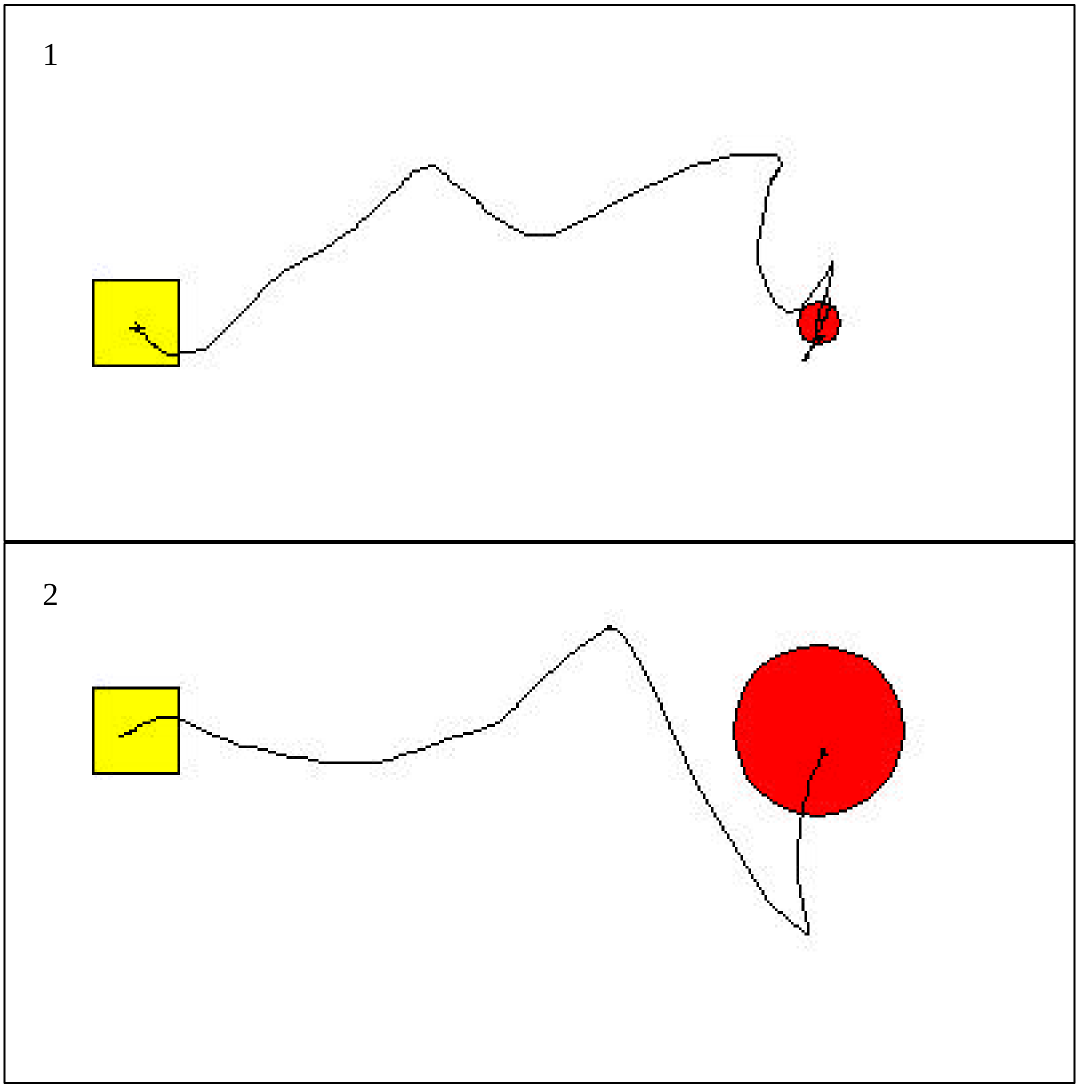


Figure 16: Mouse paths by a 4 year 3 month old male; (1) when clicking on a 16 pixel target 256 pixels way; and (2) when clicking on a 64 pixel target 256 pixels away.

| Age | Mean | Standard Deviation | Coefficient of Variance | Significant Differences |
|---|---|---|---|---|
| **4 years** | 1.95 | 0.59 | 0.30 | $5^{**}$, adult$^{***}$ |
| **5 years** | 3.24 | 0.60 | 0.19 | $4^{**}$, adult$^{***}$ |
| **Adult** | 7.80 | 1.08 | 0.14 | $4^{***}$, $5^{***}$ |

$^{*}$ = $p < 0.05$, $^{**}$ = $p < 0.01$, $^{***}$ = $p < 0.001$

Table 9: Fitts' Index of Performance (*IP*), in bits per second, based on movement time to first enter the target. Significant differences reported according to pairwise comparisons using Bonferroni's correction.

- Fitts' law models point-and-click tasks performed by 4 and 5 year olds very well (with $R^2 > 0.9$) only when first entering the target.
- Age has a significant effect on Fitts' index of performance.

Figure 17: Summary of findings with respect to movement time and Fitts' law.

### 3.7.3. Mouse Button Use

The study software recorded what mouse button participants used when clicking on targets. While all adults clicked exclusively with the left mouse button, 5 year olds were less consistent, and some 4 year olds used primarily the right mouse button. Figure 18 illustrates the results.

These results suggest software for young children should provide the same functionality through both buttons. Otherwise, children who do not consistently use the left button could be left both confused and frustrated by software that does not respond as they expect. Such experiences could lead children to mistrust particular software or even computers in general and make them feel like they are not in control.

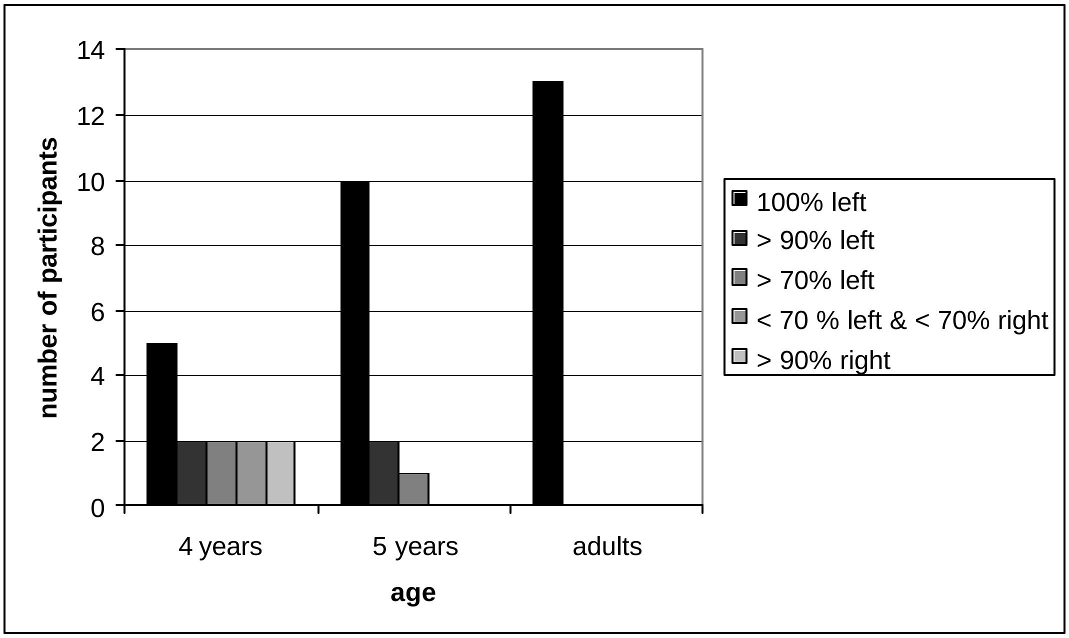


Figure 18: Mouse button use by age.

# 4. Discussion

## 4.1. Relevance of Results

In the past, some researchers have questioned the value of conducting studies like the one presented in this paper. In spite of their objections, we believe the results we presented are relevant to the design of graphical user interfaces in children's software.

As mentioned earlier, Strommen et al. (1996) criticized the use of speed, and by extension Fitts' law, when assessing ease of use by children. In spite of their concern, we believe Fitts' law can provide valuable information when used in conjunction with other statistics such as accuracy and target reentry. In particular, it can provide designers with helpful guidelines to ensure children do not have frustrating experiences trying to click on visual targets that take too long to click on. For example, using an input device that moves very slowly could prove highly accurate and have low rates of target reentry and at the same time be frustrating.

Gillan et al. (1990) expressed skepticism about using results from studies like the one presented in this paper to influence the design of graphical user interfaces based on the fact that having participants click on targets may not yield all the information needed to predict more complex interactions such as point-and-drag and the use of menus. They also proposed that complex interactions require a high level of analysis of what are user's targets, therefore making the use of guidelines and metrics cumbersome. This is likely true for applications designed for adults, but does not necessarily apply to applications designed for children. While further studies on children's use of input devices could be conducted, including Fitts' law for dragging tasks, and steering law tasks (Accot & Zhai, 1997) for the use of menus and similar tasks, these are not likely to be necessary as such interactions are not common in young children's software. Designers have used simple interactions in young children's software because complex interactions are difficult for children (Strommen, 1993) due to their developing abilities. These simple interactions provide a good match for the type of tasks participants completed in this study. In particular, simple point-and-click interfaces are quite common in software designed for young children (some examples are Benford et al. (2000), Druin et al. (2001), Hourcade et al. (2002a), Hourcade et al. (2002b)).

As mentioned earlier, Joiner, Messer, Light & Littleton (1998) have questioned the application of Fitts' law to children because they are not capable of expert, errorless performance. Their argument contradicts the studies reviewed in this paper that have successfully applied Fitts' law to children. Our data clarifies the issue, and proves both sides correct by showing very high correlations with Fitts' law up to the point when children first entered targets (see Table 6), and lower correlations afterwards (see Table 7 and Table 8). This suggests that while Fitts' law applies to children, it does not model children as well as adults when clicking on targets.

While Crook (1992) did not argue against studies like the one presented in this paper, his study suggests young children can actually manage to complete tasks similar to those necessary to use software designed for adults. However, the fact that they can complete the tasks does not mean that they find the tasks easy. The evidence reviewed and presented in this paper clearly shows that children have more difficulty using input devices in their younger years. Experiencing difficult tasks can create frustration, which in turn can make children turn away from potentially enriching educational and creative software (Druin et al., 2002a). Moreover, we believe children deserve to use software that is designed for their unique abilities. Software should not have to be more difficult to use because children are the users.

## 4.2. Implications of Results

One way to help make children's software easy to use is for designers to make use of the results of this study when deciding on the size of the visual targets in their software. The advantage of concentrating on target size is that it affects both speed and accuracy. Distance to targets on the other hand, affects only speed and controlled by users through the cursor's location.

The downside of increasing the size of visual targets is that they can occupy valuable screen space children could use for authoring, accessing more options, or pursuing other activities. This is not as problematic as it seems because children's cognitive abilities, needed to decipher the complexity of graphical user interfaces, also improve with age (Thomas, 1980). One way to reduce complexity is to reduce the number of actions available to a user (Shneiderman, 1998). This means that while a ten year-old may be able to work with an interface that has 25 actions available through icons, this interface may be too complex for a five year-old to visually process and use in an effective manner. Thus, young children who can effectively use a lesser number of icons are the same ones who need larger icons.

An alternative to point-and-click interfaces with large icons was proposed by Strommen (1993). His proposal is to "hop" between the options in a user interface. Using this technique, children could be assured to always be on a valid option, instead of having a cursor miss an icon when pointing-and-clicking. While this technique may not work for every application and may not be appropriate for use with the mouse and other input devices, it is worth considering, especially if the users are very young (e.g. three years old).

Another option is to slow down mouse motion by using operating system settings. While doing this will increase accuracy and reduce target reentry, it will also increase movement time. If children want to use software with targets that are too small for them, parents or teachers could make use of this operating system setting.

Another interesting idea suggested by the data is to use a crossing interface, such as those studied by Accott and Zhai (2002). The advantage of such an interface is that it could save time (as shown in Figure 34) and better match Fitts' law (according to Table 6). In addition, it could help children in situations such as those found by 4 year olds trying to click on 16 pixel targets, where they had very low accuracy rates, yet they reentered the target several times (see Table 5). The trouble with crossing interfaces is that there are very few examples of its use in software for adults, let alone software for children.

After selecting appropriate options to help children have a comfortable experience using software, the further challenge that children's motor skills pose on designers is that these skills change as children age. An interface designed taking into account the motor skills of nine year-olds will not work well with four year-olds. This is an extra reason, besides cognitive limitations mentioned by others (Druin, 2002b; Strommen, 1993), not to design interfaces that will fit all children (so-called "K-12", or "all ages" interfaces).

The number of different age groups to design for is likely to depend on the application at hand. However, the evidence summarized in this dissertation points to children making greater improvements in their abilities in their early years, as Kail's model predicts. This means that designers should pay greater attention to the needs for age-specialized interfaces when their target audience is younger. For example, the differences between three and four year-old children are more likely to prompt a need for different interfaces than the differences between eleven and twelve year-old children.

The need for different interfaces does not mean that separate applications should be built for each age group. One option is to design for the lowest common denominator. This would mean making the size of the visual targets and the complexity of the interface appropriate for the youngest children for whom the software is designed. Designers have to be careful when establishing the lowest common denominator due to the high variability in children's performance when they are younger. According to the data, while the average 5 year-old has a 74% accuracy rate with 16 pixel targets, a 5 year-old performing one standard deviation below the mean will have an accuracy rate of 49% (see Table 5). While designing for the lowest common denominator is easy to implement, it can also limit the availability of options and overall screen space for older, or more skilled children. In spite of this limitation, it may be an appropriate solution for simple applications that do not have extra functionality available for older children.

Another option is to design software that can be configured to use visual targets at different sizes. Windows, for example, allows users to set its icons to be larger (twice the width). Such options are more difficult to implement, but they may better accommodate more users. They could also be combined with providing more functionality to more advanced users who use smaller visual targets. This way, an interface could both adapt to users' motor and cognitive abilities. Hence, younger or less experienced users could start using software with fewer options and larger visual targets, and later move on to accessing more options with smaller visual targets. For example, interfaces for older children could involve many interactions that require reading, typing and spelling skills, while those for younger children could be based on pointing-and-clicking on a small number of appropriately sized icons with meaningful visual designs. This is in tune with Shneiderman (1998)'s recommendation of providing novices with a small number of actions and simpler interfaces.

A similar outcome could be achieved by allowing users to take different paths through an application. The paths could be designed to fit different age groups. While children could use the path designed for their age group they would be free to easily explore the paths and interfaces designed for other age groups. An example is SearchKids (Druin et al., 2001; Hourcade et al., 2002b), an application where children can retrieve contents of a digital library through different interfaces that can be accessed by navigating through a zoomable environment.

## 5. Future Work

More studies need to be conducted to gain a better understanding of the evolution of children's performance with input devices. Of particular interest is whether this evolution follows an exponential curve as proposed by Kail. These studies may also be used to find models to explain how the size of targets affects children's accuracy and target reentry levels. A natural next step would be to conduct studies with children of other ages, in particular elementary school children. It would be helpful if future studies include eighteen to twenty-two year-old adults as participants in order to better compare results across studies.

Similar studies need to be conducted to learn more about the amount of on-screen options and overall complexity children can manage at different ages. Guidelines from these studies and others combined with information on input device performance could provide powerful building blocks for the construction of age appropriate user interfaces.

## 6. Conclusion

In this paper we provided empirical results that strongly suggest that young children's motor skills affect their use of graphical user interfaces. The lower performance of young children in point-and-click tasks in terms of accuracy, target reentry and time means that user interfaces designed for them should use strategies to accommodate young users. Designers should particularly make certain that their designs are appropriate for the youngest children they intend to support and should consider designing alternative interfaces for different age groups. In doing so, they should take into account the greater variability in performance children show at younger ages. We believe the results presented in this paper provide valuable guidelines for software designed for young children. They give designers the ability to select sizes for visual targets given goals in terms of accuracy, target reentry, and speed for different age groups.

In addition to providing guidelines, our results explain how Fitts' law applies to 4 and 5 year old children pointing-and-clicking with mice. The results suggest Fitts' law describes point-and-click tasks well up to the point children first enter the target, but do not do as good a job afterwards. An additional surprising result was how using adjusted width (We) in Fitts' law's equation yielded much lower correlation coefficients than using the actual size of targets. These results, differentiating children from adults, confirm that children are a special population that deserves technologies that take into account their unique needs.

## 7. Acknowledgements

We would like to thank the children, teachers, and staff at the University of Maryland's Center for Young Children for their help in conducting this study. We would also like to thank the parents of our child participants, and our adult participants. In addition, we would like to acknowledge Jean-Daniel Fekete, Yves Guiard, Catherine Plaisant, Glenda Revelle, Ben Shneiderman and Bongwon Suh for their advice on this topic.

## 8. References

Accot, J., & Zhai, S. (1997). Beyond Fitts' Law: Models for Trajectory-Based HCI Tasks. *Proceedings of Human Factors in Computing Systems* (CHI 97). ACM Press, pp. 295-302.

Accot, J., & Zhai, S. (2002). More than dotting the i's -- foundations for crossing-based interfaces. *Proceedings of Human Factors in Computing Systems* (CHI 2002), ACM Press, pp. 73-80.

Benford, S., Bederson, B. B., Akesson, K., Bayon, V., Druin, A., Hansson, P., Hourcade, J. P., Ingram, R., Neale, H., O'Malley, C., Simsarian, K., Stanton, D., Sundblad, Y., & Taxén, G. (2000). Designing Storytelling Technologies to Encourage Collaboration Between Young Children. In *Proceedings of Human Factors in Computing Systems (CHI 2000)*, ACM Press, pp. 556-563.

Card, S. K., English, W. K., & Burr, B. J. (1978). Evaluation of mouse, rate-controlled isometric joystick, step keys, and text keys for text selection on a CRT. *Ergonomics, 21,* 601-613.

Card, S. K., Moran, T. P., & Newell, A. (1983). *The Psychology of Human-Computer Interaction.* Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Crook, C. (1992). Young children's skill in using a mouse to control a graphical computer interface. *Computers & Education, 19*(3), 199 - 207.

Douglas, S. A, Kirkpatrick, A. E., & MacKenzie, I. S. (1999). Testing pointing device performance and user assessment with the ISO 9241, Part 9 standard. *Proceedings of the ACM Conference in Human Factors in Computing Systems (CHI 99),* ACM Press, pp. 215-222.

Douglas, S. A., & Mithal, A. K. (1993). *Human Performance Evaluation of a Finger-Controlled Pointing Device*. CIS TR 92-11. Department of Computer Science, University of Oregon, Eugene, 97403-1202.

Druin, A. (2002a). The Role of Children in the Design of New Technology. *Behaviour and Information Technology, 21*(1) 1-25.

Druin, A. (2002b). Age Matters. *SIGCHI Bulletin, 34*(5), 5.

Druin, A., Bederson, B., Hourcade, J. P., Sherman, L., Revelle, G., Platner, M., & Weng, S. (2001). Designing a digital library for young children: an intergenerational partnership. *Proceedings of ACM/IEEE Joint Conference on Digital Libraries* (JCDL 2001), ACM Press, pp. 398-405.

Epps, B. W. (1986). Comparison of six cursor control devices based on Fitts' law models. *Proceedings of the 30th Annual Meeting of the Human Factors Society*, 327-331. Santa Monica, CA: Human Factors Society.

Fitts, P. M. (1954). The information capacity of discrete motor responses. *Journal of Experimental Psychology*, *47*, 381-391.

Fitts, P. M., & Peterson, J. R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology, 67,* 103-112.

Fry, A. F., & Hale, S. (1996). Processing Speed, Working Memory, and Fluid Intelligence. *Psychological Science, 7*(4), 237-241.

Gillan, D. J., Holden, K., Adam, S., Rudisill, M., & Magee, L. (1990). *Proceedings of Human Factors in Computing Systems (CHI 90),* ACM Press, pp. 227-234.

Hill, G. W., Gunn, W. A., Martin, S. L., Schwartz, D. R. (1991). Perceived Difficulty and User Control in Mouse Usage Computer Systems: Input Techniques. In *Proceedings of the Human Factors Society 35th Annual Meeting* 1991 v.1 p.295-299.

Hourcade, J. P., Bederson, B. B., Druin, A., Rose, A., Farber, A., Takayama, Y. (In Press). The International Children's Digital Library: Viewing Digital Books Online. *Interacting with Computers*.

Hourcade, J.P., Bederson, B.B., Druin, A., & Taxén, G. (2002). KidPad: Collaborative Storytelling for Children. *Extended Abstracts of Human Factors in Computing Systems (CHI 2002),* ACM Press, pp. 500-501.

Hourcade, J. P., Druin, A., Sherman, L., Bederson, B. B., Revelle, G., Campbell, D., Ochs, S., & Weinstein, B. (2002). SearchKids: a Digital Library Interface for Children. *Extended Abstracts of Human Factors in Computing Systems (CHI 2002),* ACM Press, pp. 512-513.

Inkpen, K.M. (2001). Drag-and-Drop versus Point-and-Click: Mouse Interaction Styles for Children. In *ACM Transactions on Computer Human Interaction, 8*(1), 1-33, March 2001.

International Organization for Standardization (2000). *Ergonomic requirements for office work with visual display terminals (VDTs) -- Part 9: Requirements for non-keyboard input devices.* Geneva: International Organization for Standardization.

Jagacinski, R. J., Repperger, D. W., Ward, S. L., & Moran, M. S. (1980). A Test of Fitts' Law with Moving Targets. *Human Factors, 22*(2), 225-233.

Joiner, R., Messer, D., Light, P., & Littleton, K. (1998). It Is Best to Point for Young Children: A Comparison of Children's Pointing and Dragging. *Computers in Human Behavior, 14*(3), 513-529.

Jones, S. (1998). Graphical query specification and dynamic result previews for a digital library. In *Proceedings of User Interface Software and Technology (UIST 98),* ACM Press, pp. 143-151.

Jones, T. (1991). An empirical study of children's use of computer pointing devices. *Journal of Educational Computing Research, 7*(1), 61-76.

Kail, R. (1991). Developmental Change in Speed of Processing During Childhood and Adolecense. Psychological Bulletin, 109(3), 490-501.

Kail, R., & Park, Y. (1992). Global developmental change in processing time. Merril-Palmer Quarterly, 38, 525-541.

Kaluger G. & Kaluger M.F. (1979). *Human Development: The Span of Life, Second Edition*. St. Louis: The C.V. Mosby Company.

Kerr, R. (1975). Movement control and maturation in elementary-grade children. *Perceptual and Motor Skills, 41*, 151-154.

King, J., & Alloway, N. (1992). Preschooler's Use of Microcomputers and Input Devices. *Journal of Educational Computing Research, 8*(4), 451-468.

King, J., & Alloway, N. (1993). Young children's use of microcomputer input devices. *Computers in the Schools, 9*, 39-53.

Kvalseth, T. O. (1980). An alternative to Fitts' law. *Bulletin of the Psychonomic Society, 16*, 371-373.

MacKenzie, I. S. (1991). *Fitts' law as a performance model in human-computer interaction*. Doctoral dissertation, University of Toronto.

MacKenzie, I. S. (1992). Fitts' Law as a Research and Design Tool in Human-Computer Interaction. *Human-Computer Interaction, 7,* 91-139.

MacKenzie, I. S., Buxton, W. (1992). Extending Fitts' Law to Two-Dimensional Tasks. In *Proceedings of Human Factors in Computing Systems (CHI '92),* ACM Press, pp. 219-226.

MacKenzie, I. S., Sellen, A., & Buxton, W. (1991). A comparison of input devices in elemental pointing and dragging tasks. In *Proceedings of Human Factors in Computing Systems (CHI '91)*, ACM Press, pp. 161-166.

Miller, L. T., & Vernon, P. A. (1997). Developmental Changes in Speed of Information Processing in Young Children. *Developmental Psychology, 33*(3), 549-554.

Nolan, P. R. (1988). The Design of a Squishy Mouse Consumer Products: Designing to Fit the Human. In *Proceedings of the Human Factors Society 32nd Annual Meeting* 1988 v.1 p.425-429.

Revelle, G. L., & Strommen, E. F. (1990). The effects of practice and input device used on young children's computer control. *Journal of Computing in Childhood Education, 2*, 33-41.

Salmoni, A. W. (1983). A descriptive analysis of children performing Fitts' reciprocal tapping task. *Journal of Human Movement Studies, 9*, 81-95.

Salmoni, A. W., & McIlwain, J. S. (1979). Fitts' reciprocal tapping task: A measure of motor capacity? *Perceptual and Motor Skills, 49*, 403-413.

Schellekens, J. M. H., Kalverboer, A. F., & Scholten, C. A. (1984). The Micro-Structure of Tapping Movements in Children. *Journal of Motor Behavior, 16*(1), 20-39.

Shneiderman, B. (1998). *Designing the User Interface: Strategies for Effective Human-Computer Interaction, Third Edition*. Reading, Massachusetts: Addison-Wesley.

Strommen, E. F. (1993). Is It Easier to Hop or Walk? Developmental Issues in Interface Design. *Human-Computer Interaction, 8*, 337-352.

Strommen, E. F., Revelle, G. L., Medoff, L. M., & Razavi, S. (1996). Slow and steady wins the race? Three-year-old children and pointing device use. *Behaviour & Information Technology, 15*(1), 57-64.

Sugden, D. A. (1980). Movement speed in children. Journal of Motor Behavior, 12, 125-132.

Thomas, J. R. (1980). Acquisition of Motor Skills: Information Processing Differences Between Children and Adults. *Research Quarterly for Exercise and Sport, 51*(1), 158-173.

Wallace, S. A., Newell, K. M., & Wade, M. G. (1978). Decision and response times as a function of movement difficulty in preschool children. *Child Development, 49*, 509-512.

Welford, A. T. (1968). *The Fundamentals of Skill*. London: Methuen.