It's Too Small! Implications of Children's Developing Motor Skills on Graphical User Interfaces

Juan Pablo Hourcade
Human-Computer Interaction Laboratory
University of Maryland
3180 A.V. Williams Building
College Park, MD 20742
+1 301 405 7445
jpablo@cs.umd.edu

ABSTRACT

Research has shown children's information processing speed increases with age [19] [37]. This speed has a direct impact on motor skill, as the human motor system depends on processed feedback from the perceptual system [4]. Children use their motor skills when performing Fitts' law tasks, including the operation of input devices [4]. Several experiments by psychologists and human factors researchers have confirmed that young children perform at levels below older children and adults when executing Fitts' law tasks. In spite of this evidence, human-computer interaction researchers have seldom reported using this information to influence the design of children's user interfaces. This paper surveys the relevant literature from human development, psychology and human-computer interaction, and examines its implications on the design of children's graphical user interfaces, in particular young children's need of larger visual targets.

Keywords

Children, human information processing, human development, Fitts' law, Kail's model, point-and-click, graphical user interfaces.

INTRODUCTION

"It's too small!" said one of the five year-olds using the software our team developed. She was having difficulty clicking on some of the icons. Her classmates at a kindergarten class were having similar problems. 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 click on 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 user interface designs. Instead, they have relied on their experience, design partnerships, and on testing to ensure that their designs are appropriate.

While experience, design partnerships, and testing are important elements in the creation of good designs, the awareness of research on children's information processing rates, motor skills, and proficiency with input devices can help avoid lengthier testing and lend a helping hand to those with little experience. This research explains our team's icon sizing problems with the kindergarteners by showing that children's performance in Fitts' law tasks, including the operation of input devices, increases with age.

The following sections of the paper:

- Give further background on the development of information processing speed throughout childhood and its relation to the motor system
- Explain Fitts' law
- Summarize the findings of Fitts' law studies of children by psychologists
- Summarize the use of Fitts' law in the HCI field
- Review the studies of children's use of input devices
- Discuss the implications of taking this research into account when designing user interfaces for young children, in particular as it relates to sizing visual targets in graphical user interfaces.

INFORMATION PROCESSING SPEED IN CHILDREN

As children get older, they improve the rate at which they can process information. Thomas provides a summary of the research in this area [37]. In the past few years, Kail has proposed a model for this improvement in terms of reaction time (shorter reaction times equal faster information processing speeds) [19]. Equation (1) illustrates Kail's model:

$$RT_{child} = (1 + be^{-c \times age})RT_{adult} \qquad (1)$$

where for a particular task, RT_{child} is the predicted reaction time for children, RT_{adult} 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 RT_{adult} is undergraduate students (eighteen to twenty-two years-old), as information processing rates are known to decline as adults age [19]. Other researchers have evaluated Kail's model and found it to fit their experimental data [11] [27]. Figure 1 shows a plot of Kail's model with RT_{adult} equal to 1, and the values for a and b reported in [19] ($a = 5.16$, $b = 0.21$). The values of these constants are still being evaluated, as both Miller [27] and Kail and Park [20] 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.

While Kail reports children can greatly increase their performance in information processing tasks through practice, the same is true for adults [19]. 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 [19].

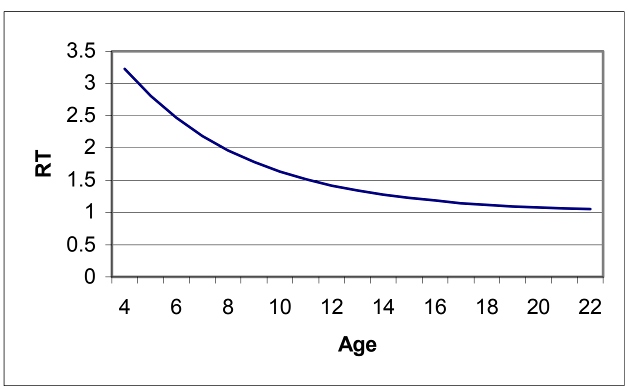

Figure 1. Plot of Kail's model with $RT_{adult} = 1$, and the values for a and b reported in [19] ($a = 5.16$, $b = 0.21$).

Card, Moran and Newell's model of human performance [4], 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 and others 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 [30] [32]. Movement in the homing phase is not continuous, but a series of micro-movements followed by micro-corrections [32]. 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 [37]. 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.

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) [10].

The equation that defines Fitts' law has undergone improvements since its inception [25] [39], and this is its currently most accepted form in the HCI community [6] [16]:

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

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):

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

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

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*).

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 [21] [31] [36] [38]. They have also found that younger children show a greater variability in their performance [21] [31]. Both these observations agree with Kail's model. Schellekens, Kalverboer and Scholten, and Salmoni have also confirmed the existence of a distance covering phase and a homing phase in children's pointing movements [30] [32]. In addition, Schellekens, Kalverboer and Scholten found the differences in performance between young children and older children and adults occurred in the homing phase [32], 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 [21].

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 [21]	5	a = 564, b = 139 (msec)
	7	a = 227, b = 123 (msec)
	9	a = 142, b = 108 (msec)
Wallace, Newell & Wade [38]	4, 5	b = 97.25 (msec)
	Adult	b = 43 (msec)
Salmoni & McIlwain [31]	1st grade	b = 137.9 (msec)
	5th grade	b = 99.0 (msec)
	9th grade	b = 95.6 (msec)
	University	b = 110.1 (msec)
Sugden [36]	6	IP = 5.43 (bits/sec)
ID = 5.585	8	IP = 6.37 (bits/sec)
	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.

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 [25].

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 [25].

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 in 1978 [3]. 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 of us have a mouse sitting next to our 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) [24], 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 [26]. 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 also proposed that HCI researchers follow Welford's advice [39] in using effective target width for Fitts' law calculations based on the normal distribution of the coordinates of study participants' selections of targets [25].

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 [6] [16]. The specifications include equation (2) and MacKenzie's proposal of following Welford's advice on using effective width in equations (2), (3) and (4).

CHILDREN AND INPUT DEVICES

Many researchers have looked at children's use of input devices in the last decade [5] [15] [17] [18] [23] [35]. They have found high correlations between study data and Fitts' model [15] [18]. They have also observed how children's performance with input devices increases with age [5] [17] [18] [23], and how younger children show a higher variability in their performance [17] [18]. Both these findings are compatible with Kail's predictions. Some researchers have also questioned the usefulness of Fitts' law when it comes to children [17] [35].

Jones 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 [18].

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 [18].

Source	Improvement in performance between ages		
	6 and 10	6 and 8	8 and 10
Jones [18]	44%	27%	13%
Salmoni & McIlwain [31]	39%	n/a	n/a
Sugden [36]	39%	17%	18%
Kail [19]	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 [21], and Salmoni and McIlwain [31], 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 conducted a study comparing drag-and-drop versus point-and-click techniques with nine to thirteen year-old children using mouse input devices [15]. 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 in [25]. She did not look at differences in performance between ages.

Joiner et al. [17] 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 et al. questioned the application of Fitts' law to children because according to them children are not capable of expert or errorless performance.

King and Alloway [22] [23] 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's findings [21], no gender effects were found.

Crook [5] 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.

Strommen et al. [35] 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 [21] [22] [23] 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.

RELEVANCE OF FITTS' LAW

In spite of Strommen et al.'s concerns, we believe Fitts' law can be a useful tool in the design of children's graphical user interfaces. It can provide helpful guidelines for sizing and positioning visual targets by modeling the time children take to click on them. These guidelines can be used to ensure children do not have frustrating experiences trying to click on visual targets that are too small for them. Yet, some researchers have put forth reasons for not using Fitts' law [5] [12] [17] [35].

Strommen et al.'s reason is that when it comes to selecting input devices for children, speed does not necessarily equal ease of use [35]. Then again, once an appropriate input device is selected, speed will correlate with ease of use. Even using a joystick, that proved to be quick yet difficult to use [35], a task that on average takes longer will be more difficult for a child than a task that on average takes a lesser amount of time. Even if children do not always have efficiency as a goal, once they decide they want to click on an icon, it makes sense to ensure that they can perform this operation in an appropriately quick and easy manner.

Gillan et al. [12] expressed skepticism about using Fitts' law to influence the design of graphical user interfaces based on the fact that a simple Fitts' law study may not yield all the information needed to predict more complex interactions such as point-and-drag and the use of menus. They also contend that complex interactions require a high level of analysis of what are user's targets, therefore making the use of Fitts' law metrics cumbersome. While further studies could be conducted, including Fitts' law for dragging tasks, and steering law tasks [1] 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. As a matter of fact, if there is one set of software that tries to avoid complex interactions, it is software designed for young children. Designers have used simple interactions in young children's software because complex interactions are difficult for children [34] due to children's developing abilities. These simple interactions provide a good match for the type of tasks Fitts' law can model. In particular, simple point-and-click interfaces are quite common in software designed for young children (some examples are [2] [7] [13] [14]).

As mentioned earlier, Joiner et al. have contended that Fitts' law should not be applied to children because they are not capable of expert, errorless performance [17]. The fact that, as reviewed in this paper, Fitts' law has been successfully applied to children [15] [18] [21] [31] [36] [38], makes this contention less credible. Moreover, if Fitts' law has been verified with people with disabilities such as cerebral palsy and Parkinson's disease, with people underwater, and even with monkeys [25], it is difficult to believe it should not be applied to children.

While Crook did not argue against using Fitts' law [5], 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. As a matter of fact, the evidence reviewed 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 [7]. 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.

IMPLICATIONS FOR INTERFACE DESIGN

One way to help make children's software easy to use is to size visual targets appropriately. From the literature reviewed in this paper, we have learned that young children's performance in Fitts' law tasks is below that of older children and adults. This means that in order for young children to have as quick access to a visual target as an adult, the visual target would either have to be closer to the cursor (reducing the amplitude A in equation (2)), or wider (increasing the width W in equation (2)). In most applications it is difficult to constrain or control where the cursor will be and by extension the distance to a visual target. Therefore, the only option designers have control over is the size of the visual target.

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 [37]. One way to reduce complexity is to reduce the number of actions available to a user [33]. 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 [34]. 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).

The further challenge that children's motor skills pose on designers is that they 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 [9] [34], 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 paper 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. This approach is easy to implement but can limit the availability of options and overall screen space for older 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's recommendation of providing novices with a small number of actions and simpler interfaces [33].

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, an application where children can retrieve contents of a digital library through different interfaces that can be accessed by navigating through a zoomable environment [7] [14].

While these recommendations are meant for graphical user interface design, the lessons learned from the reviewed literature also apply to tangible user interfaces. In particular, designers of tangible user interfaces intended for children that involve pressing physical buttons or pointing at physical items with other physical items should take into account children's developing motor skills.

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. Studies comparing children's performance with that of eighteen to twenty-two year-old adults could help in obtaining useful guidelines for children's visual target sizing needs.

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 combined with information on input device performance could provide powerful building blocks for the construction of age appropriate user interfaces.

CONCLUSION

In this paper we provided a solid empirical backing to the claim that young children's motor skills affect their use of graphical user interfaces. The lower performance of young children in Fitts' law tasks means that user interfaces designed for them should include larger visual targets. 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.

While using larger visual targets in young children's software has been no secret, this paper brings together the evidence supporting such designs. We hope experienced designers will appreciate the reviewed data confirming what they already knew. For those with little experience, we hope the information in this paper will save them time in their future designs.

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REFERENCES

1. 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.
2. 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. *Proceedings of Human Factors in Computing Systems* (CHI 2000) ACM Press, pp. 556-563.
3. 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.
4. Card, S.K., Moran, T.P., Newell, A. (1983). *The Psychology of Human-Computer Interaction.* Hillsdale, New Jersey: Lawrence Erlbaum Associates.
5. Crook, C. (1992). Young children's skill in using a mouse to control a graphical computer interface. *Computers & Education, 19*(3), pp. 199 - 207.
6. 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.
7. 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.
8. Druin, A. (2002). The Role of Children in the Design of New Technology. *Behaviour and Information Technology, 21*(1) 1-25.
9. Druin, A. (2002). Age Matters. *SIGCHI Bulletin, 34*(5), page 5.
10. Fitts, P. M. (1954). The information capacity of discrete motor responses. *Journal of Experimental Psychology, 47*, 381-391.
11. Fry, A.F., & Hale, S. (1996). Processing Speed, Working Memory, and Fluid Intelligence. *Psychological Science, 7*(4), 237-241.
12. 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.
13. 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.
14. 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.
15. Inkpen, K.M. (2001). Drag-and-Drop versus Point-and-Click: Mouse Interaction Styles for Children. *ACM Transactions on Computer Human Interaction, 8*(1), 1-33, March 2001.
16. 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.
17. 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.
18. Jones, T. (1991). An empirical study of children's use of computer pointing devices. *Journal of Educational Computing Research, 7*(1), 61-76.
19. Kail, R. (1991). Developmental Change in Speed of Processing During Childhood and Adolecense. *Psychological Bulletin, 109*(3), 490-501.
20. Kail, R., & Park, Y. (1992). Global developmental change in processing time. *Merril-Palmer Quarterly, 38*, 525-541.

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

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

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

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

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

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

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

28. Revelle, G.L., Druin, A., Platner, M., Bederson, B., Hourcade, J. P., & Sherman, L. (2002). A Visual Search Tool for Early Elementary Science Students. *Journal of Science Education and Technology, 11*(1), 49-57.

29. 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.

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

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

32. 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.

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

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

35. 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.

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

37. 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.

38. 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.

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