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Collaboration meets Fitts' law: Passing Virtual Objects with and without Haptic Force Feedback

Eva-Lotta Sallnäs[1]   Shumin Zhai[2]

[1] Royal Institute of Technology (KTH), SE-100 44 Stockholm, Sweden

[2] IBM Almaden Research Center, 650 Harry Road, San Jose, CA 95120 USA

evalotta@nada.kth.se, zhai@almaden.ibm.com

Abstract: Handing over objects is a common event during collaboration in face-to-face interaction. We investigate how such an event can be supported when the interaction takes place in virtual space. In a formal experiment, subjects passed a series of cubic objects to each other and tapped them at target areas. Their performance with and without haptic force feedback was evaluated. Furthermore, we placed our study in the framework of Fitts' law and hypothesized that object hand off constituted a collaboratively performed Fitts' law task. Our results showed that task completion time indeed linearly increased with Fitts' index of difficulty, both with and without force feedback. The time required for passing objects did not differ significantly between the haptic and nonhaptic condition. However, the error rate was significantly lower with haptic feedback than without.

Keywords: haptic feedback, collaborative environment, Fitts' law, object manipulation

1 Introduction

The internet and other communication technologies have enriched the means for collaboration across different geographical areas around the world. To date, research on computer supported collaboration has mostly focused on the textual, audio and visual modalities. The future of collaborative cyberspace can certainly go beyond these modalities. Designers and artists collaborating over distance, for example, may benefit from being able to jointly manipulate work models, feel the form, weight, surface friction, texture and softness or hardness of objects remotely, or hand off objects to each other in virtual space. In the real world, haptics is frequently involved in human-human interaction activities such as hand shaking or tapping someone on the shoulder.

We are particularly interested in object hand off as a paradigm of evaluation, because it is a type of joint haptic event between two people that requires coordinated action to accomplish. This is a common event that happens in various forms. For example, a frequent and watchful example of hand off occurs when being given a cup of coffee in an airplane – both the flight attendant and the customer have to pay attention to subtle haptic signals to ensure the hand off was securely accomplished. Intuitively, haptics may play a critical role in object hand off. The giver has to sense that the recipient has firmly grasped the object before releasing it. The recipient has to feel that the giver is releasing it before taking it towards oneself. It is difficult to imagine that such a task could be accomplished without haptic feedback.

To place our investigation in a more principled framework, we seek a quantitative model of user performance of a hand off task. We are intrigued by the possibility that object hand off constitutes a collaboratively performed Fitts' law task, with target distance to target size ratio as a fundamental performance determinant. Fitts' law has traditionally been used as a model for performance of individual tasks such as target pointing. Its contribution to user interface design and evaluation include systematic evaluation of different input devices (Card et al, 1978; ISO, 2000; MacKenzie, 1992; MacKenzie et al, 1991; Zhai, 2002) and quantitative comparison of two styles of interfaces such as crossing-based vs. pointing-based interaction (Accot and Zhai, 2002). According to Fitts' law (Fitts, 1954), the time to point at an object depends on the pointing task's Index of Difficulty (ID) defined as the logarithm of the ratio between object distance and object size. For the same distance, the greater the object is, the faster one can point at it. Although much more complex than simple target tapping, in hand off such a relation may also hold since the larger the object is, the more relative tolerance it allows in the hand off process in terms of the accuracy the giver has to target at the receiver' hand, and the accuracy the receiver could "grasp" and hold the object.

Given this background, we set out to study two issues in a collaboratively performed hand off task:

- If Fitts' law is applicable as a task performance model for a collaboratively performed hand off task.
- If haptic force feedback improves performance when passing a virtual object between two persons.

2 Related Work

A number of studies have shown that adding haptic force feedback improves single users' performance in manipulating virtual objects. The added value of haptic force feedback lies in peoples' ability to feel the object they manipulate, which makes interaction faster and more precise.

One study showed that the effect of haptic force feedback shortened task completion times when the task was to put a peg in a hole simulating assembly work (Gupta et al, 1997). Another study (Hasser et al, 1998) showed that the addition of force feedback to a computer mouse improved targeting performance and decreased targeting errors.

Although not as well studied as single user interface interaction, a few authors have investigated issues regarding joint manipulation of virtual objects in a haptic collaborative virtual environment (Basdogan et al, 2000; Ishii et al, 1994; Oakley et al, 2001; Sallnäs et al, 2000; Sallnäs, 2000).

In one study subjects were asked to play a collaborative game in virtual environments with one of the experimenters who was an "expert" player. The players could feel the objects in the common environment. They were asked to move a ring on a wire in collaboration with each other such that contact between the wire and the ring was minimized or avoided. Results from this study showed that haptic feedback enhanced perceived togetherness and improved task performance when pairs of people worked together (Basdogan et al, 2000).

In another study it was shown that subjects performed tasks significantly faster and more precisely when manipulating objects together in a haptic compared to a nonhaptic collaborative virtual environment (Sallnäs et al, 2000; Sallnäs, 2000). One task required that subjects lift cubes by pushing from each side of the object in order to build two piles from eight cubes while another task was to build one cube out of the same eight cubes. Two other tasks required that subjects place cubes in formations on the floor and in the last task subjects navigated, close together, around a formation. This study also showed that when haptic force feedback was provided subjects' perceived virtual presence was significantly improved.

Manipulation of objects can take many forms and one taxonomy illustrates a number of strategies that people use depending on the purpose of the tactile manipulation, such as investigating the weight, form, texture or softness of an object (Lederman and Klatzky, 1987).

Joint manipulation of objects can take just as many forms. One example is jointly grasping an object and moving it through an area that might have restrictions (Ruddle et al, in press). Another example is moving an object by pushing from both sides and lifting the object together. In the experiment presented here we investigate another type of joint manipulation - grasping an object and handing it to another person in a virtual environment.

The aimed movement paradigm of Fitts (Fitts, 1954) has been widely applied to performance evaluation of goal directed movements. The classic task is a reciprocal tapping task - subjects tap back and forth at two targets of controlled size and distance. In one study it was shown that a Fitts' tapping task was performed significantly faster when haptic force feedback was provided (Arsenault and Ware, 2000).

Traditionally, Fitts' law has been applied to the paradigm that one person is asked to move a pointer to a stationary target. Recently, Mottet et al (2001) found that Fitts' law could also apply to the situation where the pointer and the target are controlled by two separate persons, one moves the targets with a carriage and the other moves the pointer. Furthermore, the kinetic profiles of the relative movement between cursor and target motion were quite similar regardless if one or two persons performed the task. Mottet et al (2001) is the study closest to the present one on a collaboratively performed Fitts' law task, although Mottet et al's task did not involve object transfer.

3 Method

3.1 Apparatus

The haptic and the nonhaptic virtual environment were implemented using Reachin Technologies AB's API on a Windows 2000 PC. The haptic display systems used in this project consisted of two displays from Reachin Technologies AB with two Desktop Phantom force feedback devices from SensAble Technologies, Inc. (Figure 1.). This system provides stereo vision through Stereographics CrystalEyes 3 shutter glasses.

Figure 1: Two persons collaborating in the virtual environment using the ReachIn Display system.

In order to avoid network delays and related problems, both devices ran on the same PC. Both users had the same view of the environment. The computer screen was video recorded for later analysis.

3.2 The Collaborative Interface

The three-dimensional haptic collaborative interface was designed as a room with two larger shelves, on top of which six cubes were placed, three on each side (Figure 2.). The room also contained two smaller shelves that served as target areas, underneath the two larger shelves. Two cursors, coloured green and blue, corresponded to the tip positions of the two Phantom probes.

In both the haptic and the nonhaptic environment it was possible to grasp a cube by placing the cursor on the cube and then pressing the button on the haptic device. Once grasped, the cube could be moved in the environment. When the button was released so was the cube.

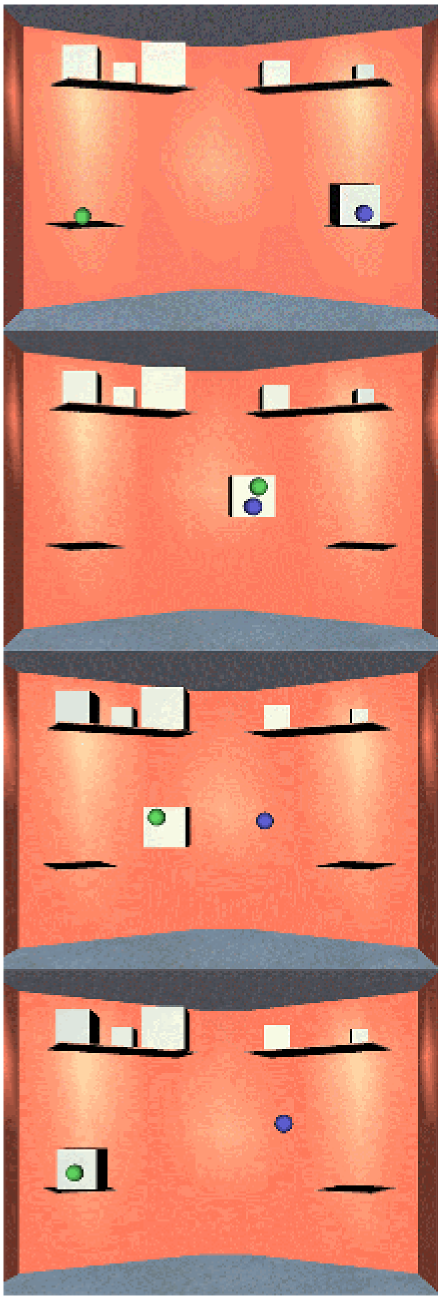


Figure 2: A sequence showing two subjects performing a hand off in the collaborative virtual environment.

The haptic user interface was developed so that all surfaces in the environment were touchable and thus provided haptic force feedback. It was also possible to "feel" gravity, the other user's impact on an object and the collision between a cube and a shelf. The haptic properties were texture, size, weight and stiffness. All other surfaces in the environment were also haptic with a certain friction and stiffness.

In the condition without haptic force feedback, the user could neither feel the cubes, walls, floor nor the shelves in the environment. In that case, the Phantom functioned solely as a 3D mouse without force feedback.

Critical to the hand off operation is its "interaction rules". It is difficult, if not impossible, to completely replicate physical interactions of the real world in virtual environments. Instead, the interaction rules attempt to afford behavior plausible to the users. In the haptic feedback condition, grasping force was implemented by means of a spring model between the center of the cube and the contact point on the surface of the spherical cursor. When two people both held the objects (both buttons pressed down), they could feel each other's action such as pushing or pulling, which facilitates haptic information exchange between the two people when they pass an object between each other.

In the non-haptic condition all forces were scaled to zero but the spring model was still geometrically present. The object stayed engaged to both cursors as long as the gaps between object and the two cursors were below 1.3 mm. If one of the gaps was greater than 1.3 mm, the cube was detached ("pulled off") from the giver so the receiver got the cube. In both conditions, the cube could be dropped if the giver released the cube before the receiver grasped it.

3.3 Task and Procedure

A within group design was used in this experiment. Each subject was seated in front of a haptic display system in separate rooms. Subjects used their dominant hand for the hand off task. Subjects were not able to communicate verbally with each other during the experiment. The experimenter instructed one subject face to face and one subject by telephone with headsets. Subjects had training trials before the first haptic and before the first nonhaptic experimental trial until they could perform hand offs correctly and felt confident in doing so.

Task difficulty was manipulated by changing cube sizes in randomized order. Six cubes with different sizes were handed off back and forth by each pair of subjects for each experimental condition. The distance (D) between the target shelves was fixed at 15.9 cm. The size of the target shelves was also fixed. The cube size (W) was 1.2 cm, 1.6 cm, 2.0 cm, 2.4 cm, 2.8 cm, and 3.2 cm respectively.

To begin the task, the experimenter took a cube from the upper shelves and placed the cube on one of the target shelves. Subjects were instructed to alternately grasp that cube, lift it and hand it to the other subject who tapped the second target shelf with the cube (Figure 2.). Subsequently, the second subject returned the cube to the first subject who then proceeded to tap the first shelf and so on. Subjects were asked to do the hand off task over a period of 60 seconds. They were instructed to avoid dropping the cube. The subjects were told when to start and when to stop doing the task. The experimenter then placed the next cube at a target shelf and the subjects proceeded with the hand off task. Each pair of subjects performed two complete sessions in each condition. Each session consisted of reciprocally handing over (back and forth) 6 differently sized objects. Each pair completed in total 24 trials. The order of target size was randomized and the conditions were balanced across subject pairs.

3.4 Subjects

Twenty-two subjects, with a mean age of 29 years, participated in the experiment. The subjects were nine students from Stockholm University and twelve students and one administrator from The Royal Institute of Technology. The subjects performed the experiment in eleven pairs, each consisting of one woman and one man except for two pairs with two men. None of the subjects had prior experience with the interface used in this study.

4 Results

Mean completion time was defined as the average time (t) in seconds to complete one task trial, measured by the interval between the taps on the two shelves with one cube. The data was analyzed using a repeated measures two-way ANOVA. The analysis of the time performance was divided into two types. The first was on the average time for performing successful (error free) trials only. For this analysis error free hand-offs were counted for each cube size in each session in both conditions. The second was on the average time for performing hand offs including error handling. This analysis included hand offs with cubes dropped. An error was recorded when subjects failed in coordinating a hand off and therefore dropped the cube. The number of cubes dropped for each cube size in each session in both conditions was recorded. Subjects were instructed to immediately pick up the dropped cube and continue the hand off task. Our analyses did not show any significant interaction between session and the performance measures. We hence used data collected in both sessions for performance comparison.

4.1 Completion Time

The result showed no significant differences ($F_{1,10}$ = 0.42, p = 0.53) between the haptic and the nonhaptic conditions regarding the average time it took to perform a successful hand off. The interaction between session and condition was not significant ($F_{1,10}$ = 0.07, p = 0.93), neither was the interaction between condition and size ($F_{5,50}$ = 0.99, p = 0.43). The mean time it took subjects to hand off a cube was 2.8 for the haptic condition and 2.9 seconds for the nonhaptic condition (Figure 3.).

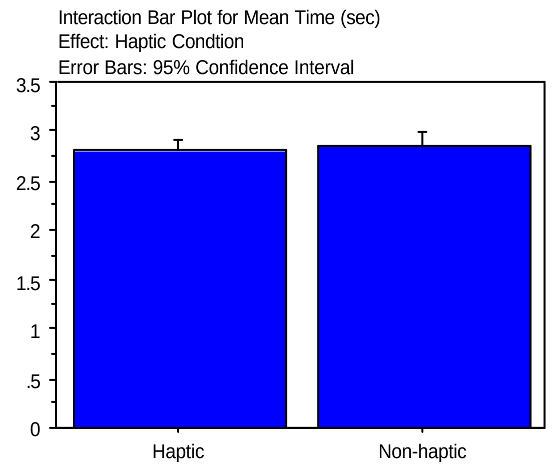


Figure 3: Mean times regarding error free hand offs in the haptic and the nonhaptic conditions.

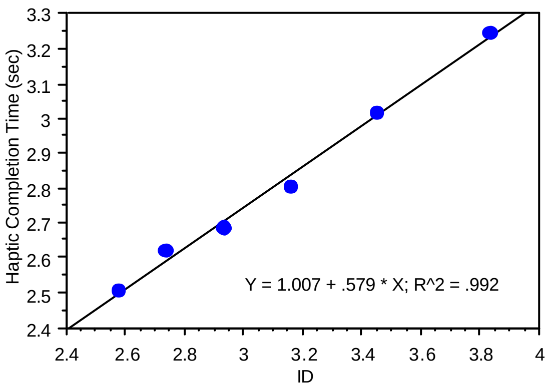
The results showed that there was a significant effect of cube size ($F_{5,50}$ = 30.2, p < 0.0001) in this experiment. This clearly demonstrated a Fitts' law effect:

$$T = a + b\,ID \qquad (1)$$

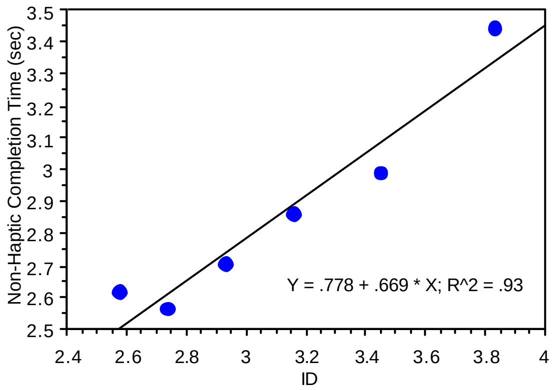
where the index is defined as

$$ID = log_2(D/W + 1) \qquad (2)$$

In this experiment, the total distance (D) was fixed at 15.9 cm. The object sizes (W) were 1.2 cm, 1.6 cm, 2.0 cm, 2.4 cm, 2.8 cm and 3.2 cm. Applying equation (2), the index of task difficulty (ID) in this experiment was: 3.8, 3.45, 3.16, 2.93, 2.74, and 2.58 bits. The fit between Fitts' law prediction and data collected in the haptic condition was remarkable (r^2 = 0.992), given that the hand off task is very different from and more complex than Fitts' traditional tapping task. Scatter-plots show linear regression between time to perform the task and Fitts' index of difficulty (Figure 4a.).



(a) Haptic condition



(b) Nonhaptic condition

Figure 4: Average time for collaboratively performed Fitts' task as a function of difficulty in both the haptic and nonhaptic condition.

Applying equation (1) and (2) for the haptic condition we have:

$$T = 1.01 + 0.579\ log_2(D/W + 1) \qquad (3)$$

Furthermore, the fit between the Fitts' law prediction and data collected in the nonhaptic condition is also good (r^2 = 0.93) (Figure 4b.). Applying equation (1) and (2) for the nonhaptic condition we have:

$$T = 0.778 + 0.669\ log_2(D/W + 1) \qquad (4)$$

4.1.1 Time to Perform Hand offs Including Errors

The result showed no significant difference ($F_{1,10}$ = 3.2, p = 0.1) between the haptic and the nonhaptic conditions regarding the average time it took to perform hand offs including errors. The haptic condition had no significant interaction with session ($F_{1,10} = 0.338$, $p = 0.57$) or size ($F_{5,50} = 0.87$, $p = 0.51$).

Including error handling, the mean time it took subjects to hand off a cube was 3.0 seconds for the haptic condition and 3.2 seconds for the nonhaptic condition .

4.2 Error Rate

The error rate data are measured as the percentage of cubes dropped. There was a significant difference between the haptic and nonhaptic conditions in error rate ($F_{1,10} = 6.5$, $p = 0.029$). The magnitude of the difference was rather large: The mean error rate was 5.2% for the haptic condition, and 10.7% for the nonhaptic condition (Figure 5.).

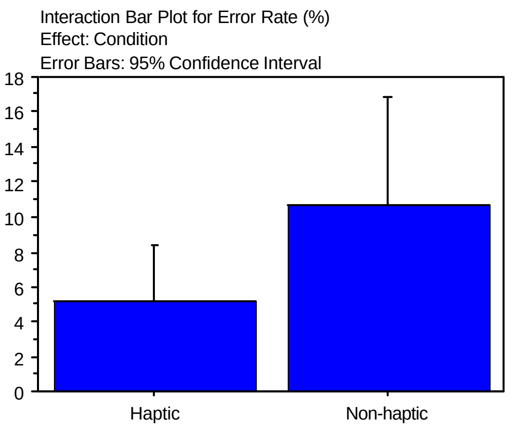


Figure 5: Percentage of errors in the haptic and nonhaptic conditions.

5 Discussion and Conclusions

5.1 Fitts' Law in a Hand off Task

The experiment presented in this paper investigated performance of a hand off task in a collaborative virtual environment. One research question was if hand off could be modelled as a collaboratively performed Fitts' law task. Fitts' law proved to hold for such a collaboratively performed task in both the haptic and the nonhaptic condition, despite the greater complexity of such a task than the traditional Fitts' tapping task. Our results clearly demonstrated that the time to accomplish a hand off task depended on Fitts' index of difficulty. As the size of the hand off object changed, the time to successfully complete a hand off trial increased logarithmically. These results are the first steps to investigate how a robust performance model such as Fitts´ law can shed light on collaboratively performed actions in virtual environments.

The task studied in this experiment departed from the most commonly researched Fitts' tasks in two ways. First, rather than single individuals, pairs of people performed our task jointly. With the exception of Mottet et al (2001), almost all Fitts' law studies have been focused on individually performed tasks. Second, our task involved object transfer rather than object tapping (also referred to as pointing reaching, or aimed movement depending on the context and background of study). To view object transfer as a Fitts' law task is not new. In fact Paul Fitts' original study (Fitts, 1954) examined three paradigms to establish the performance model later known as Fitts' law. Two of these three paradigms were object transfer (peg in hole and disk transfer). In both cases it was shown that the relative size of the object was a performance determinant just as the width of the tapping targets in his first paradigm.

What is new in our study is that the object "changed hands" in the process of being transferred from one location to another. In some sense, our task is probably the most complex task modelled so far by Fitts' law, involving two individuals and multiple stages, with the object first being moved from one position to the center, then changing "hands", then moving again to another destination.

Despite these differences, the correlation between the trial completion time, which combines multiple stages and both individuals' actions, and Fitts´ law ID was higher than we expected. In the haptic condition the correlation metric r^2 was 0.99, and in the nonhaptic condition r^2 was 0.93. The former was comparable to or better than the goodness of fit in individual target reaching tasks reported in the literature. Fitts law's applicability and robustness to this new type of task is remarkable.

Note that we only had one fixed distance (A) in our experimental manipulation. The index of difficulty was entirely controlled by varying the object size (W). This is consistent with a recent argument in the Fitts' law literature that rather than manipulating A and W combinations, Fitts' ID should be controlled by varying W under constant A, because changing the latter would tangle ID with scale effect (Guiard, 2001). Note also that the trial completion time used in Fitts' law regression was based on successful trials only. In traditional tapping studies error trials have not been handled consistently. Sometimes when a subject clicked outside the target the subject was instructed to continue until the target was hit. Other times the error trial was terminated once clicked but the time was counted in. The impact of these choices in conventional tapping tasks had not been noticeable. In our task, however, once the object was dropped, the task involved additional steps (picking up and continuing) that changed the process of the task altogether. We did not expect that the failed trials should still follow Fitts' law and we therefore used successful trial time only.

5.2 The Role of Haptics

Neither the average trial completion time to perform the hand off task successfully, nor the average task completion time including errors, did differ significantly between the haptic and nonhaptic conditions. This somewhat surprising result might be accounted for in the following ways.

One reason might be that in this experiment the task provided only short haptic events. In earlier studies subjects often performed tasks where continuous haptic feedback was essential for improved performance (Basdogan et al, 2000; Sallnäs et al, 2000; Sallnäs, 2000). In one study for example, moving a ring on a wire required that both subjects grasped the object during the entire trial of the task (Basdogan et al, 2000). In another study, subjects pushed from both sides of objects in order to move them together experiencing haptic force feedback during a high proportion of the trial time (Sallnäs et al, 2000; Sallnäs, 2000). Also, in that study subjects performed slightly more complex tasks than the hand off task.

Another reason might be that the nonhaptic condition was relaxed from its real world counterpart by the "elastic" property between the object and the cursor. The recipient could start to move the object before the giver actually released it, as long as the relative displacement between the recipient and the giver did not exceed 1.3 mm. This could have reduced the stringent timing coordination between the two participants and could be indeed taken advantage of in virtual environment design.

The advantage of haptic force feedback lies in facilitating temporal spatial coordination between the two participants when objects are transferred. Such an advantage was not reflected in the mean time to hand off objects, but in number of failed trials. The most difficult motor and perceptual event in the collaboratively performed Fitts´ law task was the actual transfer of differently sized cubes. The transfer event required that the collaborators coordinate receiving and surrendering the cube. This meant that the increasing task difficulty due to decreasing cube sizes was shared between collaborators and it was performing this motor task that produced errors. Coordinating hand offs in a nonhaptic environment required that the decision on whether or not the cube had been delivered be based on visual feedback only. When subjects got haptic feedback they could in fact communicate haptically, by testing if the other subject was holding on to the object by pulling it. This is supported by subjects' comments after the experiment:

"In the environment where you can feel, then you feel what the other person does, if both are at the object, then you can adjust so that both persons help each other to move in one direction. But in the other environment you have no idea what the other person actually does. Then it can happen that you pull in different directions…"

"You signal (to the other person) that you are at it (the object) when you push from the front (of the cube) because you felt that yourself (that you are on the object) so to say…."

Indeed, our results show that subjects dropped significantly more cubes in the nonhaptic than in the haptic condition. The consequence of error depends on the specific context of the task. Taking real world hand off tasks for example, in some cases, such as dropping a pencil on the floor, failure only means picking up the object and continuing. In other cases, such as dropping a coffee cup, it could mean spilled coffee, a broken cup or even more grave damages or injury. Subjects also commented on the fact that they felt more secure in handing over cubes in the haptic environment:

"You knew better where you had it when you could feel it….(the cube in the haptic environment)"

In conclusion, our study showed that Fitts' law could be used as a performance model for a new class of complex task collaboratively performed by two individuals, both in the haptic and non-haptic condition. It also showed that haptic feedback could help participants to coordinate their actions and reduce failures in object hand off.

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References

Accot, J. and Zhai, S. (2002). More than dotting the i's - foundations for crossing-based interfaces. *Proc. CHI: ACM Conference on Human Factors in Computing Systems*. Minneapolis, Minnesota, pp. 73-80.

Arsenault, R. and Ware, C. (2000). Eye-hand co-ordination with force feedback. *CHI Letters*, **2**(1), pp. 408-414.

Basdogan, C., Ho, C., Srinivasan, M. A. and Slater, M. (2000). An experimental study on the role of touch in shared virtual environments. *ACM Transactions on Computer-Human Interaction*, **7**(4), 443-460.

Card, S.K., English, W.K. and 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.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, **47**(6), 381-391.

Guiard, Y. (2001). Distangling relative from absolute amplitute in Fitts law experiments. *Proc. Extended Abstracts (short talks), CHI 2001: ACM Conference on Human Factors in Computing Systems*. Seattle: ACM, pp. 315-316.

Gupta, R., Sheridan, T. and Whitney, D. (1997). Experiments using multimodal virtual environments in design for assembly analysis. *Presence: Teleoperators and Virtual Environments*, **6**(3), 318-338.

Hasser, C. J. Goldenberg, A. S., Martin, K. M. and Rosenberg, L. B. (1998). User performing a GUI pointing task with a low-cost force-feedback computer mouse. *Proceedings of the ASME Dynamic Systems and Control Division*, **64**, 151-156.

Ishii, M., Nakata, M. and Sato, M. (1994). Networked SPIDAR: A networked virtual environment with visual, auditory and haptic interactions. *Presence: Teleoperators and Virtual Environments*, **3**(4): 351-359.

ISO, ISO 9241-9 *Ergonomic requirements for office work with visual display terminals (VDTs) - Part 9: Requirements for non-keyboard input devices (FDIS - Final Draft International Standard)*, 2000, International Organization for Standardization.

Lederman, S.J. and Klatzky, R.L. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology*, **19**, 342-368.

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., Sellen, A. and Buxton, W. (1991). A comparison of input devices in elemental pointing and dragging tasks. *Proc. CHI'91: ACM Conference on Human Factors in Computing Systems*. New Orleans, Lousiana, pp. 161-166.

Mottet, D., Guiard, Y., Ferrand, T. and R.J. Bootsma (2001). Two-handed performance of a rhythmical Fitts task by individuals and dyads. *Journal of Experimental Psychology: Human Perception and Performance*, **27**(6)

Oakley, I., Brewster, S. and Gray, P. (2001). Can you feel the force? An investigation of haptic collaboration in shared editors. *Proceedings of Eurohaptics 2001*, pp. 54-59.

Ruddle, R. A., Savage, J.C.D. and Jones, D.M. (In press). Symmetric and asymmetric action integration during cooperative object manipulation in virtual environments. *ACM Transactions on Computer-Human Interaction*.

Sallnäs, E-L., Rassmus-Gröhn, K. and Sjöström, C. (2000). Supporting presence in collaborative environments by haptic force feedback. *ACM Transactions on Computer-Human Interaction*, **7**(4), 461-476.

Sallnäs, E-L. (2000). Improved precision in mediated collaborative manipulation of objects by haptic force feedback. In Brewster, S., and Murray-Smith, R. (Eds.) *Haptic Human-Computer Interaction. Proceedings of First International Workshop, Glasgow, UK, August/September. Lecture Notes in Computer Science*, 2058, pp. 69-75.

Zhai, S. (2002). *On the Validity of Throughput as a Characteristic of Computer Input*, IBM Research Report RJ 10253, Almaden Research Center: San Jose, California.