

Title Page

Effect of Packet Loss on Collaborative Haptic Interactions in Networked Virtual Environments: An Experimental Study

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Abstract --- It has been widely demonstrated that haptic interaction can enrich the sense of copresence of distributed users and improve their performance in collaborative virtual environments (CVEs). However, the influence of network traffic on haptic collaboration, particularly packet loss in haptic data streams, is still largely unknown. In order to investigate the effect, we designed and conducted a series of experiments on a simulated lossy network. First, a single-user interactive task was designed to estimate the threshold that packet loss becomes just noticeable in terms of the length of burst loss (LBL). Second, a CVE was developed in which two users are required to work together on a goal-directed task through haptic collaboration. Experiments were performed to evaluate the users' task performance at different packet loss rates and their perception using subjective measurements. Finally, the effect of packet loss combined with network latency was investigated. The findings are: (1) the threshold LBL value for haptic discontinuity to become noticeable is 60.18 ms; (2) haptic collaboration performance is sensitive to packet loss rate; and (3) while the combined effect of packet loss and communication delay adversely affects collaborative haptic interactions, the influence due to packet loss rate is dominant when the delay is below a certain threshold. These results can serve as a guiding reference for the design and development of virtual telepresence systems with rich haptic collaborations.

1 Introduction

Haptic feedbacks, in addition to the visual ones, are essential for enhancing the sense of presence and immersion in virtual environments (R.J. Adams & Hannaford, 1999; Mine, Brooks, & Sequin, 1997). Users interacting with virtual objects via haptic device not only perceive kinesthetic feedbacks but also the information about the texture and local geometry, which is not possible when traditional user interfaces such as keyboard, mouse and joystick are used.

With the development of distributed interactive applications, research has also been conducted to demonstrate the significance of haptic perception for multiple users working together on cooperative tasks in collaborative virtual environments (CVEs), from a simple distributed system enabling users to feel and manipulate dynamic objects simultaneously in a shared desktop virtual environment (R. J. Adams, Klowden, & Hannaford, 2001; Brave, Ishii, & Dahley, 1998; Lotta Sallnäs, Rasmussen, & Sjöström, 2000), to complex applications such as synchronous shared editor (Oakley, Brewster, & Gray, 2001) and virtual surgery systems (Hutchins et al., 2006). A better sense of engagement and presence and improved task performance were reported in these studies.

The addition of haptic sensation in CVE has received considerable attention in recent years. Many attempts have been made to exploit collaborative haptic interactions to improve the quality of virtual interactions, thereby achieving better simulation efficacy. For example, a collaborative haptic assembly simulator was developed on top a peer-to-peer network to allow users to perform virtual assembly tasks together using haptic devices (Iglesias et al., 2008). In particular, haptics plays an important role in the virtual

training of medical tasks which are primarily collaborative work. To help retaining cardiopulmonary resuscitation (CPR) skills, a virtual collaborative training simulator was developed to allow trainees to perform CPR on haptic device while their performance were observed by remote assessors (Khanal & Kahol, 2011). Surgery as a team work also enjoys the benefit of haptic feedback in CVE (Qin, Choi, Pang, Zhang, & Heng, 2010). Research effort has been dedicated to realize multi-user virtual surgical trainers supporting collaborative haptic interactions, where disparate haptic rates and latencies among the users should be handled. Client-server architecture was implemented to support haptic interactions in the learning of blood management in orthopedic surgery (Qin, Chui, Pang, Choi, & Heng, 2010). Hybrid architecture was exploited to maintain state consistency among multiple users (Qin, Choi, Poon, & Heng, 2009; Sankaranarayanan, Deo, & De, 2009). Furthermore, the haptic communication paradigm “what-you-feel-is-what-I-feel” was proposed to enhance the learning of motor skills in needle insertion tasks, where the trainee’s hand was guided by the instructor via a pair of network-connected haptic devices (Chellali & Dumas, 2010). The paradigm was also used for guided writing and drawing (Ullah, Liu, Otmane, Richard, & Mallem, 2011).

However, the fidelity of haptic collaboration in CVEs is often compromised by many factors. One of the factors is the stochastic nature of network infrastructures, where communication delay, packet loss and jitters cannot be totally eliminated (Hespanha et al., 2000). These pose great challenges to distributed interactive applications with rich haptic collaborations (Marsh, Glencross, Pettiifer, & Hubbard, 2006). In critical applications such as telesurgery (Marescaux et al., 2002), dedicated fiber-optic lines are

employed to ensure the quality of service (QoS), which is costly to implement and prohibits the popularity of collaborative haptic applications. A possible solution is to design dedicated network architecture and protocols, combined with intelligent algorithms, to reduce the effect of unfavorable network conditions and maintain the consistency and fidelity of haptic collaboration. This requires robust understanding of the influence of network quality on psychophysical perception and user performance in haptic collaboration.

Although some studies have been conducted to investigate the effect of network delay and delay jitters on the quality of haptic collaboration, the effect of packet loss on users' psychophysical feeling during haptic interactions in CVE systems receives little attention. To fill this gap, we designed and performed three sets of experiments to systematically assess the effect of packet loss on haptic collaboration in typical distributed interactive applications. The aims of the experiments were to investigate respectively (1) the perception threshold that packet loss becomes noticeable in terms of length of burst loss (LBL), (2) the relationship between packet loss rate and task performance at different levels of LBL, and (3) the effect of packet loss in conjunction with both visual and haptic delay. The Gilbert-Elliott model (Elliot, 1963; Gilbert, 1960) is employed in the experiments to simulate packet loss in data transmission.

Length of burst loss, like packet loss rate, is a key parameter to characterize the level of packet loss of a network. It can be defined as burst length of consecutive packet losses (Shi et al., 2010). LBL is also called *burst size* in packet-switched network. In video transmission, the effect of packet loss is commonly studied in terms of LBL. It is demonstrated that when LBL reaches 60 ms (separation between two consecutive video

frames), visual data loss was easily noticed by most users (Wijesekera, Srivastava, Nerode, & Forrsti, 1999). However, the effects of LBL on haptic perception and collaborative tasks in CVE receive relatively little attention. Given a packet loss rate and mean LBL, the packet loss process can be fully defined by the Gilbert-Elliott model which is adopted in our study. It is necessary to fix the mean LBL in order to investigate the relationship among packet loss rate, network latency and haptic task performance in CVE requires, which is similar to the situations of the experiments in (Shi, et al., 2010). Hence, the first experiment was designed to determine the threshold LBL value at which haptic discontinuity due to packet loss becomes noticeable. This threshold value was then used in the rest of the experiments, where performance metrics are used to assess users' ability in performing haptic task in CVE and questionnaires are designed to evaluation their subjective perception on the collaborative haptic interactions.

The methodology and results in this study can serve as a guiding reference for the design and development of distributed interactive applications involving haptic collaborations. The rest of the paper is organized as follows. Section 2 reviews previous work concerning the effect of network conditions on collaborative work in distributed virtual environments. Section 3 introduces overall the experimental design and the Gilbert-Elliott model adopted in the study. Section 4 presents the details of the experiments and the results. Discussions on the findings of the study and a conclusion are given in Section 5.

2 Related Work

A major challenge of collaborative haptic applications is the requirement of a robust and stable network environment for data transmission. User response and performance are affected by suboptimal network conditions due to the presence of transmission delay, delay jitter and packet loss. The influence on the rendering of visual feedback for collaborative interactions has been widely studied. As mentioned, the threshold LBL for most users to notice visual data loss was found to be 60 ms (Wijesekera, et al., 1999). Packet loss rate is a key factor determining the performance of distributed interactive systems. The effect of packet loss rate and rate variations on visual feedback may vary depending on the applications (Dick, Wellnitz, & Wolf, 2005; Yajnik, Moon, Kurose, & Towsley, 1999). Recently, a detailed investigation was carried out to study the effect of packet loss on temporal discrimination of visual-haptic events (Shi, et al., 2010). However, the work focused on the visual modality without considering the effect in the haptic domain.

The effect of undesirable network conditions on distributed haptic interactions has been investigated in some early work. In the telesurgery system developed by Ottensmeyer et al., it was found that surgeons were more sensitive to latency introduced to haptic feedback than that to visual feedback (Ottensmeyer, Hu, Thompson, Ren, & Sheridan, 2000). Souayed et al. developed a distributed haptic system to investigate the effect of adverse network conditions on the user performance, where a local haptic device was used to navigate in a remote virtual environment (Souayed, Gaiti, Yu, Dodds, & Marshall, 2004). These studies did not consider haptic collaborations over the network.

The psychophysical effect caused by undesirable network conditions on haptic collaborations also received research attention. Jay et al. conducted a series of experiments to systematically study the effect of latency on haptic performance in a collaborative task, where users exchanged both visual and haptic information when they attempted to acquire a target cooperatively (Jay, Glencross, & Hubbard, 2007; Jay & Hubbard, 2005). A haptic-enabled distributed virtual reality system was developed to investigate the relationship between user-level QoS and network conditions, including delay, packet loss and jitter (Nishino et al., 2009). The users were required to perform a lifting task and handshaking in the experiments, and their perception was studied using simple subjective evaluation.

On the other hand, the effect of communication delay on haptic feedback has been investigated. It was generally agreed that users took longer time to complete a task and the performance deteriorated when haptic data were delayed due to network latency (Alhalabi, Horiguchi, & Kunifuji, 2003; Jay, et al., 2007; Wang, Tuer, Rossi, Ni, & Shu, 2003). The effect was also studied from another aspect - users' ability to perceive the haptic delay and the factors affecting delay perception. It was found that haptic delay became perceptible at a communication delay of around 50 ms (Jay, et al., 2007). The detection threshold indeed depends on system configuration. For example, perception of haptic delay was found to be affected by the amplitude and frequency of movements in a telepresence systems (Markus, Zhuanghua, & Sandra, 2010).

To achieve robust haptic communication, research has been conducted to streamline data transmission by reducing the amount of data transfer. Various perceptual deadband-based data reduction approaches have been proposed by taking advantage

of the idea that it is not necessary transmit haptic data of imperceptible changes (Steinbach et al., 2012; Steinbach, Hirche, Kammerl, Vittorias, & Chaudhari, 2011). The Weber's law of psychophysics were adopted where samples corresponding to changes smaller than the just noticeable difference (JND) in human haptic sensation were not transmitted (Hinterseer, Steinbach, Hirche, & Buss, 2005; Hirche, Buss, Hinterseer, & Steinbach, 2005). Network traffic caused by the high sampling rate of haptic feedback was thus reduced, for as much as 90%. Reduction in haptic perceptual ability of moving hands was also taken into account to further cut down data transmission while maintaining the task performance (Kammerl et al., 2010; Yang, Bischof, & Boulanger, 2008). The idea deadband-based data reduction was also extended to haptic interactions involving multiple degrees-of-freedom (Hinterseer & Steinbach, 2006).

In this paper, we have extended these studies to the haptic perception channel as there has been a growing interest in collaborative haptic interactions to enhance the feeling of copresence. We conducted a systematic study on the effect of packet loss on virtual haptic collaboration using both quantitative and subject evaluation, which, to the best of our knowledge, is not available yet in the research community.

3 The Packet Loss Model

The Gilbert-Elliott model is employed in this study to simulate packet loss in practical communication network. The model has been widely used for describing error patterns in transmission channel, including packet loss in the Internet (Haßlinger & Hohlfeld, 2008; Shi, et al., 2010). The basic principle of this model is shown in Figure 1. Here, state "0" denotes normal packet arrival whereas state "1" denotes the occurrence of

packet loss. Each of these two states may generate errors as independent events at a state-dependent error rate of $1/s$ and $1/t$ respectively. Furthermore, P_{01} is used to denote the probability of a transition from state “0” to state “1”, and P_{10} the probability of a transition from state “1” to state “0”. Since the modeling of packet loss in the Internet is considered sufficient for the purpose of our study (Shi, et al., 2010), we simplify the Gilbert-Elliott model by neglecting errors caused by attenuation distortion, thermal noises, inter-modulation noises and other factors. Hence, the values of s and t are both set to 1, and the mean loss rate P_l can be computed by

$$P_l = \frac{P_{01}}{P_{01} + P_{10}},$$

and the mean length of burst loss $\overline{LBL}$ can be computed by

$$\overline{LBL} = \frac{1}{P_{10}}.$$

P_l and $\overline{LBL}$ are two key parameters to characterize the level of packet loss of a network. A good understanding of the relationship between these two parameters and the psychophysical feeling in haptic collaboration is therefore essential for the design and implementation of efficient CVE with rich haptic interactions.

4 Experiments

Our review of the related work reveals two limitations in previous studies. First, while many studies focus on the effect of packet loss rate on haptic interaction or collaboration, they neglect the effect of LBL. When packet loss rate is high but the mean LBL is small, the effect of packet loss is indeed not significant. Second, the effect of packet loss and latency are investigated separately in many of the previous studies but not the combined

effect. These experiments do not address the practical situations where data loss and delay can exist at the same time. In this study, three experiments are designed to study users' performance and psychophysical perception during haptic collaboration in networked virtual environments.

- (i) Experiment 1 - Threshold Determination: The experiment was designed to determine the threshold LBL value beyond which packet loss is felt. This value was then applied in the subsequent experiments.
- (ii) Experiment 2 - Effect of Packet Loss Rate: The effect of packet loss rate on haptic collaboration was studied in this experiment. Two separated users, connected by a lossy network, are required to perform a goal-directed collaborative task in a shared virtual environment. The scenario is illustrated schematically in Figure 2. The users cooperate by communicating with each other through the exchange of visual and haptic information over the network. Both quantitative measurement and subjective evaluation were conducted to assess the task performance and psychophysical effect at different packet loss rates.
- (iii) Experiment 3 - Combined Effect of Packet Loss and Latency: In addition to packet loss, network latency was also considered in this experiment to study their combined effect on collaborative task requiring haptic feedback. Delay in transmission of visual and haptic data over the network was simulated. The objective was to study users' performance and perception during collaborative haptic interactions over a practical network. The results can be used as a reference to guide the design of haptic-enabled CVE and to maintain its quality to an acceptable level.

In this study, haptic discontinuity due to packet loss is considered as a physical stimulus and we are interested to understand quantitatively human sensation and perception of the stimulus. Hence, psychophysics evaluation is adopted in Experiment 1 to measure the threshold that packet loss becomes just noticeable in terms of LBL. The approach is similar to that adopted in the study of temporal discrimination of visual-haptic events (Shi, et al., 2010). The determined threshold LBL can then be used to configure the simulated networked virtual environment in Experiments 2 and 3. With the LBL value fixed, we are able to vary the packet loss rate and network delay to study their effect on the users' performance in a collaborative task and perception of the virtual collaboration experience in these experiments. Hence, quantifiable performance metrics and subjective evaluation are required for the investigation. The metric task completion time (TCT) is therefore used to quantify users' performance whilst questionnaires are used to evaluate the users' perception on the easiness of the task as well as the sense of copresence and involvement. This approach has been adopted to evaluate the effect of network delay on collaborative virtual environment (Jay, et al., 2007; Jay & Hubbard, 2005).

4.1 Experiment 1

4.1.1 Setting

The aim of the experiment is to find out the threshold LBL value at which users can feel the haptic discontinuity caused by packet loss. Here, it is sufficient to create an ordinary standalone haptic-enabled virtual environment but the force data sent to the haptic device have to be dropped intermittently on purpose. To achieve this goal, the

virtual environment is modeled such that a user is required to exert a force (only the horizontal component is considered) from the right of a virtual cube, via haptic device, to counteract a constant, computer-generated horizontal force applied from the left of the cube. The virtual environment is illustrated in Figure 3. To keep the cube stationary, the user should apply a force with approximately the same magnitude as the computer-generated force. However, data of the computer-generated force are not directly sent to the haptic device to render feedback forces, but interrupted by simulated packet loss using the simplified Gilbert-Elliott model. The force data are dropped intermittently and the extent of packet loss is controlled by varying the LBL. If the value of LBL is large enough, the user will feel slight fluctuation of the stylus and notice the movement of the cube visually. The forces in the experiments were smoothly rendered with a refresh rate as high as 1 kHz.

4.1.2 Apparatus

The experiment was performed on a computer with an Intel quad-core 2.40GHz CPU and 4GB RAM, running Windows XP, and equipped with a SensAble PHANToM Desktop haptic device. The virtual environment was built using OpenGL and OpenHaptics toolkits, and displayed on a Dell LCD monitor (screen resolution: 1440x900 pixels; refresh rate: 60Hz).

4.1.3 Participants

Twenty participants (10 male and 10 female) were recruited to take part in the experiment. Their age range was from 19 to 25 years old, and the average was 22.5 (they also participated in Experiment 3a).

4.1.4 Procedure

During the course of the experiment, every participant was required to carry out the task at different LBL values that were applied one at a time. The burst loss at each LBL value lasted for a five-second time interval in each trial. Here, the alternate force choice (AFC) procedure was adopted. At the end of each interval, the participant was prompted with a yes-no dialogue box popping up on the screen, asking whether force discontinuity was felt or not. Each participant was required to conduct 50 trials of the task. The LBL values were chosen by using the staircase method (a.k.a. up-down method) (Dixon & Massey, 1957). Here, two staircase strategies - ascending and descending - were used alternately and randomly to pick an LBL value for each of the five-second intervals. For example, in 6 consecutive trials, the first two LBL values may be taken from the ascending strategy, the next three from the descending strategy, and the last one from the ascending strategy again. That is, the alternation between the two strategies was in random (Cornsweet, 1962; Smza, 1961). In the ascending strategy, the LBL value increased from the lowest value of 30ms; while in the descending strategy, it decreased from the highest value of 100 ms. These initial values were determined empirically with pilot experiments. For both strategies, the step size was set to 16 ms initially, which was reduced by half upon a direction change (i.e. a change in response to the yes-no question, from “yes” to “no”, and vice versa) until reaching 1 ms, and the step size was then kept at this value afterwards.

4.1.5 Results

Figure 4 illustrates the threshold determination process of a participant who responded to the yes-no dialogue box regarding the feeling of force discontinuity in the 50 trials. In the figure, the circles and crosses refer to the choice of “yes” and “no” respectively; “A” refers to the use of LBL value from the ascending staircase in a certain trial and “B” refer to that from the descending staircase. The threshold LBL value was determined by averaging the LBL values at the peaks and valleys of the two staircases, except the first peak and valley in each staircase in order to reduce the effect of starting errors (Jay & Hubbard, 2005). The average threshold LBL value of the 20 participants was 60.18 ms (SD = 1.90 ms). This value was used in the following experiments.

4.1.6 Discussion

When compared this average threshold LBL value with the corresponding value for visual perception, which was estimated to be 60ms (Wijesekera, et al., 1999), it is interesting to find that they are comparable, suggesting that human’s sensitivity to visual and force discontinuity due to packet loss are about the same. Instead, we introduced packet loss into the communication channel in order to gain understanding about its effect on users’ perception during collaborative haptic interactions.

4.2 Experiment 2

4.2.1 Setting

A goal-directed virtual collaborative task requiring cooperation of two users over the network is developed for this experiment. The users exchange data of their respective local views and haptic information while they are completing the task collaboratively.

The effect of packet loss rate on their perception and task performance are investigated. Figure 5 shows a schematic diagram of the task, so-called the “ring-moving task”, and a snapshot of the experiment. Gravity and friction were both simulated. By maneuvering the stylus of a local haptic device, the users were required to cooperatively pick up a virtual ring from a pole in the virtual environment and then move it to another pole. The users shared the same view of the virtual environment during the experiment. In order to hold the ring, they need to exert forces at the rim, each from a different point, and toward the center of the ring. As the users exchange force data through the network, they could feel each other by the sense of touch through the haptic devices. Depending on the feedback force one perceived from another, both users were also required to adjust the magnitude and orientation of the forces they are applying, so that the ring can be maneuvered in a stable and balanced manner without dropping it. Packet loss was introduced into the transmission channel based on the simplified Gilbert-Elliot model, which is expected to affect the performance of the users. The virtual ring was free to move in space but the users are encouraged to take a short path in order to finish the task as soon as possible. The time to complete the task TCT was recorded to evaluate their performance. It was defined as the time taken to remove a ring from a pole and put it through the other pole.

4.2.2 Apparatus

The experiment was performed with one participant using a computer with an Intel quad-core 2.40GHz CPU and 4GB RAM, while the other using a computer with an Intel quad-core 2.0GHz CPU and 2GB RAM. Both were running Windows XP. Each computer was equipped with a Dell LCD monitors (screen resolution: 1440x900 pixels;

refresh rate: 60Hz) and a SensAble Phantom Desktop haptic device. The computers were connected by a high-speed local area network (LAN). The latency and packet loss of the LAN is very low and can be considered as zero when compared to the simulated latencies and packet losses applied in the experiments

4.2.3 Participants

Another twenty participants (different from the participants in Experiment 1), ten male and ten female, were recruited for this experiment. Their age range was from 19 to 24 years old, and the average was 22.1. They were randomized to form 10 pairs of participants (they also participated in part 2 of Experiment 3b, to be described later). Based on the results of Experiment 1, the mean length of burst loss was set to 60.18 ms. On the other hand, four different mean packet loss rates were applied in the experiment, that is, 0, 0.1, 0.2 and 0.3. The packet loss was generated using the simplified Gilbert-Elliott model.

4.2.4 Procedure

Task Completion Time

Before starting the formal experiment, each pair of participants was required to take part in a 10-minute training session in order to become familiar with the operation of the haptic device and understand the requirement of the collaborative task. After the training, each pair of them performed the task for 5 times at 4 different packet loss rates respectively. The TCT at each trial was recorded. That is, 10×5 samples were obtained at each packet loss rate.

Collaborative haptic interactions

The force profile at various packet loss rates was also recorded by the system in real time to study the effect on force data transmission when the participants were performing the collaborative task.

Subjective evaluation

In the experiment, users' perception on the quality of haptic collaboration is also evaluated subjectively with three *response variable* - ease of task, sense of copresence and sense of involvement. The response variables are delineated as follows.

- 1) Ease of task: User's perception on the easiness of the collaborative task (Lewis & Raton, 1995).
- 2) Sense of copresence: The extent that a participant feels like being present with the other user rather than a computer when performing the collaborative over the network (Garau, Slater, Bee, & Sasse, 2001; Kim et al., 2004).
- 3) Sense of involvement: The extent to which a user experienced involvement in the CVE (Basdogan, Ho, Srinivasan, & Slater, 2000; Witmer & Singer, 1998).

By making reference to the questionnaires developed in related work, a 7-point Likert questionnaire containing 10 items is designed to measure the perception of a user from these three aspects, as shown Figure 6**Error! Reference source not found.**.. The first three items are used for evaluating ease of task (Lewis & Raton, 1995; Witmer & Singer, 1998), the following five items for the sense of copresence (Kim, et al., 2004; Witmer & Singer, 1998), and the last two for the sense of involvement (Witmer & Singer, 1998). The items in the original questionnaires are modified to fit the context of the experiment. For each item, point 1 of the Likert scale refers to "strongly disagree" and 7 to "strongly

agree". That is, the higher the score given to an item, the more positive (favorable) the response is. The effect of packet loss rates on the perception of the participants in terms of ease of task, copresence and involvement were studied using the 10-item questionnaire. They were asked to respond to the questionnaire after performing the collaborative task in virtual environment.

In addition to packet loss rate, we also studied whether the participants' ability to focus, previous experience with haptic devices and gender were associated with their perception on the collaborative virtual environment. In other words, the association between these four factors, i.e. the *explanatory variables*, and the three response variables concerned in the questionnaire were investigated. Here, the immersive tendencies questionnaire (ITO) was used to evaluate the ability to focus (Witmer & Singer, 1998). The participants were required to answer the five yes-or-no questions in Figure 7 **Error! Reference source not found.** If the response to 4 or more questions was "yes", the participant was considered as having good ability to focus. Furthermore, they were asked to respond to the question about whether they had previous experience with haptic devices or not.

4.2.5 Results

Task Completion Time

Figure 8 shows the average TCT of the 50 trials at each packet loss rate. It is clear that packet loss rate is a key factor affecting the performance of the collaborative task in the experiment. Notably, the TCT at packet loss rate equal 0.3 was almost two times larger than that when there was no packet loss in the communication channel. Further, as the results show that the average TCT increased linearly with the packet loss rate,

linear regression is performed, at 95% confidence interval, to obtain an equation to describe their relationship as follows.

$$TCT = 20.11 + 83.40 \times PacketLossRate, p < 1e-05, r^2 = 0.82$$

Besides, repeated measures analysis of variance (ANOVA) was also performed on the average TCT of the 10 participants at the 4 packet loss rates, which demonstrated that the effect of packet loss rate on TCT was of statistical significance, with $F(3, 36) = 57.20, p < 1e-03, \alpha = 0.05$.

Collaborative haptic interactions

Figure 9 and Figure 10 show the forces of the two participants whose TCT were smallest (left) and largest (right) respectively at four different packet loss rate. It was observed that force discontinuities and fluctuations were more severe for the participant with largest TCT, which explains why more time was needed to finish the task. Besides, jitters in the forces became more significant when packet loss rate was increased, indicating that packet loss greatly deteriorated haptic perception of the participants. Participants had to continuously adjust the magnitude and orientation of the forces exerted on the ring in order to adapt to force discontinuity caused by packet loss and to cooperate with the counterpart on the other side of the network.

Subjective evaluation

Figure 11 shows the average scores of the items for each response variable at different packet loss rates. The result indicates that ease of task and sense of copresence decreased when packet loss rate was increased while the effect on involvement is not conclusive. Overall, the scores tend to decrease with increasing packet loss rate.

We also conducted a conservative analysis by classifying the response to an item as positive if the item scored 6 or 7 in the 7-point Likert scale (Slater, Steed, McCarthy, & Maringelli, 1998). Denote n as the number of items under a response variable, and p as the number of positive responses obtained out of the n items. Under the null hypothesis of randomly and independently assigned responses, p has a binominal distribution and therefore logistic regression can be used for the analysis (McCullagh & Nelder, 1983). Table 1 shows the mean and standard deviation of the number of positive responses for each response variable at different packet loss rates. It is clear that the number of positive responses was reduced, i.e. the participants' perception on the CVE became more negative, when the packet loss rate was high.

Logistic regression analysis was used to test the association between the four explanatory variables with the three response variables. The results are shown in Table 2. It is found with statistical significance that both packet loss rate and ability to focus were positively associated with all the three response variables. The finding indicates that these two variables are key factors determining users' overall perception on CVE that would directly affect their performance in cooperative work involving haptic interactions. Interestingly, gender is found to be positively associated with the perception on the sense of copresence and involvement. It appears to be easier for the female users to feel the presence of their counterpart in the CVE through collaborative haptic interactions in the cooperative task. As to the previous experience with haptic devices, statistical significance was only obtained for the test on the association with the participants' perception on the ease of task. This finding is reasonable in that if participants already have some experience in using haptic device, they are expected to

have a fast learning curve to manipulate the device and the virtual objects, thus considering it is easy to complete the task.

4.2.6 Discussion

As expected, the performance of the participants, in terms of TCT, decreases with packet loss rate. The relationship is found to be linear. Subjective evaluation from the aspects of the ease of task, sense of copresence and involvement reveals that packet loss exhibits significant influence on all these three aspects, when compared to the ability to focus, previous experience with haptic device and gender. It is thus a key design factor concerning the usability and robustness of a system with haptic collaboration.

4.3 Experiment 3

The combined effect of packet loss and network latency was investigated in the experiment by simulating delays in visual and haptic data channel. The experiment was divided into two parts - Experiment 3a and Experiment 3b. In the first experiment, the participants' ability to feel packet loss in the presence of delay in data transmission was studied. In the second, the combined effect of packet loss, visual and haptic delay on the participants' performance in tasks involving collaborative haptic interactions was investigated.

4.3.1 Experiment 3a

Procedure

The setting, apparatus and participants in this experiment were exactly the same as that in Experiment 1, except that different levels of haptic and visual delay were introduced

separately into the communication channel, from 0 ms (no delay) to 50 ms at a step size of 10 ms. The influence of haptic delay was first studied. The threshold LBL value at which a participant begins to feel force discontinuity caused by packet loss and haptic delay was recorded. The threshold values for the 20 participants were then obtained to calculate the average.

Results

Figure 12(a) shows the average threshold LBL value at different levels of haptic delay. It was observed that the average value decreased with delay in haptic communication and the effect was found to be statistically significant by the ANOVA test, with $F(5,114)=13.02$, $p < 0.01$. In other words, the participants became more sensitive to packet loss when the haptic delay was increased. The effect of visual delay was found to be similar, as shown in Figure 12(b). The average threshold LBL value showed a decreasing trend when the visual delay was increased. The effect of visual delay on the threshold LBL value was also significant, with $F(5,114)=10.81$, $p < 0.01$.

4.3.2 Experiment 3b

Procedure

The setting, apparatus and participants in this experiment were identical to that in Experiment 2. The participants' performance on collaborative task involving haptic interactions were studied when packet loss, visual and haptic delay were all present at the same time. Network delay affected the transmission of both visual and haptic data. The 20 participants were randomly paired and each pair was required to work together on the ring-moving task under seven levels of network delay, from 0 to 300 ms with a step size of 50 ms, and at four different packet loss rates. That is, each pair of

participants was required to perform the task 28 times (7 levels of delay $\times$ 4 packet loss rate).

Results

The TCT at each session was recorded and the average TCT of each participant pair at different packet loss rates was calculated. The results are shown in Figure 13. Notice that when the delay was further increased to beyond 200 ms, it was found that the participants could hardly finish the task and therefore the TCTs at the network delay of 250 ms and 300 ms were not available from the figure. As shown in the figure, when the delay was less than 100ms, the effect of packet loss rate on TCT was dominant while the variation in network delay did not result in significant changes of TCT (the curves corresponding to a delay of 0, 50 and 100 ms are close to each other). The results also showed that the standard deviation become larger as the delay increases. For example, the TCTs recorded at the delay of 100 ms were just slightly higher than those recorded at 50 ms delay for the four packet loss rates studied in this experiment. However, the TCT increased significantly when the delay was further increased to 150ms and 200ms, which suggests that the negative effect of network delay had become more disturbing. The network delay, combined with the influence of packet loss, hindered the operations for the collaborative task and extended the completion time. Two-factor ANOVA test was performed on the data. The effect of network delay and packet loss rate, and their combined effect on TCT were statistically significant, with $F(4,180) = 255.35$, $F(3,180) = 380.34$ and $F(12,180) = 20.82$ respectively, and $p < 0.01$ in all the three cases.

Discussion

While it is anticipated that the participants would be more sensitive to packet loss when communication delay is increased, it is counter-intuitive to find from Experiment 3a that the threshold LBL value was indeed increased. This is probably because the adverse effect due to delay is becoming more conspicuous that precludes the perception of force discontinuity caused by packet loss. Experiment 3b shows that the TCT for the ring-moving task only varied slightly when the network delay was small (below 100 ms), and the variation was primarily caused by packet loss. The combined effect of packet loss and delay became more significant when the delay was further increased.

5 Conclusion

With the advancement of internet and communication technology, it has become possible for people to interact in the cyberspace without physically meeting each other. The interactions are conventionally achieved through the exchange of visual, audio or text data over the network. Research has been extended to study the feasibility to allow geographically separated users to interact and cooperate in a distributed virtual environment by the sense of touch. The work primarily focuses on the effect of network delay while packet loss receives relatively less attention. The psychophysical feeling of users in haptic-enabled CVE under different network conditions is also largely unknown, making it difficult to develop an effective and robust application with intensive haptic-based collaboration. In this study, we attempt to investigate the relationship between packet loss and users' psychophysical feeling in haptic collaboration. The results can serve as a guiding reference for the design of such systems so that the quality of service

can be maintained. To this end, three experiments were conducted on a simulated lossy network, where the users could feel each other and manipulate virtual objects cooperatively, to investigate the effect of packet loss on interactive haptic collaboration.

While the findings in this study has provided insight into users' perception during collaborative haptic interactions in CVE, a large scale investigation with more participants is needed to improve the sample size so that more conclusive evidence can be obtained to further support the findings. Another limitation is that in Experiment 2 and 3, the study was conducted only with a simple goal-directed ring-moving task. It is not clear whether the influence of network traffic conditions on users' performance is task specific. The results might vary depending on the nature of the collaborative task. However, the task designed in this study is quite generic in the sense that the maneuvers involved are commonly found in virtual object manipulations. The results have potential for use as a reference in the design of CVE requiring haptic rendering. Future work includes investigating the effect on other types of collaborative tasks and developing methods and algorithms to counteract these effects.

Acknowledgement

The work described in this paper was partly supported by the General Research Fund Scheme sponsored by the Research Grants Council of Hong Kong (Project Number CUHK412510); the RGC Direct Allocation Grant (A-PJ38) and the Block Grant (1-ZV6C and 1-87RF) of the Hong Kong Polytechnic University.

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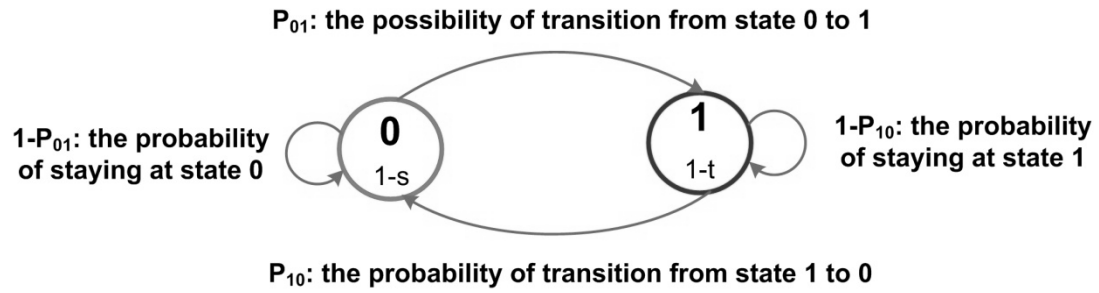


Figure 1. The Gilbert-Elliott model employed to simulate packet loss: 0 and 1 represent the 'good' state and 'bad' state (with packet loss) respectively.

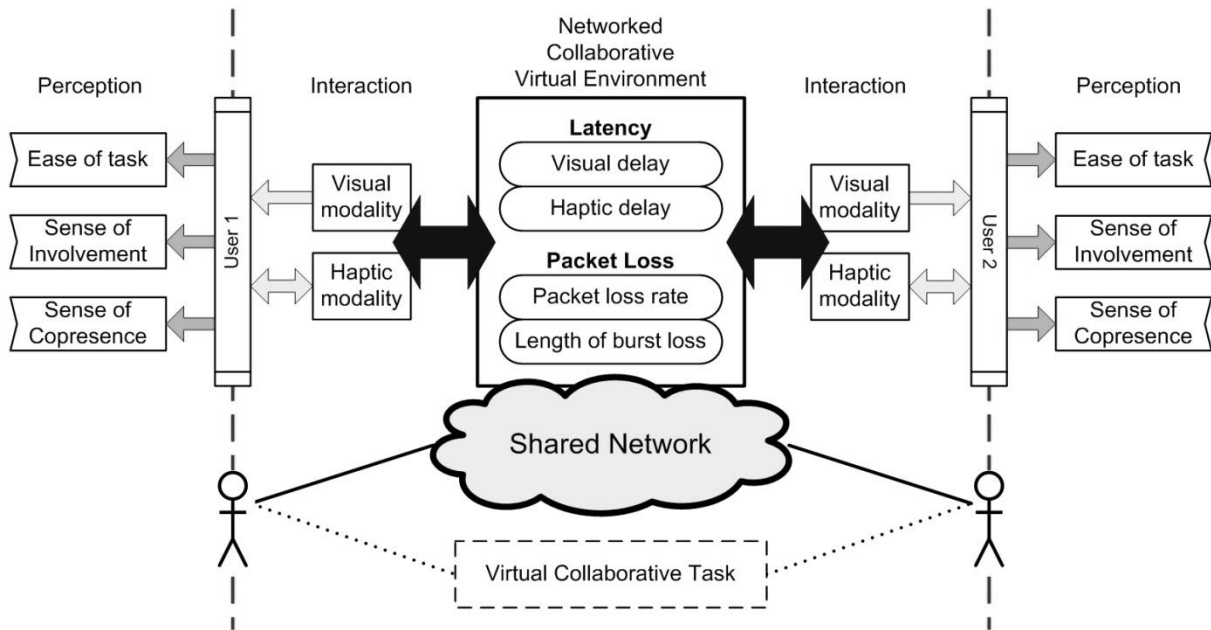
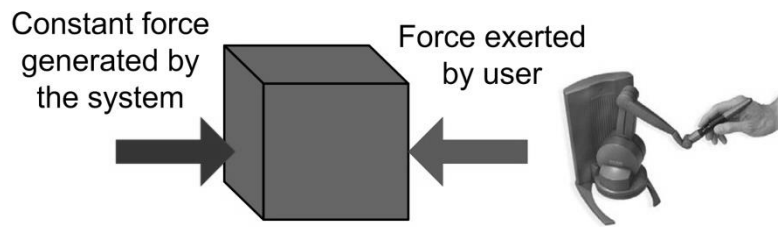


Figure 2. A conceptual model for the interactions between users performing collaborative task in a networked virtual environment.

(larger than 1 column-width)



(a)



(b)

Figure 3. (a) Schematic diagram illustrating the setting in Experiment 1: user is required to exert a force on the cube to counteract the constant force generated by the system. (b) The actual experimental setting.

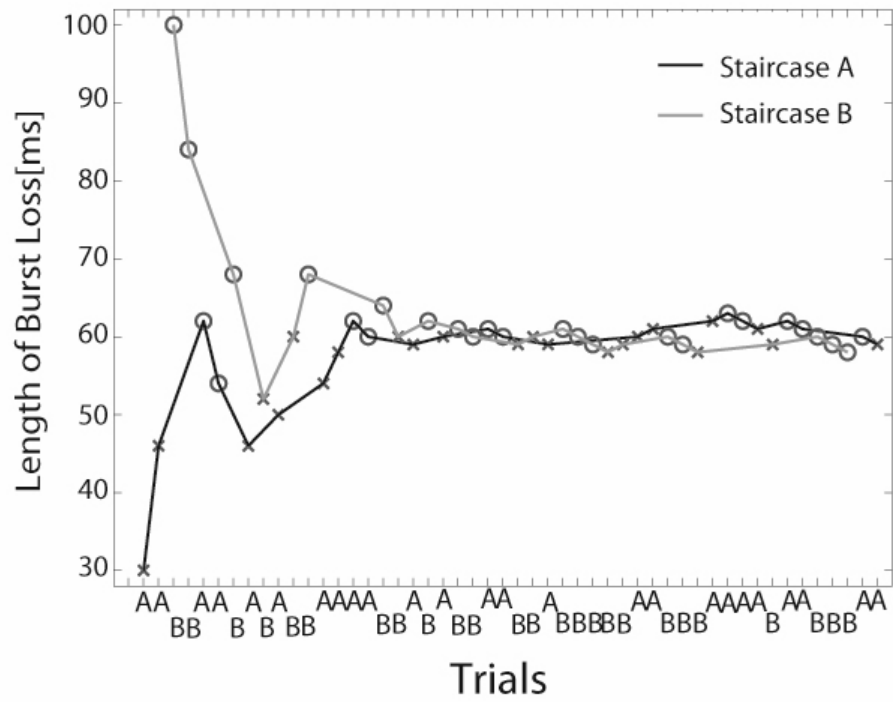


Figure 4. Threshold determination process of a participant responded to the yes-no dialogue boxes regarding the feeling of force discontinuity in the 50 trials.

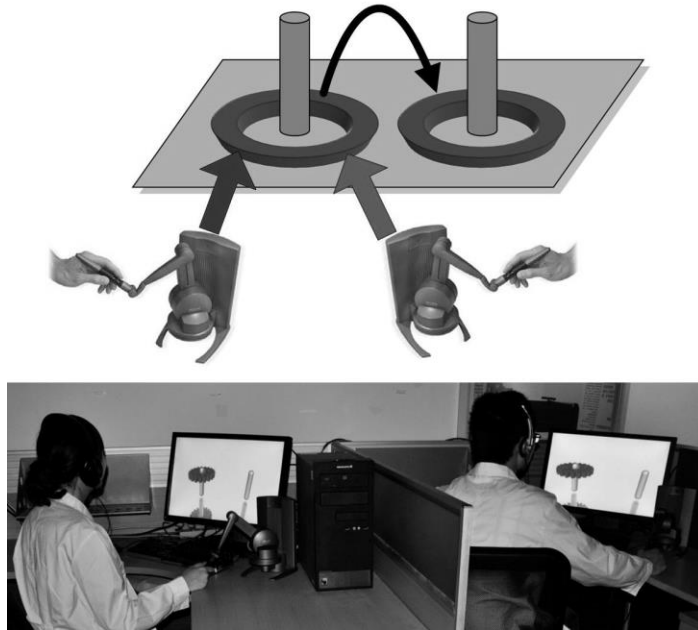


Figure 5. Schematic diagram illustrating the goal-directed task where two participants were required to work together, pick up a ring from one pole and move it to the other via haptic devices (top). A snapshot of the experimental setup (bottom).

Ease of task:

1. I adapted to the collaborative virtual environment quickly.
2. I was in control of the haptic device to complete the task.
3. I was clear when I first perform the task.

Sense of copresence:

4. I had a sense of being with the other participant.
5. There were times during which I thought the haptic device was vanished and I were directly working with the other participant.
6. I worked with the other participant harmoniously in the collaborative task.
7. My experience in working with the other participant on the task today is similar to that when I manipulate real objects cooperatively with another person (e.g. shifting a box, moving a chair or lifting luggage).
8. Overall, I had a sense that I was interacting with another person rather than a machine.

Sense of involvement:

9. I was aware that I was interacting in a collaborative virtual environment.
10. I was completely absorbed in the collaborative virtual environment.

Figure 6. Questionnaire used to measure the perception on the ease of task, sense of copresence and involvement.

1. Do you easily become deeply involved in movies or TV dramas?
2. Are you good at blocking out external distractions when you are involved in something?
3. When playing sports, do you become so involved in the game that you lose track of time?
4. Are you easily disturbed when working on a task?
5. Do you ever become so involved in doing something that you lose all track of time?

Figure 7. Questionnaire used to measure the ability to focus.

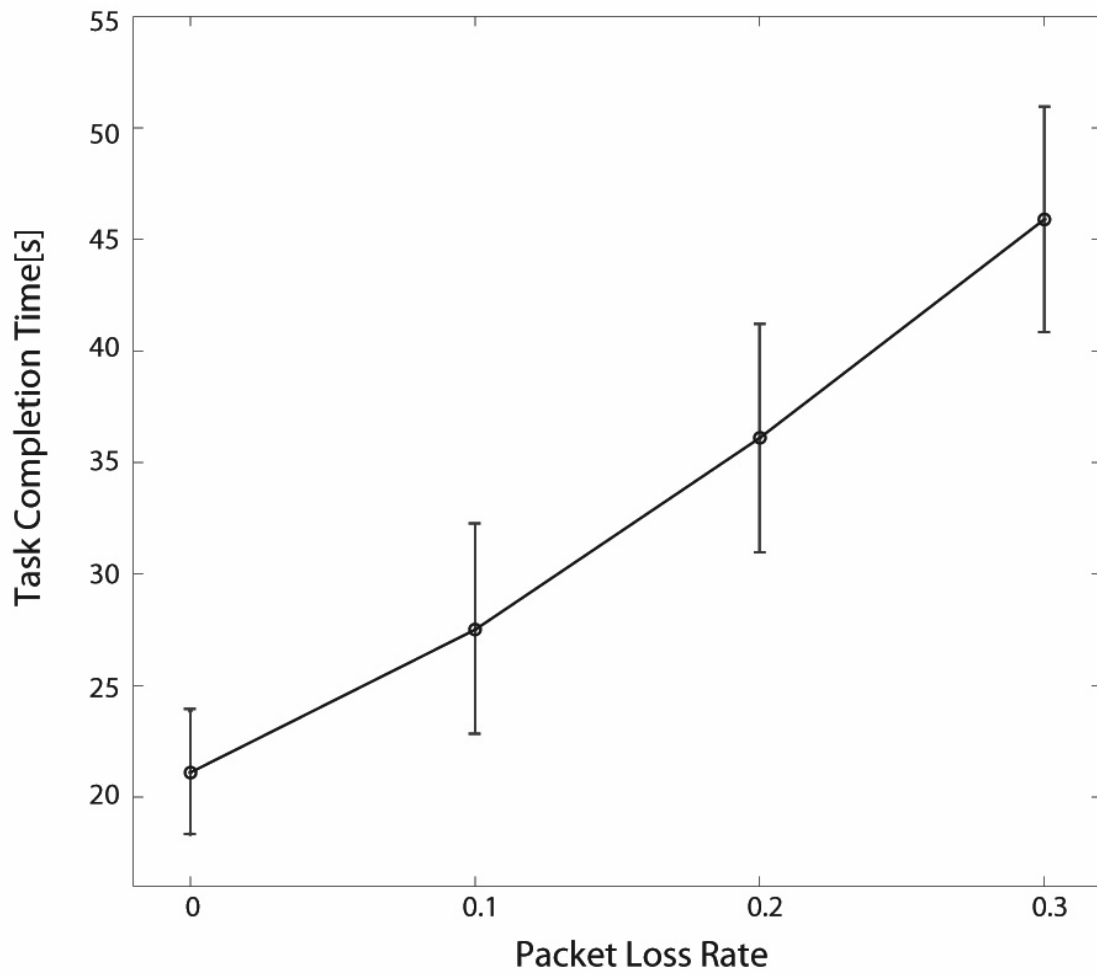


Figure 8. Variation of task completion time with packet loss rate.

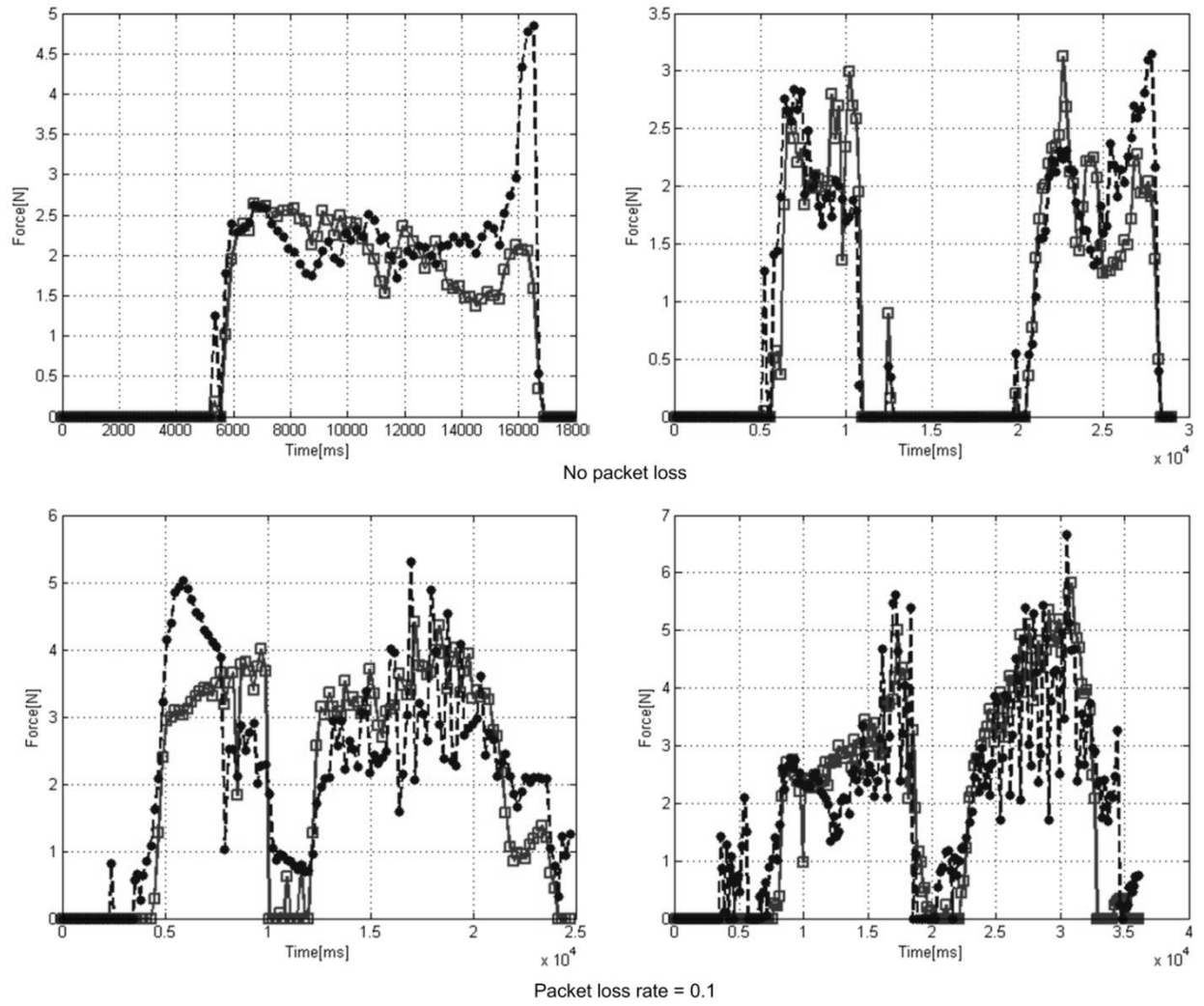


Figure 9. Force variation of participant pairs who spent the shortest (left) and longest (right) time to complete the task at zero packet loss and at the rate of 0.1. The force profiles for a pair of participants are represented using solid line with squares and dashed line with dots respectively.

(larger than 1 column-width)

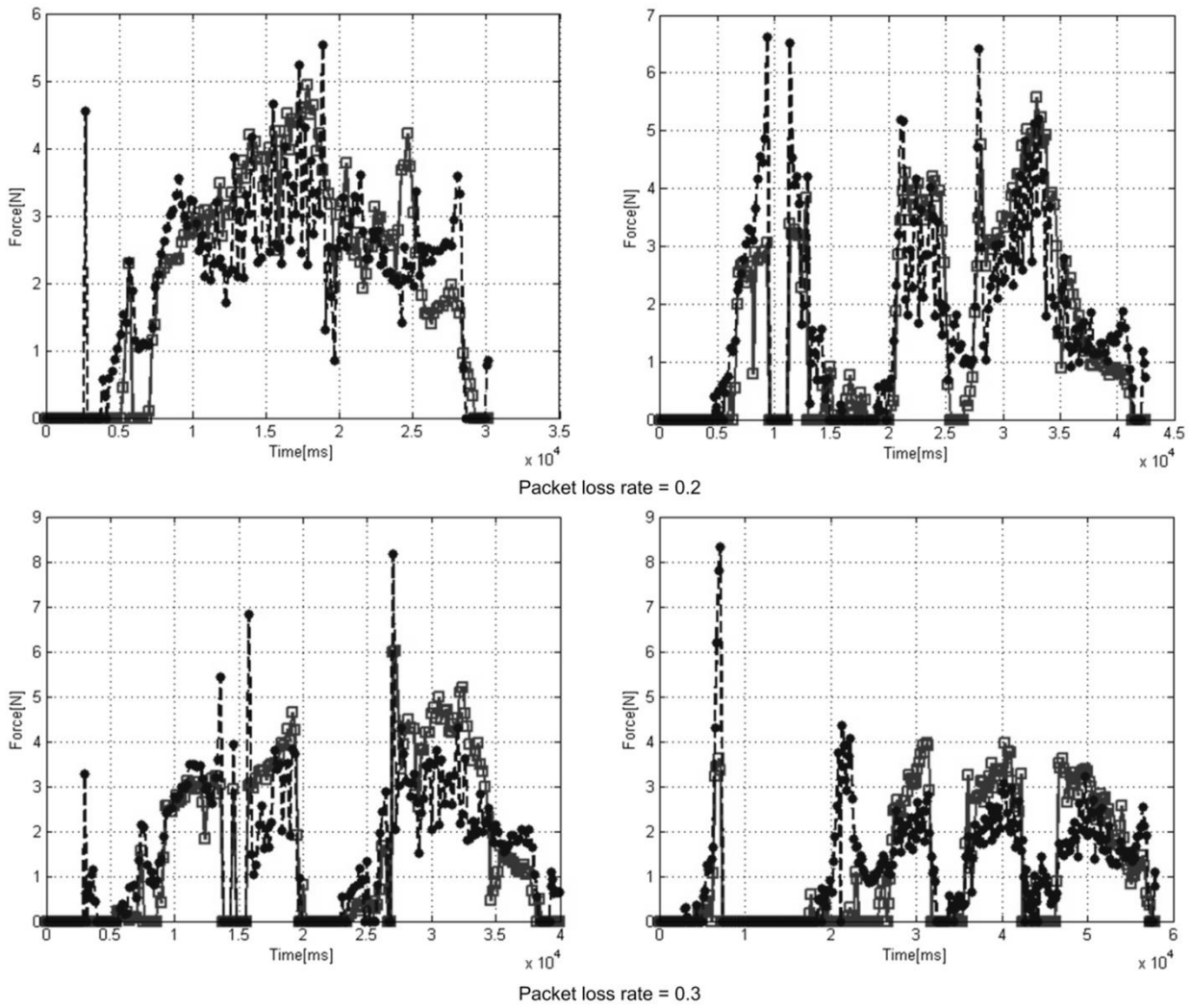


Figure 10. Force variation of participant pairs who spent the shortest (left) and longest (right) time to complete the task at the packet loss rate of 0.2 and 0.3 respectively. The force profiles for a pair of participants are represented using solid line with squares and dashed line with dots respectively. (larger than 1 column-width)

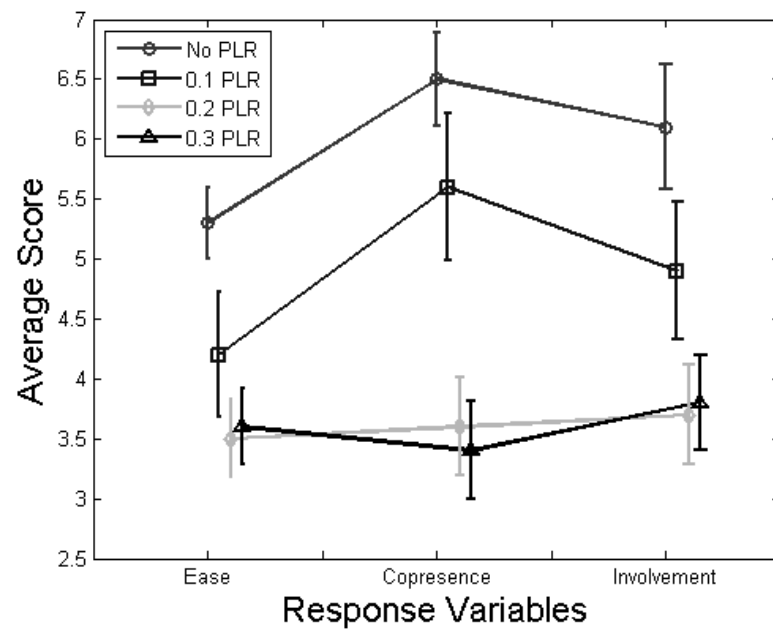
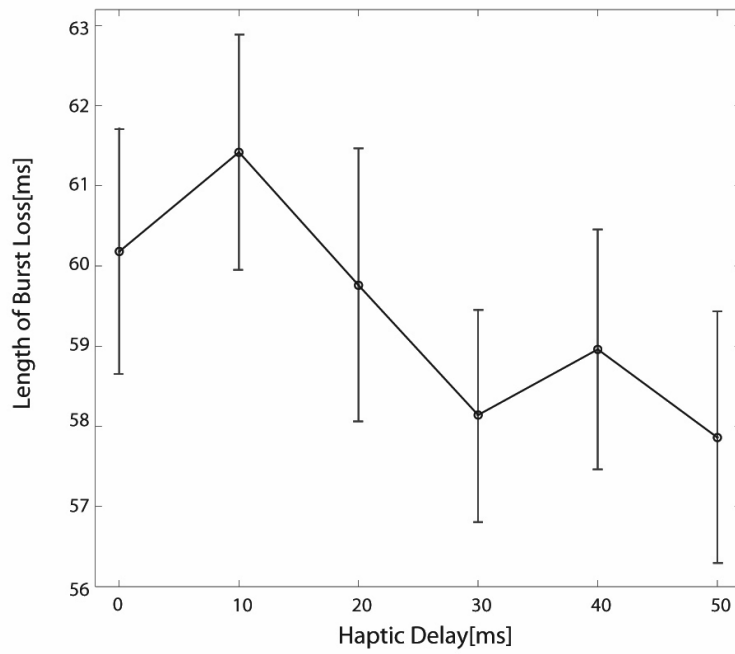
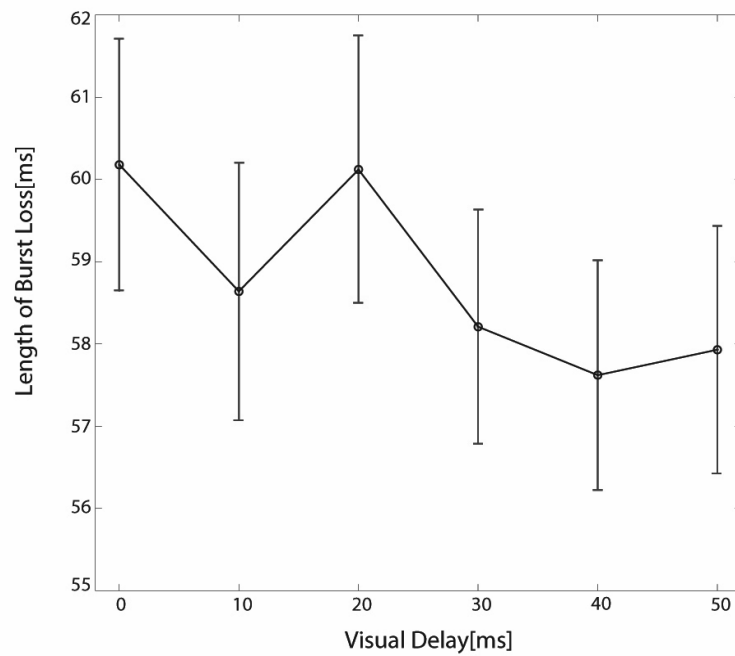


Figure 11. Average scores of each response variable at the packet loss rates (PLR) of 0, 0.1, 0.2 and 0.3.



(a)



(b)

Figure 12. The threshold LBL values obtained at different levels of (a) haptic and (b) visual delays.

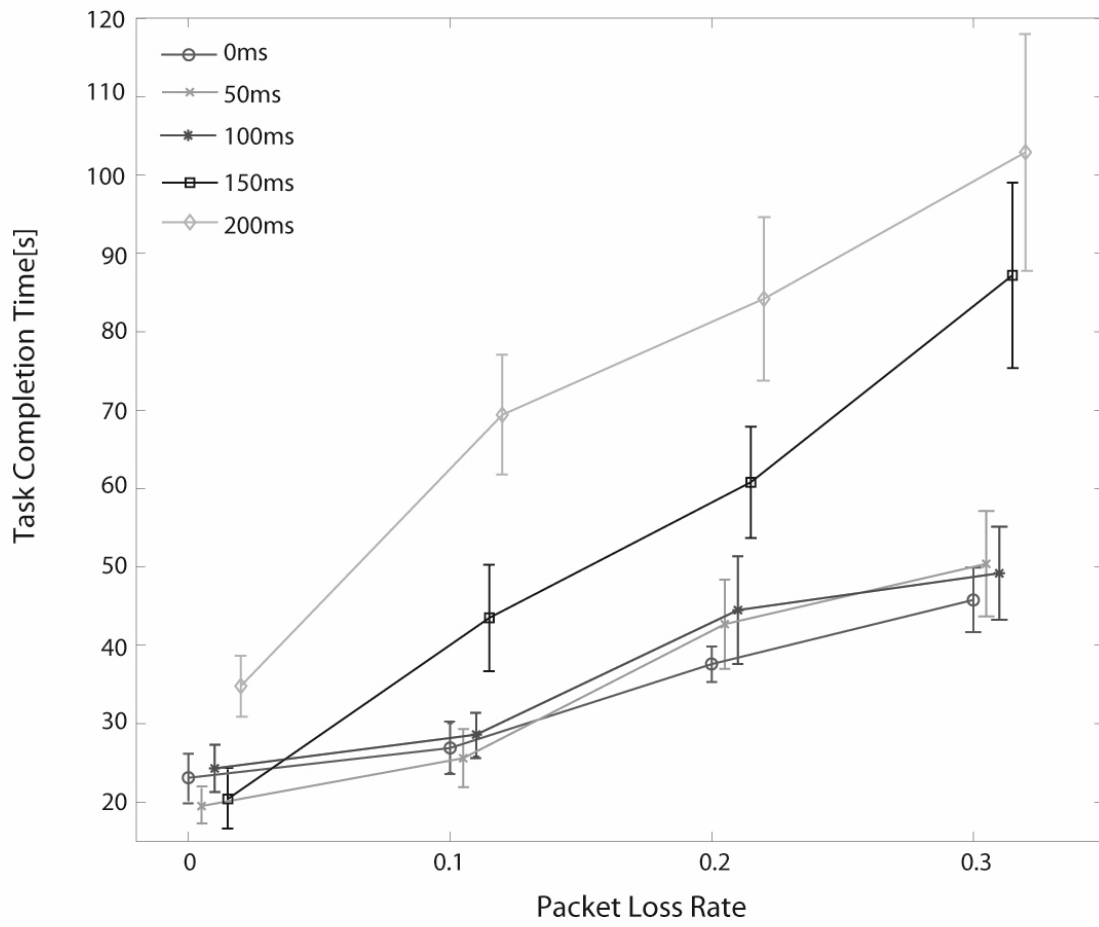


Figure 13. The combined effect of packet loss and latency on task completion time.

Table 1. Mean and standard deviations of counts of positive response for each response variables.

	Packet Loss Rate			
	0.0	0.1	0.2	0.3
Ease ($n=3$)	2.2±0.3	2.1±0.4	1.8±0.3	1.6±0.5
Copresence ($n=5$)	4.5±1.3	4.0±1.3	3.1±1.5	3.1±1.3
Involvement ($n=2$)	1.8±0.4	1.5±0.2	1.0±0.3	1.1±0.5

Table 2. Association between response variables and explanatory variables.

			Deviance χ^2		
	d.f.	5% χ^2	Ease	Copresence	Involvement
Packet loss rate	3	7.815	18.6	36.7	20.7
Ability to focus	1	3.841	9.7	9.7	18.5
Haptic experience	1	3.841	15.4	1.8	0.47
Gender	1	3.841	0.86	12.9	18.6