Quality-of-Experience in Human-in-the-Loop Haptic Communications

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Abstract: With the worldwide rapid development of 5G networks, haptic communications, a key use case of the 5G, has attracted increasing attentions nowadays. Its human-in-the-loop nature makes quality of experience (QoE) the leading performance indicator of the system design. A vast number of high quality works were published on user-level, application-level and network-level QoE-oriented designs in haptic communications. In this paper, we present an overview of the recent research activities in this progressive research area. We start from the QoE modeling of human haptic perceptions, followed by the application-level QoE management mechanisms based on these QoE models. High fidelity haptic communications require an orchestra of QoE designs in the application level and the quality of service (QoS) support in the network level. Hence, we also review the state-of-the-art QoS-related QoE management strategies in haptic communications, especially the QoS-related QoE modeling which guides the resource allocation design of the communication network. In addition to a thorough survey of the literature, we also present the open challenges in this research area. We believe that our review and findings in this paper not only provide a timely summary of prevailing research in this area, but also help to inspire new QoE-related research opportunities in haptic communications.

Keywords: QoE; human-in-the-loop; haptic communications; kinesthetic signals; tactile signals; haptic

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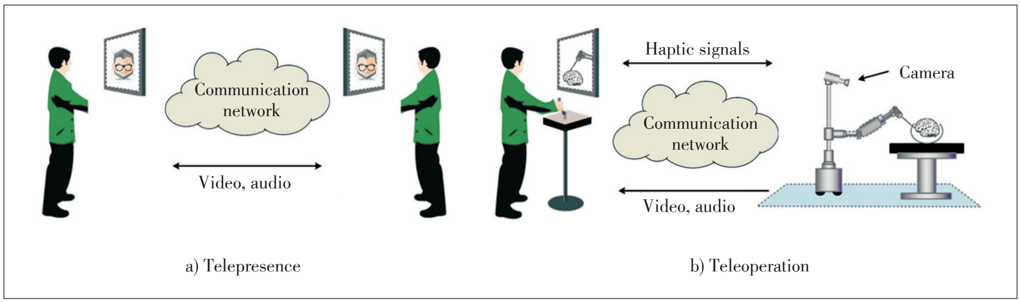
1 Introduction

The advent of mobile phones in the late 1980s broke the geographic barrier of landline telephones, so that we can have auditory conversation and interaction from anywhere. The past decade has witnessed the global blooming of mobile internet where audio-visual communications shape the way humans interact with technical systems or each other. Most recently, the world embraces the rise of the fifth generation (5G) of mobile networks, an excellent enabler of haptic communications, which will promote the human-to-human and human-to-machine interaction from the current audio-visual experience to the next-generation audio-visual-haptic perception.

Fig. 1a illustrates the conventional audio-visual communications (also known as telepresence), where one user remotely interacts with another user by exchanging audio/visual signals through the communication network. **Fig. 1b** demonstrates a typical haptic communication scenario for bilateral teleoperation. The global loop of haptic interaction consists of a human operator, a remote robot and the communication network. The audio/visual signals are transmitted from the remote robot to the operator, while haptic information exchanged bidirectionally between the human operator and the remote robot. Different from the conventional audio-visual communications, the “haptic” modality enables humans to actually alter the physical world remotely. It is obvious that in this human-in-the-loop haptic communication system, the quality of experience (QoE) of the human operator plays an important role in the operating/interacting performance of the entire system.



◀**Figure 1.**
A comparison of conventional audio-visual communications and audio-visual-haptic communications.

A comprehensive definition of QoE was presented in [1] for the conventional audio-visual communication as "the degree of delight or annoyance of the user of an application or service. It results from the fulfillment of his or her expectations with respect to the utility and/or enjoyment of the application or service in the light of the user's personality and current state." In the context of haptic communications, the QoE inherits all genes from that of the conventional audio/visual communication, while extending the audio-visual perception to a third dimension, the haptic perception, referring to the sense of touch.

In this paper, we summarize the prevailing studies on QoE strategies in haptic communications. We should point out that this survey stands at the communication perspective, and reviews the QoE-related techniques, algorithms and mechanisms operating in the haptic communication chain. For the perspective of automotive control, a comprehensive review of network designs for the Quality of Control (QoC) can be found in [2]. A survey of various control systems stabilizing the global haptic communications can be found in [3]. The mechanical design of haptic interface devices is out of the scope of this paper.

The roadmap of this survey is shown in **Fig. 2**. We first introduce the user-level QoE models derived from the psychophysical factors of human haptic sensations in Section 2. Based on these models, various haptic applications are developed to enhance the performance of user perception, such as haptic-enabled virtual reality (VR) gaming and haptic-enabled cinema. In Section 3, we stand at the application level, and illustrate QoE-oriented designs in latest haptic applications including haptic data reduction schemes, multiplexing schemes for the multi-user transparency and the perceivable synchrony of multi-modal data delivery. In Section 4, we present the network-level QoS-related QoE management, focusing on the QoS-related QoE modeling which provide guidance to the resource allocation of haptic signals. Finally, Section 5 concludes the paper with the future work and a summary.

2 User-Level QoE Management

The haptic perception of human beings generally refers to the sense of touch, composed of kinesthetic sense and tactile sense. In haptic communications, the human haptic perception is tightly connected to physical stimuli. As a result, we will first review the psychophysical impact factors of haptic interactions, based on which the user-level QoE models are develop in the literature.

2.1 Psychophysical Impact Factors

The haptic sensation is directly relevant to the human psychophysical perception mechanism. The kinesthetic sense allows for the perception of the position and orientation of our body parts and joints and external forces and torques applied to them. Hence, position, velocity, angular velocity, force, and torque all fall into the category of kinesthetic information. On the other hand, the tactile perception is sensed by different types of mechanoreceptors in the skin and allows humans to feel the surface texture (see [4] for details about the five psychophysical dimensions of tactile perception of textures), friction, temperature, etc. [5].

Haptic interactions generally involve both kinesthetic and tactile perceptions. For example, when a human operator controls a robot to grasp a rubber ball, the force and torque (kinesthetic) feedback presents the mass of the ball while the friction (tactile) feedback tells the texture of the surface. Since the haptic perception is an integration of multi-dimensional influence factors, the sense of touch is considered as the most complex sense to study [6]. A summary of the psychophysical factors and corresponding human perception mechanism and exemplar signal generation approaches [7]–[14] are listed in **Table 1**.

2.2 Human Haptic Perception Models

The first human haptic perception study was performed by Weber [15], who examined the precision of the

▲**Figure 2. Roadmap of this survey.**

▼**Table 1. Psychophysical factors, corresponding human perception mechanism and exemplar signal generation approaches**

	Kinesthetic sense	Tactile sense
Signal type	Position, velocity, angular velocity, force, and torque	Surface texture and friction
Human perception mechanism	Sensed by the muscles, joints, and tendons of the body	Sensed by different types of mechanoreceptors in the skin
Exemplar signal generation solutions	Using high torque motors to generate kinesthetic force feedback, such as Geomagic Touch (used to be called as Phantom Omni [7]) and Omega 3 [8]	Multi-pin display attached to the human skin [9]–[11], or using vibrators to display vibrotactile stimuli [12], such as TPad [13] and TeslaTouch [14]

touch sense and developed the famous Weber's law [16]. In this perceptual law, the perceivable difference between two stimuli, the Just Noticeable Difference (JND), is proportional to the initial stimulus itself, which can be expressed as

$$\triangle I = k \cdot I, \tag{1}$$

where k is a constant; I and $\triangle I$ denote the initial stimulus and the JND, respectively. The constant k, also called the Weber fraction, depends on the investigated stimulus, e.g. force, stiffness or velocity, and is generally obtained via experiments [16]. From Eq. (1), we can conclude that the human haptic perception system has different sensitivity with respect to the magnitude of the initial stimulus, e.g. the JND of large initial force is larger than that of a small initial force. Larger JND results in smaller sensitivity. In addition, the change of kinesthetic stimulus is linearly proportional to its intensity. Later, Fechner developed a logarithm model to reveal the relationship between the intensity of the stimulus and the change of kinesthetic perception in the brain [17]. Weber's linear model and Fechner's logarithmic model were proved essentially equivalent by Dahaene [18]. Since the linear model is simpler than the logarithmic counterpart, Weber's law is widely accepted as the QoE model of kinesthetic perception, which is then widely adopted in kinesthetic data reduction (see Section 3.1.1 for details).

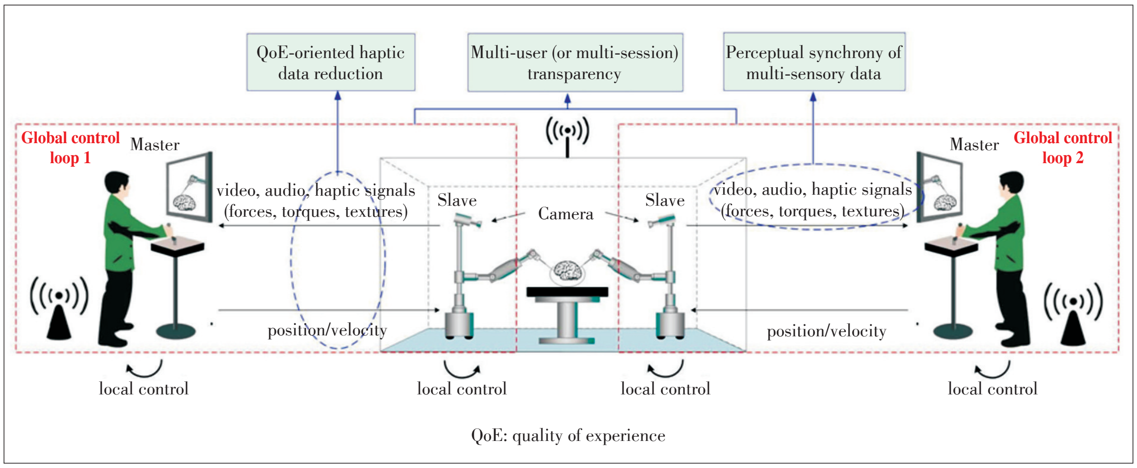
The kinesthetic signal involves large amplitude/low frequency force feedback, and has been shown to lack realism due to the absence of high-frequency transients (e.g., tapping on hard surfaces) and small-scale surface details (e.g., palpation of textured surfaces). Fortunately, the tactile signal provides an enhanced fidelity compared with the kinesthetic signal. The state-of-the-art tactile perception models concentrated on the modeling of vibrotactile texture signals [19]–[21]. Surprisingly, there is a strong similarity between texture signals and speech signals. This characteristic is then utilized in tactile data reduction technology (see Section 3.1.2 for details). As the rapid advances of machine learning algorithms, data-driven modeling and rendering approaches have been proposed for sophisticated tactile primitives, e.g., surface textures [22], viscoelasticity reactions [23], and thermal properties [24].

3 Application-Level QoE Management

The key objective of haptic applications is to satisfy the user's demand on haptic perceptual experience. In this section, we will summarize the key enablers of application-level QoE management, including QoE-oriented haptic data reduction, multi-user transparency, and perceptual synchrony of multi-sensory data, whose operational regions are illustrated in **Fig. 3** by using an exemplar haptic teleoperation application with two teleoperation sessions, respectively.

3.1 QoE-Oriented Haptic Data Reduction

It is known from Section 2.1 that two types of haptic signals (i.e. kinesthetic and tactile signals) are sensed by different human perception mechanisms and therefore, possess different properties. In addition, they have different tolerance on the communication delay. In particular, kinesthetic interactions are delay sensitive and will experience performance degradation in the presence of communication delay. The delay requirement of tactile interactions is quite relaxed compared with kinesthetic counterparts. On the other hand, the extreme high packet rate of kinesthetic feedback introduces a heavy burden to the network. The tactile feedback also contains multi-modal signals. Both kinesthetic and tactile interactions prefer



QoE: quality of experience

Figure 3.▶ Application-level QoE management in an exemplar haptic teleoperation application with two teleoperation sessions.

a data reduction module to improve the efficiency of the system. Therefore, in this section, we will review the data reduction solutions of kinesthetic and tactile signals, which are of significant importance to haptic communications.

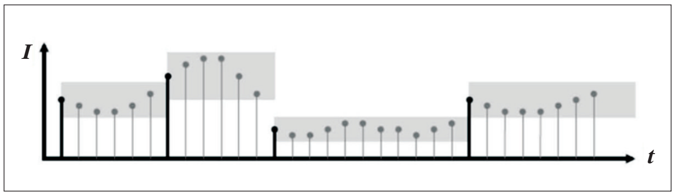
3.1.1 Kinesthetic Codecs

In order to guarantee system stability, a high sampling rate of 1 kHz (or even higher) for the kinesthetic signals is required in the implementation of teleoperation systems over the network. The haptic sensor readings are typically packetized and transmitted once available in order to keep the communication delay as small as possible. As a result, 1 000 or more haptic data packets need to be transmitted every second between the master and the slave devices in addition to the audio and video streams. This phenomenon introduces a severe burden to the communication networks. In order to address this problem, perceptual data reduction schemes [25]– [32] were developed based on the Weber's law.

This principle dynamically selects the to-be-transmitted samples according to human perception thresholds (as shown in **Fig. 4** for a 1-DoF example). Samples with black dots represent the output of the perceptual deadband (PD) data reduction scheme. The perception thresholds are represented by deadbands, illustrated as gray zones in Fig. 4. Grey samples falling within the current deadband can be dropped, indicating that the signal change is too small to be perceived by human beings. This way, the PD data reduction strategy can reduce the average packet rate by approximately 80%–90%.

This single degree-of-freedom (DoF) approach has been extended to 3-DoF [29], [30], and has been refined with velocity-dependent force thresholds [32]. Furthermore, an error-resilient PD data reduction scheme were proposed in [33] to reduce the impact of packet losses.

In the presence of communication delays, the aforementioned haptic data reduction schemes have to be combined with stability-ensuring control schemes, e.g. wave variable (WV) scheme, time-domain passivity approach (TDPA), and model mediated teleoperation (MMT). The haptic packet rate reduction scheme has been combined with the WV control scheme in [34] and [35]. The resulting approach operates on haptic signals in the time domain (i.e., directly on the force and velocity signals). This scheme, however, is suited only for constant communication delay. Xu et al. [36] combined the haptic packet rate reduction approach with the TDPA control scheme to reduce the packet rate over the communication network while preserving system stability in the presence of time-varying and unknown delays. This scheme is named TDPA+PD in the following. Compared to the existing WV-based haptic data reduction approaches, this scheme robustly deals with time-varying delays. Similarly, Xu et al. [37] incorporated a perception-based model update scheme into a point cloud-based MMT control architecture. This scheme is called MMT+PD in the following. The stability of the MMT architecture requires a stable and precise parameter estimation method to model the environment on the slave side. To address this issue, online environment modeling approaches were proposed for static objects [37], deformable objects [38], and movable objects [39]. Simple object models such as a rigid plane/sphere, a deformable thin membrane, or a freely movable cube are employed to approximate the remote environments. In [40], a passivity-based model update scheme was proposed to guarantee system stability during model update. In summary, the goal of our previous works in the area of MMT is to achieve stability while improving the transparency for networked interaction with simple or complex environments. MMT, however, can become computationally expensive and also requires a large amount of data to be transmitted between the slave and the master. Furthermore, its applicability is reduced as the environment dynamics increase.



▲ **Figure 4. Perceptual deadband principle. The perception thresholds (boundaries of gray zones) are a function of the stimulus intensity *I*. Samples that fall within the deadbands can be dropped (adapted from [25]).**

3.1.2 Tactile Codecs

Towards the compression of vibrotactile signals, offline algorithms were proposed in [41] and [42] with known prior knowledge of the surface texture (e.g., pre-scanning procedure). The first online compression of vibrotactile signals can be found in [43] for bilateral teleoperation. The compression algorithm is inspired by the similarities observed between texture signals and speech signals. Thus, a well-developed speech coding technique, the Algebraic Code-Excited Linear Prediction coding (ACE-LPC) [44], is adapted for developing a perceptually transparent texture codec. The authors of [43] reported a compression rate of 8:1 with a very low bitrate (4 kbits/s) on data transmission. An extended version of this compression algorithm was proposed in [45], in which the masking phenomenon in the perception of wide-band vibrotactile signals was applied to further improve the efficiency of the texture codec.

Table 2 summarizes the human perception models and corresponding data reduction solutions for both kinesthetic and tactile signals, denoting as kinesthetic codecs and tactile codecs, respectively.

3.2 Multi-User Transparency

For the exemplar haptic teleoperation application shown in Fig. 3, the ideal system transparency is defined in this context as a perfect match between the master and slave positions and force signals, or alternatively a match between the environment

▼**Table 2. Overview of the human perception models and corresponding data reduction solutions (reproduced from [3])**

<table>
<tr><th>Haptic type</th><th>Human perception model</th><th colspan="5">Data reduction solutions</th></tr>
<tr><td rowspan="5">Kinesthetic</td><td rowspan="5">Weber’s law (linear) [16];
Fechner’s law (logarithmic) [17]</td><td>Without considering network conditions</td><td colspan="4">considering network conditions</td></tr>
<tr><td rowspan="4">Perceptual deadband schemes:
Single DoF [2];
3-DoF [29], [30]</td><td>Solutions</td><td>Known const. delay</td><td>Unknown const. delay</td><td>Time-varying delay</td></tr>
<tr><td>WV+ PD</td><td>[34]</td><td>[35]</td><td>-</td></tr>
<tr><td>TDPA+ PD</td><td>[36]</td><td>[36]</td><td>[36]</td></tr>
<tr><td>MMT+ PD</td><td>[37]</td><td>[37]</td><td>-</td></tr>
<tr><td rowspan="2">Tactile</td><td>Data-driven ML models</td><td>[41], [42]</td><td colspan="4">-</td></tr>
<tr><td>Similar to speech signal</td><td>[43], [45]</td><td colspan="4">-</td></tr>
</table>

DoF: degree of freedom
ML: maximum likelihood
MMT: model mediated teleoperation
PD: perceptual deadband
TDPA: time-domain passivity approach
WV: wave variable

impedance and the impedance displayed to human operators [46]. When multiple users are remotely operating at the same environment (e.g. the patient’s organ in Fig. 3), the maintenance of multi-user/multi-session transparency becomes a crucial but evitable problem. The state-of-the-art solutions basically focus on two aspects: plug-and-play (PnP) mechanisms to increase the interchangeability of multiple haptic interfaces, and the multi-user/multi-session synchronization strategy.

3.2.1 PnP Mechanisms

For the multi-user scenario of a given haptic application, it is essential to enable flexible and dynamic connections among multiple haptic interfaces and devices in order to support a rapid session setup and to ensure the interoperability of the employed components, e.g., detailed knowledge exchange of system parameters, functional capabilities, and the requirements of the deployed hardware (e.g. the description of DoF, workspace, and maximum forces/torques).

In [47], an Extensible Markup Language (XML)-based description language was proposed for virtual environment (VE)-based teleoperation systems. Based on this language, a web interface was developed in [48] to facilitate the PnP of haptic devices for a server-client-based teleoperation infrastructure. Another trend of the PnP mechanism [49] is to leverage the existing internet session and presence protocols, e.g. session initiation protocol (SIP).

3.2.2 Multi-User/Multi-Session Synchronization Strategy

In order to maintain the performance of the multi-user scenario in haptic communications, Schuwerk et al. [50]–[52] proposed to integrate the data compression, communication and control aiming at providing stable and perceptually transparent visual-haptic collaboration between two or more users. A VE-based teleoperation system [50] was developed based on the client-server architecture where the server manages the state consistency of the distributed VE, while the haptic feedback is computed locally at each client. The PD data reduction principle was adopted to reduce the update rate of network traffic from the server to the client. However, this work neglected the communication delay which may lead to unavoidable inconsistencies in the VE states. A delay compensation strategy was proposed in [52] to solve this problem. Then, the work of [51] was further extended in [52] for deformable objects.

3.3 Perceivable Synchrony of Multi-Sensory Data

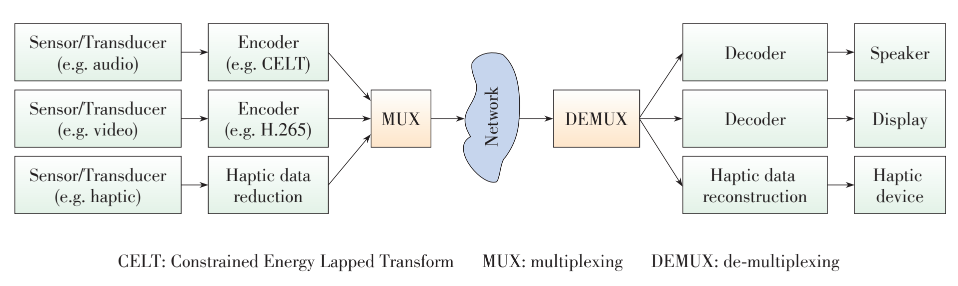
From Fig. 3, we can observe that a third modality, the haptic signal, is transmitted from the remote environment to the human operator in haptic communication, in addition to the audio and visual modalities in conventional multimedia communications. It is well known that video data are bandwidth hungry, while the haptic signal has relatively higher delay requirement than the video and audio signals. Therefore, a perceivable synchrony of multi-sensory data streams should be achieved in order to provide a satisfactory QoE performance.

3.3.1 QoE Factor of Perceivable Delay for Multi-Sensory Data Synchronization

The first investigation on the effects of latency in human-machine interactions was conducted by Robert Miller in 1968 [53] through experiments of simple interaction events as keyboard typing and audio conversations. It was reported in [53] that a time delay of 100 ms is perceived as instantaneous. Yuan et al. [54] studied the perceived delays for multi-sensory data delivery in mulsemedia services via extensive subjective tests. It was reported that haptic media could be presented up to 1 s behind video contents, air-flow media could be released either 5 s before or 3 s behind the video contents, while achieving an unperceivable asynchrony.

3.3.2 Application-Level Multiplexing Scheme

The state-of-the-art application-level multiplexing schemes for multi-sensory data delivery were presented in [55]–[58] with a typical structure shown in **Fig. 5**. This kind of scheme is able to multiplex different media modalities, with minimum computation cost and response time. They can interact with different network layers (such as the application layer for handling haptic data representation and the network layer for handling QoS requirements), and can also interact with the haptic-audio-video application to optimize network resources utilization to fit specific application needs. A synchronization approach is implemented in the multiplexing scheme for timely de-multiplexing of the communicated data in order to recover



▲**Figure 5. An application-level multiplexing scheme for synchronized multi-sensory data delivery.**

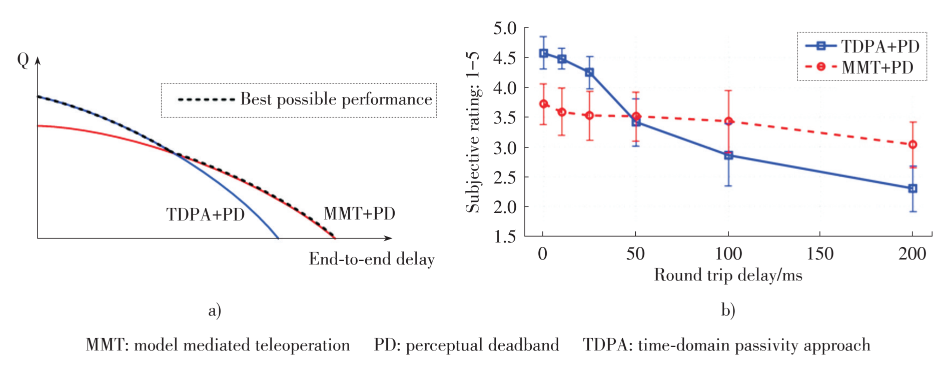
individual media streams.

4 Network-Level QoE Management

In the literature review process of QoE-oriented designs in haptic communications, we discovered that most research work in this area was conducted at the application layer, leaving the network-level less visited. Pioneer work in this research area lies in the QoE-oriented resource allocation (RA) based on QoS-related QoE models. In this section, we will focus on the development of QoS-related QoE metric which provides a vital guidance to RA mechanisms.

The RA approach developed in [59] takes full advantage of the QoE-delay model developed in [60]. It is known that different control and communication approaches lead to different types of artifacts in haptic communications. Based on the characteristics of control schemes, XU et al. [60] proposed a hypothesis between the QoE and the end-to-end delay for different control schemes as shown in **Fig. 6a**, then obtained a QoE-delay model based on the subjective test results of a VE-based spring-damper teleoperation system, as shown in **Fig. 6b**. This model was later utilized in [59] to guide the network resource allocation of multi-session haptic communications aiming at achieving the maximal QoE performance.

Leveraging the bidirectional information exchange characteristic of haptic signals, Aijaz [61] developed a symmetric downlink and uplink RA strategy for haptic communications. Condoluci et al. [62] first assumed that the QoE performance is inversely proportional to the communication delay. Under this assumption, they [62] performed a data-driven study on the delay characteristic of haptic information, and then developed a soft resource reservation strategy aiming at minimize the communication delay of haptic data.



▲**Figure 6. a) Hypothesis between quality of experience and delay for different control schemes; b) subjective tests results of a virtual environment-based spring-damper teleoperation system (adopted from [60]).**

5 Conclusions and Future Work

In this paper, we performed an extensive review on the research activities of QoE-oriented designs in haptic communications, starting from the user-level QoE (psychophysical) impact factors and models, the application-level QoE management (including perceptual haptic data reduction, transparency maintenance in multi-user scenario, and the perceptual synchrony of multi-sensory data), to the network-level QoS-related QoE management.

Compared with the QoE-related technologies in conventional audio-visual communications, QoE in haptic communications is a relatively young research direction, with new open challenges and exciting new research opportunities. Potential future research directions may related but not limited to the following aspects:

(1) Exploring the relationship among QoE, quality-of-task (QoT), quality-of-control (QoC), and QoS: The user experience of haptic communications is influenced by the network conditions (e.g. delay, jitter, and packet loss), the adopted control scheme, and the complexity of assigned tasks (e.g. free space versus contact and soft objects versus rigid surface). A thorough consideration of all impact factors will absolutely enhance the accuracy of QoE performance models, and provide a better guidance to various applications, e.g. the preferred control scheme of a given task under a given QoS setup.

(2) Low-latency video coding: It is well known that video streams are bandwidth hungry. The user perceivable delay constraints violation problem will become even more severe when high resolution video cameras are adopted in haptic communications. Therefore, low-latency video coding should be included in the application-level multiplexing scheme in order to assure the perceptual synchrony of multi-sensory data. The state-of-the-art video coding standard, H.265/HEVC, provides special support for low-delay video applications. The development of parallel processing tools, the new “dependent slice segments” concept and the new “hypothetical reference decoder process-

ing” concept, makes the low-delay video encoding and decoding a reality. In addition, intra-block refreshing [63], insignificant frames dropping [64], and key frame selection mechanisms will also help realize low-delay video coding technology.

We expect that this paper can promote the research activities in the abovementioned developed research directions for QoE in haptic communications, and also trigger the development of complex multi-sensory media systems, including senses of audio, visual, haptic, olfaction, and gustation, as well as the associated QoE studies.

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