Delays and User Performance in Human-Computer-Network Interaction Tasks

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Objective: This article describes a series of studies conducted to examine factors affecting user perceptions, responses, and tolerance for network-based computer delays affecting distributed human-computer-network interaction (HCNI) tasks. **Background:** HCNI tasks, even with increasing computing and network bandwidth capabilities, are still affected by human perceptions of delay and appropriate waiting times for information flow latencies. **Method:** Conducted were 6 laboratory studies with university participants in China (Preliminary Experiments 1 through 3) and the United States (Experiments 4 through 6) to examine users' perceptions of elapsed time, effect of perceived network task performance partners on delay tolerance, and expectations of appropriate delays based on task, situation, and network conditions. **Results:** Results across the six experiments indicate that users' delay tolerance and estimated delay were affected by multiple task and expectation factors, including task complexity and importance, situation urgency and time availability, file size, and network bandwidth capacity. Results also suggest a range of user strategies for incorporating delay tolerance in task planning and performance. **Conclusion:** HCNI user experience is influenced by combinations of task requirements, constraints, and understandings of system performance; tolerance is a nonlinear function of time constraint ratios or decay. **Application:** Appropriate user interface tools providing delay feedback information can help modify user expectations and delay tolerance. These tools are especially valuable when delay conditions exceed a few seconds or when task constraints and system demands are high. Interface designs for HCNI tasks should consider assistant-style presentations of delay feedback, information freshness, and network characteristics. Assistants should also gather awareness of user time constraints.

INTRODUCTION

Human-computer interaction (HCI) tasks have evolved from distributed users working on terminals attached to mainframes, through a period of personal computing autonomy, and now back to a period remotely available information systems and computing functionality. In computer network environments (from LAN to Internet), users have a wider range of choice for processing tasks among their own local systems as well as among remote computers or other humans via network connections. What was once considered "time-sharing systems" can now be described as a broader realm, which are described in this article as human-computer-network interaction (HCNI), that suggests (but is not simply a return to) prior time-sharing computing tasks.

Communications delay, and its impact on user interactions, is certainly not a new phenomenon in computer systems. Since the 1960s, computer science researchers have been concerned with issues of appropriate synchronization and coordination of performance in time-sharing systems (Bauer, 1966; Smith, 1966). Studies of the physiological and psychological impact of interaction delays on HCIs have been ongoing for decades, highlighting an aspect of human

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performance with delayed sensory feedback (see, for example, Emurian, 1991; Moray, 1981; Smith, Ansell, & Smith, 1963). HCNI applications, in contrast to previous terminal-based systems, reflect a wider range of active demands on system resources, with human-scale multimodal and multimedia performance demands that are much more sensitive to delay (Ferrari, Ramaekers, & Ventre, 1992; Holzman, 1999; Nahrstedt & Smith, 1995; Oviatt et al., 2000).

Despite the optimistic hopes of some technologists, HCNI system delays have not been eliminated with increased processor speed and bandwidth capacity. Tremendous increases in computer processing speed and network bandwidth capacities have been coupled with increased file sizes and numbers of users of shared network bandwidth. User expectations as well as system use create new demands that make quality-of-service considerations still relevant (Ferrari et al., 1992; Nahrsted & Smith, 1995). From both software and human perspectives, excessive delays in HCNI applications can degrade system performance for humans and computers (Angrilli, Cherubini, Pavese, & Manfredini, 1997; Billard & Pasquale, 1992, 1993; Sears & Jacko, 2000; Temple & Geisinger, 1990). Interaction delay has been identified as a leading problem for long-term management of Internet-based applications (Khosrowpour & Herman, 2000) and the development of e-business (Rose, Khoo, & Straub, 1999).

After decades of research and multiple generations of computer networks, the problem of delay in HCNI applications remains a considerable issue in maintaining high-quality HCIs. Improved computer network usability and performance necessitates a better understanding of delay effects and its mediators. However, determination of acceptable network delay from a quality-of-service perspective does not fully address the cognitive and physical ergonomics aspects of delay in HCNI task environments. Describing and improving quality of HCNI system performance requires addressing three distinct criteria (Ferrari et al., 1992; Nahrsted & Smith, 1995):

- calculation of absolute transmission delays based on infrastructure limitations,
- determination of user perception and acceptance of these absolute delays, and
- negotiation to manage and mitigate negative responses to delay.

Of these, only the first can be described by the computer scientist as a purely objective performance criterion. However, even human factors and ergonomics studies of user interactions frequently focus purely on absolute delay rather than on user experience of that delay.

The authors' initial motivations for the research presented here was to address three additional questions regarding delay tolerance and performance in HCNI task environments:

- Which factors other than infrastructure-based absolute delay affect user perception of and tolerance for HCNI delays?
- What is the interplay between absolute delay and these other factors in mediating delay tolerance in an HCNI task context?
- What user interaction techniques can be used to address the elements of delay tolerance?

This article describes a series of experimental studies designed to focus on answers to these questions describing user perceptions and performance during HCNI delays. These studies were conducted in two "sets," incorporating preliminary experiments regarding perceptions of task interaction. These studies span two continents and nearly a decade, attempting to address both long-standing questions of human perception of delay and more recent questions of delay tolerance in exchanging large data files. The definition of "appropriate" delay in HCNI applications requires an understanding of the factors affecting users' delay tolerance and the general and situational expectations that users have for tolerance. As described in the next section, users' perception of, and response to, network-based interaction delays are influenced by user experience, contextual factors (e.g., task load, deadlines), and user perceptions of network throughput factors (e.g., bandwidth, availability).

INVESTIGATING DELAY TOLERANCE IN HCNI TASKS

As illustrated in Figure 1, a number of factors influence user perception of delay and tolerance for delay. These factors may appear separately or in combination in a study of HCNI behaviors

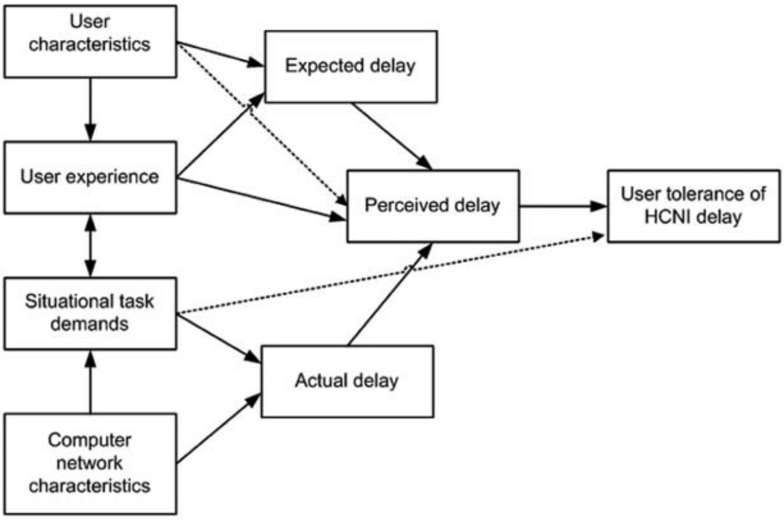

Figure 1. Preliminary descriptive model of network, task, and user factors affecting delay tolerance for human-computer-network interaction (HCNI) tasks.

and can be seen as providing answers to the delay tolerance questions described earlier:

- Which factors other than infrastructure-based absolute delay affect user perception of and tolerance for HCNI delays?

The experiments reported in this article examined three different classes of HCNI factors: task-related *user experience with HCNI tasks* (evaluation and estimation of task performance and computer network behavior), *computer network characteristics* (bandwidth, file transmission characteristics and protocols), and *situational task demands* (task urgency, location and size of files to be exchanged).

The illustration presented in Figure 1 suggests a testable model of potential interactions among these factors, addressing the second delay tolerance question:

- What is the interplay between absolute delay and these other factors in mediating delay tolerance in an HCNI task context?

Components of *actual delay* (which can be directly observed and calculated) contribute to actual delay experience and tolerance but also interact with both the user's *expected delay* (as estimated prior to task start on the basis of prior experience with similar tasks and network performance) and *perceived delay* (the user's internal estimation of elapsed time).

A comprehensive model of delay tolerance, the authors suggest, should incorporate combinations of user, task characteristics, and computer network infrastructure. This organization is reminiscent of Bailey's (1996) description of HCI and usability as incorporating elements of the human, activity, and context. However, *context* in our studies reflects both temporary situational contexts (task deadlines) and temporary network infrastructure (currently available bandwidth) affecting the priority for and barriers to completion of HCNI tasks. Caldwell and Paradkar (1995) reported that user, task, and context factors (e.g., user expectations, amount of information, degree of emergency, sender-receiver distance, and frequency of network use), and not simply network capacity factors, could significantly influence users' tolerance of HCNI delays.

The authors have collaborated across a period of several years to conduct a series of studies to address issues of the multistage model presented in Figure 1. A preliminary series of three experiments was conducted in China between 1997 and 1999. These experiments were intended to focus on task factors and example cognitive mechanisms affecting delay perception in HCNI tasks. A second set of three experiments,

TABLE 1: Summary of Experimental Designs, Preliminary Experiments 1 Through 3

Experiment	Independent Variables Across Experiments: Interaction Partner	Independent Variables Across Experiments: Delay Control	Independent Variables Within Experiment	Dependent Variables
1	Human	Self-control	Between: gender Within: task type and difficulty level	Expected delay
2	Human	Passive experience	Between: gender Within: task type, difficulty level, interaction delay	Perceived delay, delay tolerance
3	Computer	Passive experience	Between: gender, Type A personality Within: task type, difficulty level, interaction delay	Perceived delay, delay tolerance

conducted in the United States in 2003 and 2004, built on these preliminary studies to address additional issues of situational contexts and user expectation and experience in delay tolerance. Together, these studies were designed to explore the following general research hypotheses:

- A user's tolerance for a task-related HCNI delay is determined by the comparison of expected, actual, and perceived delay.
- A user's expectation of delays is affected by both delay conditions attributable to computer network capabilities (outside of the user's control) and the user's experience of those delays in similar prior task performance contexts.
- A user's perceived delay in an HCNI task is affected by a combination of delay condition and attention allocated to time during task performance.
- A user's ability to accurately perceive delay is limited to a small range of actual delay periods and is affected by the mechanism of delay perception used.

Detailed results of the preliminary studies have been presented elsewhere (Wang, 2002; Wang, Caldwell, & Zhang, 2002); the next section provides a brief summary of important outcomes of those studies and their influence on the design of the U.S. studies.

SUMMARY OF PRELIMINARY STUDIES

The three preliminary experiments focused on user perceptions of delay in HCNI tasks, including mechanisms of delay perception and possible task factors influencing delay tolerance. A summary presentation of the general design of the three experiments is shown in Table 1.

Experimental Designs

Two independent variables were fixed within experiments but varied across experiments. In Preliminary Experiment 1, users had active control of the HCNI task delay before sending information; in Preliminary Experiments 2 and 3, the computer controlled the delay, causing the participants to passively experience delay. In Preliminary Experiments 1 and 2, study participants were instructed that the HCNI interaction partner was human; in Preliminary Experiment 3, participants were instructed that the HCNI partner was a computer. (In both Experiments 2 and 3, the partner was a computer. Thus, Preliminary Experiments 2 and 3 together represent a test of the independent variable of perceived partner type.)

In each of the preliminary experiments, gender, task type (search vs. calculation), and task difficulty (easy vs. hard) were independent variables. In Preliminary Experiment 1, the main independent variable was expected delay. In Preliminary Experiments 2 and 3, perceived delay and delay tolerance were the main dependent variables. Three independent groups of 30 students (15 male, 15 female) were recruited for each preliminary experiment.

TABLE 2: Summary of Major Findings, Preliminary Experiments 1 Through 3

Experiment	Effect	Dependent Variables	Major Finding	Implication
1	Active estimation/ expectation of delay	Expected delay	Reasonable range of expected delays for tasks range from 0–30 s	Generation of delay ranges for passive delay experience experiments
1	Active estimation/ expectation of delay	Delay estimation and tolerance	Accurate estimation of delays ~2–5 s, accuracy shifts with task difficulty	Delay estimation affected by task factors; delay tolerance functions not strictly linear
2 and 3	Delay estimation and tolerance	Task difficulty, task type	Expected delay higher for difficult task in search, but not calculation, when partner is computer	Lower tolerance for delay in "computer tasks"; acceptance of delay for computer doing "human tasks"
1, 2, and 3	Active vs. passive estimation/ expectation of delay	Delay estimation strategy	Task simulation strategy: 83% of participants in Experiment 1, 0 in Experiments 2 and 3; mental counting 13.4% in Experiment 1, >90% in Experiments 2 and 3	Passive delay affects delay estimation strategy: changes from task simulation to counting
1, 2, and 3	Active vs. passive estimation/ expectation of delay	Delay estimation, task difficulty, task type	Tolerance for delay modified by active vs. passive delay, perceived partner, and task difficulty in HCNI task	User experience/ perception, task situation variables, and network factors jointly affect delay estimation and tolerance

Note. HCNI = human-computer-network interaction.

Results

Results from Preliminary Experiment 1 confirmed that participants had a limited range of accurate perceptions of actual delay and reported three distinct strategies (mental simulation of the HCNI partner's task performance, "one thousand one"–style counting, and qualitative intuition) to estimate appropriate delays. However, when experiencing passive delays in Preliminary Experiments 2 and 3, no participant reported using mental simulation as a time estimation or delay tolerance evaluation strategy. Reported use of the counting strategy, however, increased from 13.4% in Preliminary Experiment 1 to 90% in Preliminary Experiment 2 and to 96.7% in Preliminary Experiment 3.

Expected delays were reported as higher for difficult search tasks than for easy search tasks during passively experienced delays (as compared with actively controlled delays). However, there was no difference in the reports of expected delays in the interaction of task difficulty and active versus passive delay for the less visually complex calculation task.

The results of expected delay estimations in Experiment 1 were used to define the range of computer-generated delays for Preliminary Experiments 2 and 3. Randomly generated delays ranged from 0 to 34 s were used in Preliminary Experiments 2 and 3 on the basis of mean delays of 4 to 27 s, depending on task type and complexity in Preliminary Experiment 1.

When participants believed that the HCNI partner was a computer, they tolerated less delay for calculation tasks, regardless of calculation difficulty, than when they believed the partner to be human. However, they reported the same tolerance for delay for search tasks whether the believed partner type was computer or human. Thus, the participants were willing to moderate their perceived delay and delay tolerance on the basis of their expectations of the type of task and interaction partner—especially if the task is seen as one that a computer is designed to do well.

Previous research (Richter & Salvendy, 1995) had indicated that participants do perceive computer software as having personalities similar to those of humans in computerized tasks. The results of Preliminary Experiments 1 through 3 (see Table 2) indicate that expected delay and tolerance for actual delay can be adjusted by user awareness and experience of situational information, such as collaboration partner, task type, and task difficulty level. As a result of these findings, further study of task impact factors became an area of emphasis for the U.S.-based experiments.

Despite the significant effects of task factors on user delay perception and delay tolerance, the authors chose to focus on network factors rather than human cognitive task factors to extend the HCNI research study for the U.S. experiments. The choice of network bandwidth and file size factors enabled the authors to perform additional study of the interactions of network and task factors, as shown in Figure 1, on actual and perceived delay and user delay tolerance.

U.S.-BASED HCNI EXPERIMENTS

The results of the preliminary experiments suggested the need for further examination of the interactions of task, network capability, and user experience of network capability and their effects on delay tolerance. Specifically, the delay estimation strategy results from Preliminary Experiments 2 and 3 suggested that user experience of and tolerance for delay are directly attributable to delay estimation strategies and ratios of experienced to expected delay. Thus, these factors became a central emphasis of the U.S.-based HCNI experiments. However, rapid increases in file exchange capabilities through high-speed networks available in China in 1998 through the United States in 2004 indicated that additional HCNI study should be focused on user experiences of file sharing and cloud computing tasks rather than just on distributed task coordination among human partners.

Three U.S.-based HCNI experiments designed to address hypothesized effects of task, network, and user factors on delay tolerance were conducted at a major U.S. university. In Experiment 4, a delay evaluation model based on Figure 1 was tested using a scenario-based survey of file downloading activities. Experiments 5 and 6, conducted as two subexperiments with the same participants, examined user delay expectations and tolerance evaluations of tasks conducted with simulated interactive Web sites. In all three experiments, the major HCNI task focus was that of file exchange and downloading activity.

File downloading is clearly a major focus of task performance in distributed network environments. However, it is important to recognize that the main goal of the user is not simply the sequence of clicks required to select and download the file but the actual receipt of the file required to complete required work- or entertainment-related tasks. In addition, the action to select and download a file is the same whether the file is a single Web page or small document of a few kilobytes or a major database, image, or other multimedia file of many megabytes (MB). Thus, the tasks involved in Experiments 4 through 6 highlighted the importance of file content to user task completion. Experiments 5 and 6 focused more specifically on Web browsing tasks that include file downloading in addition to the network bandwidth and situation factors studied in Experiment 4.

Prior research suggests that if the delay in seeing a requested Web page is more than 10 s, then a user's flow of thought will be interrupted (Nielsen, 1994). Although Preliminary Experiments 1 through 3 suggested a range of effects of delay on user expectations and behavior, Experiments 4 through 6 further emphasized the type of Web-based interactive tasks explored in Nielsen's (1994) work. File importance and time availability (as task situation factors) were systemically investigated for their

TABLE 3: Experimental Design of Independent and Dependent Variables, Experiment 4

Independent Variable	Levels
Bandwidth (between subjects)	56 Kbps, 1 Mbps, 10 Mbps
File size (between subjects)	10 KB, 1 MB, 100 MB, 1GB
Delay condition (within subjects)	50%, 100%, 200% of expected delay
File importance (within subjects)	Low, medium, high
Time availability (within subjects)	50%, 100%, 200% of expected delay
Dependent Variable	**Range**
Comparison of delay condition with expectation	7-point Likert-type scale from 1 (*too short*) to 7 (*too long*); 4 (*equal*) is midpoint
Delay tolerance for delay condition ("downloading time is tolerable")	7-point Likert-type scale from 1 (*strongly disagree*) to 7 (*strongly agree*); 4 (*neutral*) is midpoint

Note. Kbps = kilobits per second; Mbps = megabits per second; KB = kilobytes; MB = megabytes; GB = gigabytes.

effects on delay tolerance in Experiment 4. The objectives of Experiments 5 and 6 were to verify user delay perception patterns in Web browsing tasks, to address delay effects on performance and tolerance (as elaborated in Experiment 4), and to study how delay feedback mediates delay effects. Additional details for each experiment are presented in the following sections.

EXPERIMENT 4: NETWORK CHARACTERISTICS AND DELAY TOLERANCE

Design and Methods

Participants in Experiment 4 were asked to consider the effects of multiple task situation factors and their potential effects on the user's expectations of delay in file downloading tasks. Five factors were investigated in a mixed factorial design. At the beginning of the experiment, participants were asked to estimate their expectation of the delay required to download a file of a specified size across a network of specified bandwidth capability. This initial expected delay estimate was used as the basis for manipulating levels of independent variables in the experimental conditions.

Available network bandwidth and file size were between-subjects factors (kept fixed for each participant), and delay condition, file importance, and time availability were within-subjects factors (made to vary on the basis of situational conditions generated, presented by the experimental software). The initial delay expectation given by the participant was used to explicitly calculate the three levels of delay condition and time availability to be numerical values of 50%, 100%, and 200% of the initial delay expectation. File importance was presented as having three levels: low, medium, and high.

The use of the factors delay condition, file importance, and time availability was based on the use of situational factors situational distance, content importance, and task urgency in previous studies of user tolerance for media delay (Caldwell & Paradkar, 1995; Caldwell, Uang, and Taha, 1995). The use of midpoint-anchored Likert-type scales to evaluate user delay tolerance was pretested for this application in Preliminary Experiments 2 and 3. A summary of the independent and dependent variables in Experiment 4 is presented in Table 3.

As in prior delay tolerance studies (Caldwell et al., 1995; Caldwell & Paradkar, 1995), participants were asked to estimate their delay tolerance for each delay, file, and time availability condition, resulting in a within-subjects presentation of 3^3 (27) conditions. These conditions were anchored on the participants' own estimate of expected delay for the single file size and network bandwidth combination they

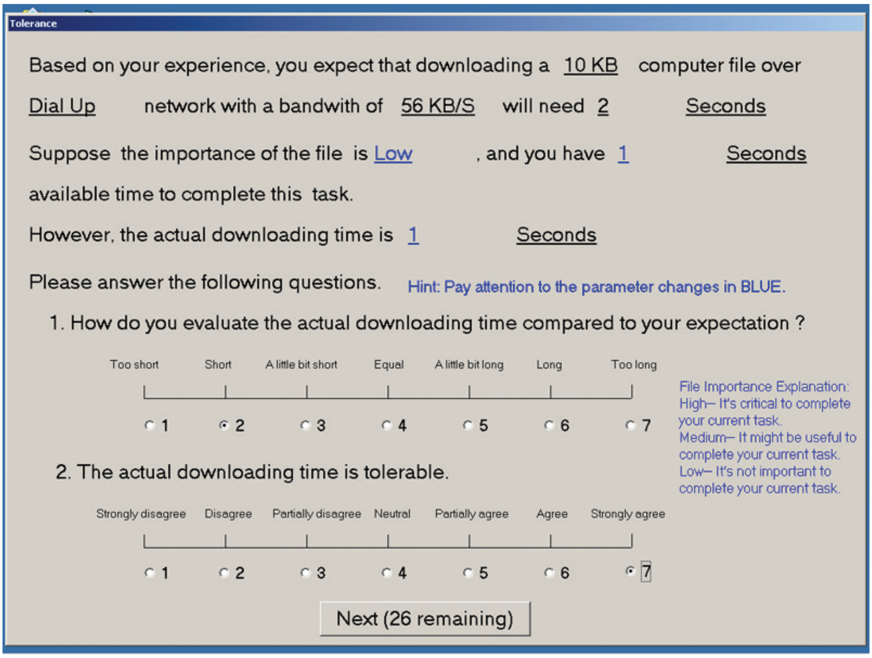

Figure 2. Example of computer-generated displays for delay tolerance evaluations, Experiment 4.

were presented. Participant data were collected by means of a computer-generated survey that managed the order of presentation, calculated explicit values of delay condition and time availability for display within each scenario presentation, and collected Likert-style evaluation data as well as initial demographic data. An example of the data collection screen is presented in Figure 2.

The focus of Experiment 4 data collection was on perceived delay acceptance and tolerance based on the anchoring on expected values rather than on directly experienced delays. Actual downloading experiences, with a within-subjects design of this type, would have become impractical and was considered unnecessary, given the direct referencing of the participant's own expectations in each presentation. Research hypotheses addressed in Experiment 4 included the following:

- Users identify distinct expected task- and situation-specific delays and develop delay tolerance on the basis of those expectations.
- User tolerance for situation-specific delay is a function of network, task, and situational factors.
- User tolerance for situation-specific delay is based on a ratio of delay condition to expected delay and not simply on delay condition.

In Experiment 4, 60 university students (23 female and 37 male) from a midwestern U.S. university voluntarily participated. Of the 60 participants, 93.3% had 2 or more years of experience with high-bandwidth networks, including DSL, cable, and T1 networks; 88.3% used one of these network types as their primary Internet connection. (This level of access to high-bandwidth connections was not available to Chinese participants in Preliminary Experiments 1 through 3.)

Results and Discussion

Delay expectation and networks. As expected, participants developed file download delay expectations based on information provided regarding network bandwidth and file size. ANOVA results revealed main effects for file size and network bandwidth on delay expectation. Specifically, delay expectation increased as file size increased, $F(3, 48) = 41.376, p < .01$, and delay expectation decreased as network speed increased, $F(2, 48) = 21.992$, $p < .01$. Regression analysis indicated that delay expectation can be predicted by the following regression equation:

$$\text{Log delay}_{exp} = 2.01 + 0.002^*(\text{file size, in MB}) - 0.985^*(\text{bandwidth, in Mbps})$$

MANOVA results showed that time available for task completion, $F(2, 96) = 30.277$, $p < .01$, $\eta_p^2 = .387$; delay condition, $F(2, 96) = 260.247$, $p < .01$, $\eta_p^2 = .844$; and file importance, $F(2, 96) = 10.010$, $p < .01$, $\eta_p^2 = .173$, have main effects on situation-specific delay perception. The delay condition is presented directly to participants as a between-subjects variable (all 27 within-subjects scenarios use the same combination of network type and file size). Thus, the only plausible explanation of situation-specific differences is that the change in expected delays causes changes in the ratio of delay condition to expected delay. Additional interaction effects revealed by the MANOVA help describe participants' experience of task- and situation-specifi delays.

The interaction of delay condition and bandwidth was significant, $F(4, 96) = 4.624$, $p < .01$, $\eta_p^2 = .162$. Although the perception of the ratio of delay condition to expected delay shows an overall increase as the actual downloading time increases, the perception was dependent on network bandwidth. Perception of the ratio of delay condition to expected delay is sensitive to network bandwidth change but only when the ratio is not near 1. Participants' tolerance of low-speed (dial-up) network delays was most sensitive to tolerance ratio changes (away from 4 on the 7-point scale).

The interaction of file download delay condition and time available for task completion was also significant, $F(4, 192) = 3.756$, $p < .01$, $\eta_p^2 = .073$. When the expected delay is close to the delay condition (ratio of delay condition to expected delay = 1), tolerance for delay is linearly related to the ratio of time required to time available for task completion. When delay conditions were longer than expected (ratio = 2), users were more sensitive to the ratio of time required to time available, and overall tolerances were lower. When delay conditions were shorter than expected (ratio = 0.5), tolerances for delay were higher, and users were less sensitive to the ratio of time required to time available.

Delay tolerance and networks. The delay conditions presented to participants in Experiment 4 were calculated on the basis of participants' delay expectation. All study main effects (file size, network bandwidth, time availability, file importance, and ratio of delay condition to expected delay) on tolerance for delay were statistically significant. Participants were willing to wait more expectation cycles while downloading small files (10 kilobytes) compared with large files (bigger than 1 MB), $F(3, 48) = 7.996$, $p < .01$, $\eta_p^2 = .333$. However, for large files bigger than 1 MB, there was no significant difference in relative delay tolerance.

Delay tolerance was shown to increase significantly as a function of increasing network bandwidth, $F(3, 48 = 3.577$, $p < .05$, $\eta_p^2 = .130$; time availability, $F(2, 96 = 82.983$, $p < .01$, $\eta_p^2 = .634$; relative delay, $F(2, 96) = 295.180$, $p < .01$, $\eta_p^2 = .860$; and file importance, $F(2, 96) = 8.211$, $p < .01$, $\eta_p^2 = .146$. Although participants were willing to accept extra delay to get important files, the delay itself was rated as intolerable. Three two-way interaction effects were detected, all of which were significant at the $p < .01$ level: delay condition by network bandwidth, $F(4, 96) = 4.317$, $\eta_p^2 = .152$; available time by actual time, $F(4, 192) = 15.049$, $\eta_p^2 = .239$; and delay condition by file importance, $F(4, 192) = 6.069$, $\eta_p^2 = .112$.

Consider, for example, the interaction effect between delay condition and network bandwidth. The effect of network bandwidth is not significant when the ratio of delay condition to expected delay = 0.5; tolerance ratings are generally high and not sensitive to network bandwidth. However, the effect of network bandwidth becomes significant as the delay condition increases to ratios of 1.0 and 2.0 of delay expectation. For the same level of relative delay (constant ratio), the corresponding absolute delay (elapsed time) decreases as the network bandwidth increases, and less absolute delay leads to an increase in delay tolerance. As time available for task performance increases (lower perceived time pressure), delay tolerance does not decay

TABLE 4: Experimental Design of Independent and Dependent Variables, Experiments 5 and 6

Experiment	Independent Variable	Levels	Dependent Variables (Both Experiments)
5	Delay Condition	5 (1, 5, 10, 30, 120 s)	Estimated delay (seconds); ratio of delay condition to expected (rating); delay tolerance (rating); task satisfaction (rating); time to re-request page (measured seconds); time to give up (measured seconds)
	Feedback type	3 (no feedback, immediate feedback, feedback delayed 6 s)	
6	Delay condition	5 (1, 5, 10, 30, 120 s)	
	Delay feedback format	3 (elapsed delay, elapsed and projected total delay, elapsed delay and countdown remaining delay)	

as quickly with increasing ratio of delay condition to expected delay. This is because higher network bandwidth enables a lower overall time required to obtain files and increased perceived ability to receive necessary files of a given size in a given time.

Regression analysis showed that the ratio of delay condition to expected delay is a good predictor of delay tolerance. The regression model was significant, $F(1, 598) = 1595.424$, $p < .01$, $R^2 = .727$, and can be described as

$$\text{Delay tolerance} = 8.919 - 1.014*(\text{delay condition to expected delay})$$

Time availability and file importance had main effects on the ratio of delay condition to expected delay. Given that the delay condition is presented to participants directly, it is reasonable to conclude that time availability and file importance both influence delay expectation. In other words, in file downloading tasks, delay expectation is determined by task and context factors of file size and network bandwidth but is adjustable depending on situation-specific factors of time availability and file importance.

EXPERIMENTS 5 AND 6: FEEDBACK AND DELAY TOLERANCE

Design and Method

Two subexperiments (Experiments 5 and 6) were conducted to investigate the delay effects and the mediation effect of delay feedback in HCNI. Experiment 5 investigated the effect of the presence of delay feedback at different time points (immediate feedback vs. delayed feedback vs. without feedback). Experiment 6 investigated the effect of different types of delay feedback (current elapsed delay vs. elapsed delay and delay projection vs. elapsed delay and counting-down delay projection). Overall, the experimental tasks in Experiments 5 and 6 represented HCNI performance when actual task requirements are not specified in advance (as they were with file exchange tasks in Experiment 4).

The experimental activity for Experiments 5 and 6 involved Web site browsing and included one practice task and three formal tasks. In each browsing task, the Web site would experience a forced delay of a specific period before providing the requested information; the delay was generated by the computer and was not a function of external network traffic. Participants had the option of requesting the Web page information again or canceling the request and starting another task. Research participants conducted tasks for both Experiments 5 and 6 within a single task period.

Delay condition and presence of delay feedback were the primary independent variables studied in Experiment 5. Five delay levels (1, 5, 10, 30, and 120 s) were used in the study. Delay feedback had three levels: without feedback, immediate feedback, and delayed feedback (after 6 s). In Experiment 6, delay and format of delay were the independent variables, with the same five delay levels as Experiment 5. The format of delay information had three levels: elapsed delay information, elapsed delay and projected total delay information, and elapsed delay and countdown delay projection information.

Experiments 5 and 6 had six dependent variables: estimated delay, ratio of delay condition to expected delay, delay tolerance, participant satisfaction with the task, time to request a Web page again, and time to give up on the task. Time to give up and time to request again were selected as performance measures examining participants' tolerance for delay in completing the experimental task. Given the focus on direct measurement of participant behaviors with respect to delay, delay conditions were directly experienced in terms of real-time delays in Experiments 5 and 6. See Table 4 for a summary of independent and dependent variables in Experiments 5 and 6.

In a real-world Web site browsing task, requesting the same Web page again will increase the workload of the Web server and increase the probability of additional delays. Excessive server load will lead to performance degradation or system breakdown, limiting user task performance. Giving up on the task also has a negative impact on users' task performance, because in addition to potentially not completing the task, any time spent waiting before canceling the request will have been wasted. Thus, these two variables were selected as proxy measures of aggregate system and individual task performance. Specific hypotheses tested in Experiments 5 and 6 include the following:

- User tolerance and performance with passively experienced Web site delays will decrease with increasing delay condition.
- User perception of Web site delay will be affected by the total actual delay and by the presence of delay projection feedback information.
- User tolerance for Web site delays will increase with the presence of delay projection feedback information as compared with delay tolerance in the absence of feedback.
- User tolerance for Web site delays will be affected by the format of delay projection feedback.

In Experiments 5 and 6, 30 university students (11 female and 19 male) voluntarily participated. All participants completed both experimental tasks of both studies within 1 hr.

Results and Discussion

Feedback-moderated delay perception. Delay condition was significantly correlated with perceived delay across both experiments. However, because delay projection feedback in Experiment 6 was always the actual delay, there is a potential inflation of this correlation in Experiment 6. MANOVA results found that perceived delay was not related to the type of delay feedback, $F(2, 58) = 1.936$, *ns*, across tasks in Experiments 5 and 6. The variance of perceived delay was reduced dramatically when counting-down delay projection was presented. Therefore, we can assume that the presence of countdown delay eliminated the need for delay perception in Experiment 6; those data will not be included in additional analysis.

Because the presence of feedback was not the primary factor influencing perceived delay, data were aggregated (except for countdown delay feedback) to study the relationship between delay condition and perceived delay in Web browsing tasks. As in prior studies of user tolerance for delay across multiple time scales, regression and other analyses of perceived delays use a logarithmic scale (Caldwell, 2000; Caldwell & Paradkar, 1995; Caldwell et al., 1995). Shorter delays (<10 s) were overestimated, delays of approximately 10 s were correctly estimated, and delays of 10 to 80 s were underestimated. However, delays longer than 100 s were overestimated again, and there was another delay range of approximately 80 to 100 s that could be estimated correctly. Perceived delay at the 120-s delay level was significantly longer than 120 s, $t(89) = 1.846$, $p < .05$). These latter findings are in contrast to Vierodt's law (Wang, 2002; Wang et al., 2002; Woodrow, 1951). This might be an important finding for delay perception laws, as will be addressed later in the General Discussion.

Feedback and task performance. Task performance impacts were measured by the time to click on the "Request Again" and "Give Up" buttons as well as the frequency of clicks to try to obtain updated Web page information.

Three feedback conditions in Experiment 5 were task without feedback, task with immediate feedback, and task with delayed feedback. Delay feedback was provided after 6 s in the task with delayed feedback, thus negating feedback at delay levels of 1 s and 5 s. Therefore, two sets of comparison were used to compare the feedback effect. The first comparison was without feedback versus immediate feedback at all five delay levels. Clicking "Request Again" was not affected by the existence of immediate delay feedback. However, clicking did differ depending on the delay levels, $\chi^2(4) = 165.508$, $p < .01$, with increases in clicks. The number of clicks on "Request Again" increased with increasing delay condition level. Table 5 shows the descriptive statistics of average time to click "Request Again" for the two feedback conditions (without vs. immediate). Participants were willing to wait significantly longer (approximately 5 s), $t(109) = -1.778$, $p < .05$, before clicking "Request Again" if immediate feedback was provided.

Comparing only the delay levels at which delayed (6 s) feedback was provided, three delay levels (10, 30, and 120 s) indicated that clicking "Request Again" was independent of delay feedback (without vs. immediate vs. delayed feedback), $\chi^2(2) = 2.939$, $p = .230$; delay was still the factor influencing the participant's behavior of clicking "Request Again," $\chi^2(2) = 102.183$, $p < .01$. When the delay condition was 10 s or more, participants were willing to wait 5 more seconds before clicking "Request Again" in the task with immediate feedback than in the task without feedback and to wait 6.4 more seconds before clicking "Request Again" in the task with delayed feedback than in the task without feedback. Both the time difference between immediate-feedback and without-feedback tasks, $t(106) = -1.726$, $p < .05$, and the time difference between delayed-feedback and without-feedback tasks, $t(103) = -2.167$, $p < .05$, were significant. However, the time difference between immediate-feedback and delayed-feedback tasks was not significant, $t(95) = 0.371$, *ns*.

Tests of the format of delay feedback (immediate feedback vs. immediate feedback + delay estimation vs. immediate feedback + counting-down delay estimation) and delay condition indicated that clicking behavior depended on the delay levels, $\chi^2(4) = 147.838$, $p < .01$, and the format of delay feedback, $\chi^2(2) = 8.741$, $p < .05$. The probability of clicking "Request Again" could be significantly reduced when counting-down delay estimation was provided. The number of clicks decreased when delay estimation and counting-down features were added; additionally, the mean time to click "Request Again" also decreased (see Table 6). Compared with the task without any delay projection, the feature of counting-down delay projection showed a significant effect on the time to request again, $t(72) = -1.778$, $p < .05$. This finding suggests that delay estimation had two interesting effects on the behavior of clicking "request again." First, participants were less likely to click "Request Again" when delay estimation was provided. Second, participants waited less time before clicking "Request Again" when delay estimation was provided.

TABLE 5: Effect of Feedback on Time to Click "Request Again," Experiment 5

	Time[a]		
Feedback Type	*M*	*SD*	*n*
Without feedback	15.15	10.52	60
Immediate feedback	20.20	18.83	51

[a]Reported in seconds.

TABLE 6: Effect of Immediate Feedback Type on Time to Click "Request Again," Experiment 5

	Time[a]		
Feedback Type	*M*	*SD*	*n*
Immediate feedback	21.43	16.19	48
Immediate feedback + delay projection	19.21	24.00	40
Immediate feedback + counting-down delay projection	14.57	19.81	26

[a]Reported in seconds.

TABLE 7: Effect of Delay Level on Decision-to-Quit Frequency and Time, Experiment 5

	Decision to Quit				
	Frequency		Time[a]		
Delay Level[a]	No.	%	*M*	*SD*	*N*
10	4	4.4	7.80	2.52	90
30	25	27.8	22.13	6.92	90
120	86	95.6	48.10	25.30	90

[a]Reported in seconds.

TABLE 8: Effect of Delay Level on Decision-to-Quit Frequency and Time, Experiment 6

	Decision to Quit				
	Frequency		Time[a]		
Delay Level[a]	No.	%	*M*	*SD*	*N*
1	0	0	0	0	90
5	2	2.2	3.55	0.90	90
10	4	4.4	5.09	3.16	90
30	14	15.6	15.97	8.54	90
120	64	71.1	46.48	32.88	90

[a]Reported in seconds.

With regard to the effect of delay feedback (no feedback vs. immediate feedback vs. delayed feedback) on time to quit, this can be compared directly because no participants clicked the "Give Up" button in the 1- and 5-s delay levels in Experiment 5; thus, delay levels included in the analysis were 10, 30, and 120 s. As delay levels increased, the frequency of clicking "Give Up" increased significantly in both Experiment 5, $\chi^2(2) = 164.893$, $p < .01$ (see Table 7), and Experiment 6, $\chi^2(4) = 210.024$, $p < .01$ (see Table 8). The feature of counting-down delay projection significantly reduced the waiting time before clicking "Give Up" compared with the task without delay projection, $t(56) = 2.87$, $p < .01$.

Feedback and task preference. The ratings of task preference were collected after participants completed all activities in Experiments 5 and 6. One-factor MANOVA results showed that in Experiment 5, the presence of delay feedback had a main effect on task preference according to a 7-point Likert-type scale, $F(2, 58) = 31.764$, $p < .01$, $\eta_p^2 = .523$, with participants preferring the task with delay feedback the most ($M = 5.73$, $SD = 1.44$) and the task without delay feedback the least ($M = 2.27$, $SD = 1.62$). In Experiment 6, MANOVA results showed that the format of delay feedback had a main effect on task preference, $F(2, 58) = 37.733$, $p < .01$, $\eta_p^2 = .565$. Participants preferred the task with counting-down delay estimation the most ($M = 6.50$, $SD = 1.04$) and the task without delay estimation the least ($M = 3.53$, $SD = 1.50$).

Feedback and delay tolerance. In both Experiments 5 and 6, delay condition was presented as a within-subjects factor, and tolerance was the dependent variable. MANOVA results in both tasks showed that the actual delay had a substantial main effect on tolerance rating: Experiment 5, $F(4, 116) = 177.544$, $p < .01$, $\eta_p^2 = .860$; Experiment 6, $F(4, 116) = 163.576$, $p < .01$, $\eta_p^2 = .849$. As delay condition increased, user tolerance for delay condition decreased. Neither the presence of delay feedback nor the format of delay feedback showed significant effects on delay tolerance.

Because the effects of delay feedback on tolerance ratings were not statistically significant, tolerance ratings in Experiments 5 and 6 were merged to examine the relationship between delay condition and tolerance. Two ways to analyze this relationship include calculating the mean of tolerance ratings at each delay level and calculating the mean of the delays with the same tolerance rating (from 1 to 7). The delay tolerance curve based on these merged findings was best fit by an exponential decay function:

$$\text{Delay tolerance} = 5.514 * e^{-0.0115*\text{delay}},$$

with a calculated goodness of fit $R^2 = .9206$. The calculated delay at which user tolerance dropped below 4 (the midpoint of the tolerance range, suggesting that further delays were intolerable) was 16.28 s.

GENERAL DISCUSSION

The collection of six experiments described in this article (including summary elements of three preliminary experiments) have addressed the impacts of user experience and expectation, network bandwidth capacities, and task situation factors on user perception and tolerance of delays in HCNI tasks. The outcomes of these experiments suggest areas of further research investigation as well as direct practitioner-oriented guidelines for user interface designs for HCNI applications. A summary of distinctive outcomes from these studies is presented in Table 9.

The most immediate finding is that user perception and tolerance for delay is a highly dynamic process and is affected by the amount of active user involvement in the task: Passive waiting is different from active working. Thus, guidelines for delay management should explicitly address mechanisms to differentiate when the user is actively involved in HCNI tasks or simply waiting for a task to complete before continuing. This difference affects variables ranging from task perception to estimates of network behavior to tolerance for delayed file access and downloading.

Design Guidelines

Preliminary Experiments 2 and 3 suggest that delay tolerance can be modified on the basis of user estimates and experiences of tasks that are considered more cognitively complex by humans. Unlike calculation or other "computer-based" tasks, search and other complex tasks may result in additional user tolerance for delay (because those tasks require more time for humans to complete). Passively experienced delays, in Experiments 5 and 6 as well as Preliminary Experiments 2 and 3, require delay management strategies to help limit degrading tolerance for delay. Although immediate feedback is not always required, users experiencing longer network delays do in fact increase tolerance for delay (and reduce system loads) when feedback acknowledging the delay is provided.

Countdown feedback was a preferred form of delay estimation for users, with relative benefits greater than those of simply providing elapsed time feedback. The presence of countdown feedback may also moderate user behavior in task situations with limited time available for task completion. In highly urgent, time-limited situations, countdown feedback may in fact increase network cancellations; however, this is because the user decides that the task cannot be completed and thus continuing is no longer useful. Users may find this type of cancellation more beneficial than deciding (and hoping) that waiting "just a little longer" without feedback will result in task success.

Users' responses to delays are affected both by their ability to accurately estimate and perceive the delay condition (as suggested by Vierodt's law) and by situation-based task constraints. Task constraints, such as impending deadlines or user ability to control delay, strongly affect how much users expect and experience delay. The user's expectation of delay is, in turn, affected by multiple factors. The experiments reported in this article demonstrate main and interaction effects of prior user experiences, current situation and task requirements, and local behavior of computer network infrastructure and bandwidth use. Furthermore, the influence of task requirements can include elements of task complexity, information exchange volume (such as file size and type), or performance capabilities of other HCNI interaction partners. In short, there is no single experience of delay; HCNI interfaces must provide sufficient information to allow users to process delay in the broader task or entertainment context of file access, exchange, and use.

A user's willingness to re-request an HCNI file exchange can be attributable to a lack of appropriate feedback or user impatience, similar to the phenomenon of repeated pushing of elevator buttons. However, because additional commands can further affect network load and response capabilities, there are substantial system performance costs associated with this form of mismatch between user expectations and network performance. In more extreme cases, a destructive positive feedback control loop can result, with user responses to unacceptable delays creating additional network demands. How can HCNI designers give users a sense that the file is coming in the same way that the sound of elevator movement can reduce the number of button pushes?

TABLE 9: Working Questions and Operational Factors With Distinctive Result Outcomes, Experiments 1 Through 6

Question	Set/Study Addressed	Factor/Variable	Distinctive Outcome
What factors affect user delay perception and tolerance?	Preliminary Experiment 1	Task complexity	There are task and complexity effects.
		Active delay estimation strategy	Task simulation is most often used.
	Preliminary Experiments 2 and 3	Type of HCNI partner	Type of partner is more important for complex tasks.
		Passive delay estimation strategy with partner	Mental counting is used.
	Experiment 4	Network characteristics	Network infrastructure affects expectations.
		Task situation factors	Time available and file importance affect expectations.
	Experiments 5 and 6	Preference for task performance	Feedback improves task preference.
		Expected task-based and network-based delay	There is exponential decay of tolerance with delay.
		Task restart or cancel	Re-requests increase with increasing delay.
What interplay exists between absolute delay and other factors?	Preliminary Experiment 1	Selection of delay strategy, task complexity, total delay	Accurate delay estimation depends on duration.
	Preliminary Experiments 2 and 3	Type of HCNI partner, passive experience of absolute delay	Tolerance for software delay is higher in "human complex" tasks.
	Experiment 4	Network characteristics, situation factors, ratio of delay condition to expected delay	There is sensitivity to ratio of delay condition to expected delay, not simply to absolute delay.
	Experiments 5 and 6	Delay condition, presence of elapsed delay feedback	Delay estimation is accurate only in limited ranges.
		Decision to re-request or cancel task	Presentation of absolute delay feedback affects requests and cancels.
What techniques address elements of delay tolerance?	Preliminary Experiments 2 and 3	Active control vs. passive experience of delay	Passive delay affects strategy and experience of delay estimation.
	Experiment 4	Quality of network service and expected delay	Situation and network factors affect expectation and tolerance.
		Ratio of delay condition to expected delay	Ratio is strong predictor of tolerance.
	Experiments 5 and 6	No, immediate, or delayed feedback	Presence of feedback reduces re-requests, increases giving up.
		Total delay projection vs. delay countdown	Countdown delay provides multiple sources of information.

Note. HCNI = human-computer-network interaction.

Results of these experiments suggest that an anthropomorphized "HCNI assistant" with awareness of current network delays and user task constraints could significantly affect user tolerance for delays. Countdown delay information, and even opportunities for the user to input "maximum time allowed" for HCNI tasks, could significantly improve user acceptance and task satisfaction. Such assistants should be seen as supporting the user in the completion of the user's task in the face of network delays rather than simply demonstrating a computer-generated barrier to task completion requiring passive waiting. Given that delays are more easily managed and tolerated when the user is actively working, users should also be given more explicit options to move delay-prone HCNI tasks to the background (cognitively and not only on the screen).

A relatively new concept developed by the authors' research is that of "information freshness" (Caldwell, 2005, 2008; Wang & Caldwell, 2003). At this point, relatively few HCNI applications give users the opportunity to specify, or discover, the "expiration date" of any information being exchanged. Professionals in highly time-critical situations, such as National Aeronautics and Space Administration spaceflight operations, develop an intuitive sense of when data have become "frozen," or no longer trusted because of a lack of change. Information freshness relates to both the consideration of HCNI updates that reflect the current state of the world and the ability to access HCNI data while they are still useful to conduct necessary tasks. Although the mechanisms for doing so are beyond the scope of this article, the results of these experiments indicate that users can benefit by being provided with routine feedback about the freshness and relevance of HCNI data on an ongoing basis during critical and time-sensitive tasks.

Research Indications

As the authors expected, users' experience of acceptable delays was a function of more variables than simply elapsed time. From the task simulation estimations of Preliminary Experiment 1 through the "time to give up" measures of Experiment 6, users modified their perceptions of, and responses to, HCNI delay conditions on the basis of a number of factors. Researchers investigating development of appropriate quality-of-service metrics cannot focus solely on absolute time measures of delay. Experiments 4 through 6 demonstrated that in both task estimation and direct experience contexts, delay tolerance is directly affected by ratios of delay condition to expected delay as well as by ratios of delay condition to time available for task performance. Thus, quality-of-service management systems should incorporate more explicit considerations of task importance, task urgency, and user expectations as important "activity cycles" affecting acceptable delay estimates.

Delay tolerance frequently reflects exponential, rather than linear, decay characteristics. This finding has been shown in the authors' other studies of delay tolerance and distributed task coordination, including spaceflight mission operations (Caldwell, 2005, 2008). Because linear delay tolerance can be shown as a special case of a multiparameter exponential function, research should in fact consider exponential decay as the basic model of delay tolerance of users in HCNI tasks.

Preliminary Experiments 1 through 3 and Experiments 4 through 6 are separated by multiple factors: time, technology development, culture, and task type. Thus, the authors are hesitant to suggest generating a robust structural equation model in support of Figure 1 from aggregating data from the two sets of experiments. Nonetheless, the results of Experiments 4 through 6 do indicate that users estimating task demands prior to direct HCNI task behavior, as well as during direct experience of delays, do address multiple relationship paths in their estimation and monitoring of acceptable HCNI delay. Further testing of these relationships cannot focus solely on a single factor or a simple elapsed time delay measure if it is abstracted from the larger context of user constraints, expectations, and situations affecting delay tolerance.

CONCLUSION

Despite drastic improvements in computing power and network bandwidth speed, the increase in size and complexity of computer applications and distributed HCI environments indicates that noticeable delays will continue to affect user performance and satisfaction. Although some predictions by computer science communities across several decades suggested that a new generation of computing capability might obsolete the study of user responses to delay, these predictions have not borne true. In fact, increasing bandwidth enables the sharing of larger files (e.g., movies, remote research data) in a feasible period. Complex computing architectures, such as cloud computing, can also be subject to significant delays, as users develop expectations to achieve processing and file exchange tasks that are even more computationally intensive.

Rapid changes in engineering physical state, with highly coupled and cascading event progressions, reflect the importance of delay awareness and mitigation in distributed control rooms managing chemical process, nuclear power, or electric grid applications. Even in more pedestrian consumer applications, the ability of increasing numbers of users to easily create and exchange files of gigabyte and even terabyte size will continue to force HCNI designers and researchers to consider how best to appropriately include and support user awareness and effective response to network delays.

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