HUMAN-COMPUTER INTERACTION, 2002, Volume 17, pp. 1–61

The Scope and Importance of Human Interruption in Human–Computer Interaction Design

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ABSTRACT

At first glance it seems absurd that busy people doing important jobs should want their computers to interrupt them. Interruptions are disruptive and people need to concentrate to make good decisions. However, successful job performance also frequently depends on people's abilities to (a) constantly monitor their dynamically changing information environments, (b) collaborate and communicate with other people in the system, and (c) supervise background autonomous services. These critical abilities can require people to simultaneously query a large set of information sources, continuously monitor for important events, and respond to and communicate with other human operators. Automated monitoring

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and alerting systems minimize the need to constantly monitor, but they induce alerts that may interrupt other activities. Such interrupting technologies are already widespread and include concurrent multitasking; mixed-initiative interac-

tion; support for delegation and supervisory control of automation, including intelligent agents; and other distributed, background services and technologies that increase human–human communication.

People do not perform sustained, simultaneous, multichannel sampling well; however, they have great capacity to manage concurrent activities when given specific kinds of interface support. Literature from many domains shows deleterious consequences of human performance in interrupt-laden situations when interfaces do not support this aspect of the task environment. This article identifies why human interruption is an important human–computer interaction problem, and why it will continue to grow in ubiquity and importance. We provide examples of this problem in real-world systems, and we review theoretical tools for understanding human interruption. Based on interdisciplinary scientific results, we suggest potential approaches to user-interface design to help people effectively manage interruptions.

1. INTRODUCTION

"Interruption-driven environment: A workless workplace that consists of returning email, voicemail, and pages; faxing phone lists; attending meetings; running meetings; scheduling meetings; and organizing your PDA" (Netscape Communications Corporation, 1998).

1.1. Improvements in Technology Can Cause Increased Human Interruptions

Technological advances allow people to simultaneously perform more activities, even though their cognitive capabilities have not increased. When not designed for people's unchanging cognitive limitations, technology can have unfortunate effects. For example, the telephone supports remote communication with other people in a way that would be impossible or very difficult to do otherwise. However, people do not typically use the telephone in isolation but in a normal, complex, integrated workplace. When it rings, the telephone introduces a sudden, loud noise that can interrupt the concentration of others. The interruption is an unavoidable cost of adding the telephone to an already multifaceted, real-world workplace.

Some computer-based interrupting technologies can also be problematic when integrated into real-world settings. Such technologies are widespread and include concurrent multitasking support; mixed-initiative interaction; support for delegation and supervisory control of automation, including intelligent agents; and many other kinds of distributed, backgrounded services and technologies that increase human–human communication. These technologies support human multitasking by allowing users to delegate tasks to automation or to other people. The selected agent works in the background while the delegator does other things. For example, artificial-intelligence technology can perform complex tasks through intelligent, semiautonomous computer systems, for example, intelligent decision aids, intelligent software agents, and autonomous robotic vehicles.

1.2. Trends in Technological Progress Make Human Interruption a Central HCI Design Problem for the Future

Information technologies continue to improve, driving a wholesale shift in how people will use computers. Human–computer interface will experience a revolutionary shift away from direct manipulation to a style based on delegation and supervision.

Negroponte (1995) said,

> Future human–computer interface will be rooted in delegation, not the vernacular of direct manipulation—pull down, pop up, click, and mouse interfaces. "Ease of use" has been such a compelling goal that we sometimes forget that many people don't want to use the machine at all. They want to get something done. What we today call "agent-based interfaces" will emerge as the dominant means by which computers and people talk with one another. (pp. 101–102)

Intelligent-agent technology is an example of computer support that supports people's natural ability to simultaneously perform several tasks. People think in parallel and act in serial—asynchronous parallelism (Edmondson, 1989). A user can delegate one or more tasks to intelligent software agents and then begin or resume another activity(ies) while the computer works in the background.

Semiautonomous and user multitasking technologies have clear utility, but they have different user interface (UI) requirements than have traditional, manual, single-task systems. Multitasking systems require intermittent interaction between user and computer. Users do not maintain constant focus on a single task, but switch between multiple tasks and intermittently supervise the processing of their delegated tasks. These intermittent interactions necessarily entail interruptions. Before an intelligent agent can communicate with its user, it must first interrupt the user from the other activity they are performing.

People have a natural ability and predisposition to multitask (Cherry, 1953; Cypher, 1986; Woods, 1995), but that ability can be unreliable and highly vulnerable to external influence (Preece et al., 1994, p. 105). When people multitask, they are susceptible to internal and external events that cause them to make mistakes. Computer systems support many kinds of important multitasks, for example, writing a report, collaborating with other people, projecting budgets, emergency 911 dispatching, flying an airplane, or managing a nuclear power plant. Mistakes in some of these contexts are more consequential and expensive than in others. Therefore, one must design system interfaces for interrupt-laden work environments to prevent expensive human errors and minimize their costs. There is little guidance as to how to best solve this important interface problem, and there are several examples of computer systems with ineffective *ad hoc* solutions.

Interrupting people does not always cause them to make errors (Lee, 1992, p. 81), and people are able to successfully perform multiple, concurrent tasks. In other situations, people make frequent errors with spectacular consequences. This article asserts that the design solution for the UI of a computer-based, multitasking and/or communication mediating system is the key determinant of human success or failure when using it. There is no mature design wisdom or guidelines about how to solve this problem.

1.3. Goals and Overview

This article reviews experimental and applied evidence of interruption-management problems and existing design guidance for explicitly designing successful interruption management. It also provides a theoretical foundation for improved design guidance and suggests specific computer-based support for improved interruption management. Section 2 reviews basic research that describes the effects of interruptions on human performance in a variety of contexts and individual differences that may mediate these effects. Section 3 provides evidence for the importance and ubiquity of the interruption-management problem. This section characterizes the problems associated with interruption management in three systems: complex flight decks, Aegis weapon system, and Interactive Situation Assessment and Rollup Tool. The section concludes with an extensive list of other application domains in which interruptions significantly and obviously affect human performance. Section 4 reviews the existing design guidance for incorporating interruptions in multitasking situations, and it presents two theoretical frameworks to consider contextual and individual effects for sensitive interruption management. Section 5 focuses on methods to coordinate interruptions that must be integrated into a multitasking work stream. It discusses four basic coordination solutions: immediate, negotiated, mediated, and scheduled. Interruptions can be delivered at the soonest possible moment (immediate), or support can be given for the person to explicitly control when then they will handle the interruption (negotiation). Another solution has an autonomous broker dynamically decide when best to interrupt the user (mediated), or to always hold all interruptions and deliver them at a prearranged time (scheduled). Section 6 summarizes approaches to manage interruptions in multitasking environments. It emphasizes the role of design interventions to most effectively improve human performance in such situations. We classify computer-based, interruption-management support into the three phases of interruption: after the interruption but before task switching, during the switch—while processing the interrupting task, and after the switch—resuming the interrupted task(s).

2. HUMAN INTERRUPTION

Interruptions affect human behavior, and researchers have empirically observed these effects. In a series of experiments by K. Lewin and his students, Zeigarnik (1927) was first to publish the relation between interruptions and selective memory. This work is the basis of an observed psychological phenomenon called the "Zeigarnik Effect" (Van Bergen, 1968); that people can recall details of interrupted tasks better than those of uninterrupted tasks.

Researchers have since documented other effects of interruption. Cohen (1980) found that unpredictable and uncontrollable interruptions induce personal stress that can negatively affect performance after interruptions. Interruptions can cause an initial decrease in how quickly people can perform post interruption tasks (Gillie & Broadbent, 1989; Kreifeldt & McCarthy, 1981). They also can cause people to make mistakes, reduce their efficiency, or both (Cellier & Eyrolle, 1992; Gillie & Broadbent, 1989; Kreifeldt & McCarthy, 1981; Latorella, 1996a, 1996b, 1998).

People also have individual differences in their ability to accommodate interruptions while they multitask (Braune & Wickens, 1986; Joslyn, 1995; Joslyn & Hunt, 1998; Kermis, 1977; Kirmeyer, 1988; Morrin, Law, & Pellegrino, 1994), in their ability to recall information about interrupted tasks (Atkinson, 1953; Husain, 1987), in their performance on interrupted tasks (Cabon, Coblentz, & Mollard, 1990; Weiner, 1965), and in how they handle interruptions in human–human communication (e.g., Lustig, 1980; West, 1982; Zimmerman & West, 1975).

People, however, have some natural abilities to dynamically adapt their behaviors to accommodate interruptions. The normally deleterious effects of interruptions can be mitigated when an operational environment allows flexibility in task performance, a variety of methods for responding to interruptions, and/or specific training (Chapanis, 1978; Chapanis & Overbey, 1974; Hess & Detweiler, 1994; Jessup & Connolly, 1993; Karis, 1991; Lee, 1992; Ochsman & Chapanis, 1974; Zijlstra & Roe, 1999). Speier, Valacich, and Vessey (1997) found work contexts where the introduction of interruptions actually increases human performance. When human decision-makers performed simple, nonchallenging, tasks they tended to occupy their unused cognitive capacity with non-task-related things. The occurrence of interruptions required them to focus more deeply on the primary task and this resulted in better overall human performance. Speier et al. also found, however, that this phenomenon does not hold for complex or cognitively demanding tasks. When people were cognitively engaged in demanding tasks, interruptions decreased their performance.

Some research has identified the aspects of multitasking situations that influence the effects of interruption on people's performance. Czerwinski, Chrisman, and Rudisill (1991) found an inverse relationship between task similarity—between the primary and the interruption tasks—and people's ability to remember information about the interrupted task after interruption. Gillie and Broadbent (1989) found weak evidence that the similarity between the interruption and current tasks and the complexity of the interruption task directly affected the disruptiveness of interruptions. They also found that allowing users to review their foregrounded activity prior to handling interruption did not necessarily help them recover that activity after interruption. They asserted that the negative effect of interruption on memory was caused by memory interference created by interruption tasks that were complex or similar to the pre-interruption task. Speier et al. (1997) found a negative relationship between interruption frequency and human performance on complex tasks.

3. EXAMPLES OF INTERRUPTION-MANAGEMENT

This section describes three application domains that demonstrate the need for intentional human–computer interaction (HCI) design to support interruption management. The first two, complex flight decks and the Aegis weapon system, demonstrate user difficulties and safety implications of systems designed without intentional interruption-management HCI. The third, Interactive Situation Assessment and Rollup Tool (ISART), provides an example of recognizing this problem during the design phase of a research platform. The section also presents samples of other application domains that require interruption management.

3.1. Complex Flight Decks

The role of pilots is becoming increasingly supervisory and decreasingly manual controller. However, modern automated and computer-aided commercial flight decks are not specifically designed to support interruption management.[1] Issues associated with the alarm-management problem on com-

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1. Specific flight decks are not identified as particularly problematic because the problem arises in all flight decks to some degree by virtue of the multitasking and collaborative nature of piloting.

plex flight decks have been well documented (e.g., Boucek, Veitengruber, & Smith, 1977). System alarms are only one form of interruption on flight decks. Other interruptions take the form of more subtle attention-directing aural, visual, and tactile cues from a variety of onboard systems (e.g., datalink messaging systems [see Williams, 1995]), as well as communications among the crew and radio communications with other National Airspace System (NAS) operators, such as Air Traffic Management (ATM) operators (e.g., Barnes & Monan, 1990; Monan, 1979). The broader issue of task management, or how pilots normatively and actually proactively and reactively behave in this multitasking environment, has received more notice. Task management is now considered a goal of pilot performance on the same level as the more traditional "aviate, navigate, communicate" goals (Abbott & Rogers, 1993). Funk and his colleagues considered interruption management as a rational process given available resources and prioritization of tasks (Funk, 1996; Funk & Braune, 1999), an approach closely related to work in strategic workload management (e.g., Raby & Wickens, 1991).

Analyses based on entries in the Aviation Safety Reporting System (Barnes & Moran, 1990; Chou & Funk, 1990, 1993; Madhaven & Funk, 1993; Monan, 1979; Turner & Huntley, 1991) demonstrate that interruption management is not optimally performed and that errors are contributing factors in aviation incidents. Field studies (Damos & Tabachnick, 2001), particularly those using process-tracing methodologies (Loukopoulos, Dismukes, & Barshi, 2001) also show that flight-deck interruptions are frequent, emerge from a variety of sources, and have a variety of effects. Dismukes, Young, and Sumwalt (1998) describe accidents that can be partially attributed to interruption on the flight deck. In particular, interruptions can result in failure to appropriately complete checklist items (Degani & Weiner, 1990), hindering the effectivenss of the very device designed to correct or mitigate errors before they have severe consequences. Unfortunately, such severe consequences have been realized and partially attributed to pilot interruption in aviation accidents (Adams & Pew, 1990; Adams, Tenney, & Pew, 1995; National Transportation Safety Board, 1973, 1988). Linde and Goguen (1987) explicated the limitations of training as an effective means to improve pilots' interruption-management performance. Dismukes et al. (1998) provided six strategies for cockpit resource management that may help reduce crews' vulnerability to the deleterious effects of interruptions. These strategies recommended that pilots be aware of the dangers interruptions can cause, strategically manage tasks (considering workload and criticality of tasks) to reduce particularly damaging interruptions, and allocate crew responsibilities as pilot-flying and pilot-not-flying. If an interruption occurs, the authors suggested that pilots (a) identify the interruption, (b) recall what they were doing when interrupted, and (c) decide how to resume the interrupted task.

To understand the factors that determine when an interruption will most likely have negative consequences, Latorella (1996b, 1998) studied the effects of interruptions on flight-deck performance in a 747-like flight simulation using airline pilots as participants.[2] This study demonstrated the effects that abruptly delivered ATM instructions can have on commercial pilot performance in descent and approach flight phases. Participants' performances of ongoing procedures were about 53% more likely to contain errors when an ATM interruption occurred. Some errors were operationally significant: For example, participants failed to tune to the tower frequency on approach about 14% more often when in an interrupted condition. This error caused confusion and increased radio frequency congestion and, if left uncorrected, could prevent a pilot from receiving life-saving instructions in time to take appropriate evasive action. The study also identified specific contextual factors that were hypothesized to affect pilot performance in flight-deck interruption management. Significant performance effects were found for independent variables that characterized the ongoing task's presentation modality (aural and visual), interrupted task's presentation modality (aural and visual), interaction of presentation modalities, goal-level of the interrupted procedure at which the interruption occurred, type of association between the tasks on either side of an interrupted procedure, and manipulation of environmental stress (proximity to ground and landing). These effects were reflected in a variety of performance measures developed to specifically measure interruption-management performance in the flight-deck environment. The most sensitive measures to these task factors included acknowledgment time to the initial ATC call (interruption), initiation time of the task required by the interruption, and performance errors in the execution of the interrupting task and interrupted procedure. Participant differences were also significant in these results, but were not further explored.

3.2. Aegis Weapon System

The U.S. Navy's Aegis[3] Combat System is a good example of a critical, real-world system that interrupts the people who use it. Defense industry

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2. This article uses the term "participants" instead of subjects as per the APA style guidelines.

3. The core of the U.S. Navy's warfighting fleet are the CG-47 Class Cruisers and the DDG-51 Class Destroyers equipped with the Aegis Combat System. They will comprise the significant majority of the Surface Combatant Fleet through the year 2030. For further reference, the banner image for U.S. Navy home page http://www.navy.mil/ is Aegis Ships . One example is the USS Stout DDG 55; http://www.spear.navy.mil/ships/ddg55/.

groups refer to the Aegis Combat System as the most complicated embedded system on the planet. It incorporates several kinds of subsystems, including the Combat Information Center, where 30 to 35 sailors control the combat system. Control is divided into separate jobs or submodes, where individual sailors are tasked to focus on specific responsibilities.

These ships are, in Navy terminology, "fully mission capable" and have functioned successfully since they were initially deployed 25 years ago. Several improvements have provided operators with more of the information they need to make good decisions. An alert tool is used as a central mechanism to deliver this information to operators. This mechanism is designed somewhat like an e-mail tool that is open all the time, receiving a continual stream of diverse messages and time-critical task assignments from many different automated systems.

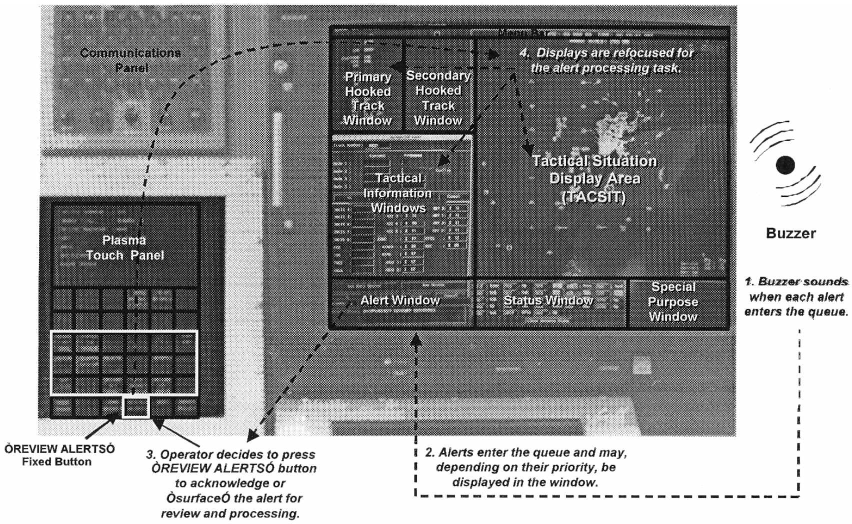
No matter how critical, each alert is also an interruption. The volume of alert-based information has increased exponentially over 25 years. The Navy recognizes that its ships will not be fully mission capable in the future without improving the design of the UI to support the operators' ability to effectively handle large volumes of alert-based information. Aegis operators typically receive several alerts per minute during high-stress operations. For example, the operator for the Aegis Identification Supervisor (IDS) submode is responsible for determining and maintaining the accuracy of the identity (friend, foe, or neutral) of hundreds of contacts (aircraft and other vehicular tracks) visible to the ship's radar. It was recorded during the ASCIET '96 exercise (All Services Combat Identification Evaluation Team)[4] that IDS operators received alerts at an average sustained frequency of one every 11.5 sec. Informational alerts (about 90% of those received) require 5–10 sec each to review and acknowledge, and action alerts require 30–60 sec to accomplish the associated tasks.

This is a problem with human-interruption design that needs a better HCI solution. Alert handling in the current system is manually intensive, and the system controls the order in which operators are allowed to handle alerts. There is a potential for operators to quit using the alerting tool when they become highly stressed. However, this closes a critical information channel that Navy decision-makers need to stay fully mission capable.

Figure 1 shows the UI for an IDS operator and the steps required to process an alert. The Alert Window only displays the top three priority alerts in the queue. The operator must press the Review Alerts button to review each alert. Step 3 always calls the top alert in the queue, which may not be the same as that announced by the buzzer in Step 1. Note that no alert-based informa-

4. A yearly joint-forces war game to determine how to prevent "friendly fire" accidents.

Figure 1. **Aegis Identification Supervisor (IDS) interface (Aegis Baseline 6 Phase 1). The console is grayed out and annotation has been added to explain the UI design for the current alerting mechanism.**



tion is reflected in the Tactical Situation (TACSIT) display until the operator manually surfaces the top alert in the alert queue. The Navy has recognized the potential consequences of this situation, and has determined that the UI for the Aegis alerting mechanism must be re-designed to support future mission requirements.[5]

3.3. Interactive Situation Assessment and Rollup Tool

The ISART is a research project at the Navy Center for Applied Research in Artificial Intelligence (NCARAI). It is an example of how intelligent decision aids running in the background cause the unintentional side effect of increasing user interruption (Ballas et al., 1996; Kushnier, Heithecker, Ballas, & McFarlane, 1996). ISART is an evolving research platform for investigating

5. The Office of Naval Research is sponsoring a program call the Knowledge Superiority and Assurance Future Naval Capabilities (KSA FNC). Daniel McFarlane, Lockheed Martin Advanced Technology Laboratories, is leading a KSA FNC team project starting in 2002 called Human Alerting and Interruption Logistics–Surface Ship (HAIL–SS). The goal is to transition modern human-alerting technologies, founded on research done at NCARAI (Navy Center for Applied Research in Artificial Intelligence), into the production of future Aegis systems being produced by Lockheed Martin Naval Electronics and Surveillance Systems–Surface Systems.

UI-design methods for intelligent command and control systems. In the mid-1990s, the ISART research team incrementally increased the capability of ISART by introducing new intelligent decision aids. ISART first included an intelligent decision aid that advised on the deployment and maintenance of a standard sector air defense of an aircraft carrier. Researchers then added an aid to support situational awareness by interactively deducing complex relationships among observed manmade objects and groups of objects in the environment. The ISART team later added an intelligent decision aid that automatically deduced occurrences of standard enemy attack patterns and alerted the user. While each decision aid provided useful assistance, the team found that they also placed new interaction demands on the user. The interaction between human and computer gradually shifted from a direct manipulation style to a delegation and supervisory style. Each additional aid became a potential source of interruption or distraction for the user.

3.4. Additional Application Domains

Other application domains require interruption-management support: intelligent tutoring systems (Galdes & Smith, 1990), computer-mediated communication (Bannon, 1986; McCarthy & Monk, 1994), telephone communications (Katz, 1995; Stuart, Desurvire, & Dews, 1991), U.S. Navy's Multi-Modal Watchstation (MMWS; Obermayer & Nugent, 2000; Osga, 2000), Navy damage control systems (Perse, Callahan, & Malone, 1991), office environments (Rouncefield, Hughes, Rodden, & Viller, 1994; Speier et al., 1997; Zijlstra & Roe 1999), and Internet instant messaging (Czerwinski, Cutrell, & Horvitz, 2000a, 2000b). This design problem also applies to areas of air-traffic control, Internet push technology, head-mounted display systems, unmanned air vehicles, medical-device monitoring and procedures, automated command and control, automated highway systems, and intelligent software agents.

4. DESIGN WISDOM

Evidence from complex flight decks, Aegis Combat System, and ISART research project indicates the critical need for intentional HCI design to manage interruptions. The breadth of application areas for which interruption management should be considered emphasizes the ubiquity of this design problem and the need for design guidance.

Some design-relevant literature comes from researchers, not intending to study the effects of interruptions directly, included interruptions in their test scenarios (Field, 1987; Kreifeldt & McCarthy, 1981; McDonald & Stevenson, 1996; Williams, 1995). Including interruptions in test scenarios is particularly important for usability assessments of UIs of devices that will be used in dynamic, interruption-rich environments.

Formal design standards rarely include advice for interruption management. Notably, the United States' Human Engineering Design Criteria for Military Systems, Equipment, and Facilities (MIL–STD–1472F, 1999) is widely used, especially in Department of Defense system acquisition and development, and does not include guidence for interruption management. If design-guidance documents address interruption management, most only identify it as a problem. For example, Rubinstein and Hersh (1984) identified 93 guidelines for UI design. Guideline 12, "Interrupt with Care" (p. 64), identifies user interruption by computer as an important problem, but the authors do not give specific design direction on how to successfully "interrupt with care."

Smith and Mosier (1986) proposed guidelines that recognize the need to "provide flexibility in sequence control by allowing a user to interrupt or cancel a current transaction, in ways appropriate to task requirements" (p. 277), and that "interruptions should be announced in a manner not disruptive to the ongoing work" (p. 364). Although Smith and Mosier do not provide guidance for context-sensitive presentation and integration of interruptions, they do specify UI features that would support more flexible interrupt handling in multitasking environments. These interface features included distinct controls to handle different interruption methods (p. 277), a cancel option to erase changes since the last save (p. 277), controls to allow pausing and resumption of task streams (p. 280), and indicators of paused status (p. 280); controls to suspend a sequence and preserve current transaction status (p. 280) and indicators of suspended status (p. 280); and notification of messages received during absence when users resume use of a system (p. 364), nondisruptive notification of arriving messages (p. 364), indication of the priority of received messages (p. 365), and nondisruptive notification of messages received (automatic queuing to ensure that incoming messages do not disrupt current user information handling tasks; p. 399).

There are a few sources of design wisdom that describe how to intelligently introduce interruptions. Burton and Brown (1979) reported on their effort to design a computer-based tutor for an ICAI (Intelligent Computer-Assisted Instruction) system that teaches math skills. The tutor is an intelligent aid that runs in the background and monitors user performance on math-learning games. It is built to detect human-learning errors and interrupt the user with attempts to help overcome learning problems. Burton and Brown said that the design problem of when to interrupt is critical to the success of the ICAI system. Although interrupting students for coaching purposes was sometimes useful, they said, "Every time the coach tells the student something, it is robbing him of the opportunity to discover it for himself. Many human tutors interrupt far too often" (Burton & Brown, 1979, p. 15). Burton and Brown proposed 12 design guidelines to determine when and how to interrupt the user. Their guidelines make user interruption context sensitive. For example, “If a student is about to lose, interrupt and tutor him only with moves that will keep him from losing” (principle 4), and “Do not tutor on two consecutive moves, no matter what” (principle 6). Galdes and Smith (1990) said that Burton and Brown’s guidelines are useful, but are not significantly rigorous and need to be empirically validated. A more empirical approach would be to observe how expert human tutors interrupt their students and apply these interruption strategies to ICAI. Galdes and Smith analyzed the teaching behaviors of expert human tutors and identified successful interruption strategies. Galdes and Smith then presented these strategies as design guidelines to build an ICAI tutorial system that must interrupt people. These guidelines, like those of Burton and Brown, suggest that timing of an interruption must be context sensitive.

Cooper and Franks (1993) said that creating general theoretical tools for researching human interruption was beyond the scope of their work. However, they suggested an informal and non-general definition and framework of human interruption based on cognitive limitations related to processing unexpected communication events. Cooper and Franks identified human interruption as a complex cognitive process that can be used as a model for the design of combined symbolic and connectionist, hybrid, computational sytems. They suggested that human interruption can be defined as “any disturbance to the normal functioning of a process in a system.” Cooper and Franks identified useful dimensions of interruption in their framework: source, effects (degree and extent), content, applicability, duration, mechanism for recovery, and state space of the underlying system (Cooper & Franks, 1993, pp. 76–78).

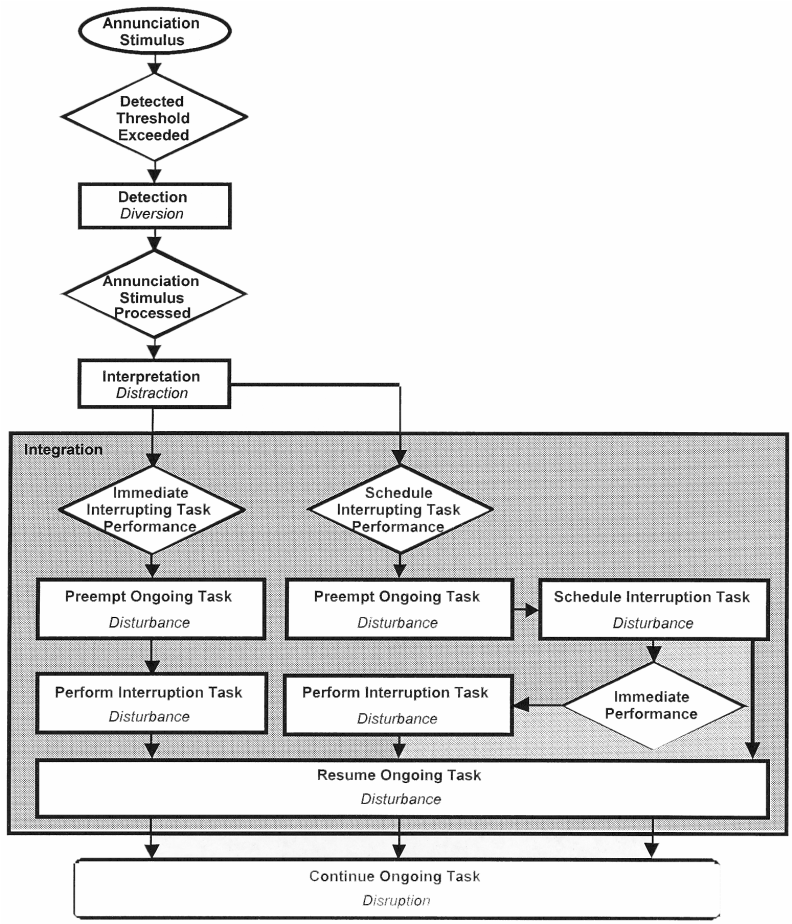
Alert design addresses many issues associated with interruption management. For example, Obermayer and Nugent (2000) presented a list of UI-design guidelines to create alerting and attention management systems. The list summarizes two documents (literature review and design guide) that helped software engineers at the U.S. Navy’s Space and Naval Warfare Systems Center San Diego (SSC San Diego) design an Attention Allocation Subsystem for the MMWS. The MMWS is an advanced research platform for investigating powerful decision-support tools for Navy tactical decision-makers. Obermayer and Nugent said, “The designer should be aware that presentation of an alert or alarm is an interruption, and that the operator may be prone to error upon returning to the original task.” Their guidelines contained seven items or “important alert system characteristics”: (a) only present alerts that are necessary to task success; (b) make the degree of attention-getting cues used to interrupt the person relative to the importance of the alert; (c) use cues to lead the user’s attention to what they probably need to do next; (d) manage simultaneous competing messages; (e) give the operator ultimate control over when and whether to handle interruptions; (f) support a searchable archive of alert messages; and (g) provide "interrupt-resistant" UI support to reduce the errors caused by human interruption.

In summary, prior design guidance indicates the necessity for considering context to improve interruption management, and suggests simple control requirements to accommodate interruptions, but does little to explicate the contexts that are important to consider or intelligently manage these interruptions. The *states of activity* and *states of understanding* theoretical frameworks (Brennan & Hulteen, 1993; Clark & Schaefer, 1987; Lee, 1993; Miller, 1968; Pérez-Quiñones, 1996) and the *conversations for action* models (Winograd & Flores, 1986) generally describe how humans become aware of interruptions to dialog and respond to new requests for action(s). However, specific theoretical foundations for the interruption-management process and characterization of the factors that affect successful interrupt and ongoing task(s) performance are necessary to develop a more comprehensive understanding of human behavior in interruption management and necessary to develop HCI guidelines to support this behavior. The two following theoretical models support further guidance for intentionally designing systems that support effective interruption management. The first provides an information-processing-stage model of interruption management, and suggests measures to assess the quality of interruption-management performance. The second provides a taxonomy of eight topical dimensions that affect interruption management behavior.

4.1. Interruption Management Stage Model

Latorella (1996b, 1998) proposed the interruption management stage model (IMSM), a theoretically based and empirically supported model of human interruption in complex systems (Figure 2). This model serves to (a) organize basic research addressing perception, memory, attention, motivation, scheduling, and planning to identify task (interrupted and interrupting), environment, and operator factors relevant to interruption management; (b) characterize interruption management as information processing stages—with the understanding that it is a simplification of actual mental processes; (c) charactrize people's interruption management behaviors in the context of these stages; (d) characterize the deleterious effects of interruptions in terms of these stages; and (e) suggest dependent measures useful for sensitively measuring these deleterious effects. Latorella (1996b, 1998) specifies the characteristics of an interruption, interrupted task set, and presumed performance motivations assumed as the circumstances of this model. These circumstances assume that an operator is engaged in an ongoing task set, which is a sequence

Figure 2. **Model of interruption-management stage (Latorella, 1996b, 1998).**



of familiar, discrete tasks that can be described by a goal hierarchy. Interrupted tasks in this set are assumed to be resumable from the point of interruption. Interrupting tasks are familiar and, while not incongruous to the general frame of expectations associated with the ongoing task set, are unpredictable. Interruptions consist of an annunciation signal plus a set of activities to be performed. Operators are assumed to be motivated to perform all the tasks of the ongoing set and of the interruption within certain relevant environmental constraints (e.g., implicit deadlines).

Interruption management behaviors are defined by the stages that are accomplished in the processing of an interruption. The IMSM specifies five interruption management behaviors, that is, responses to the onset of an interruption: (a) *oblivious dismissal*, the interruption annunciation is undetected and the interruption is not performed; (b) *unintentional dismissal*, the significance of the annunciation is not interpreted and the interruption is not performed; (c) *intentional dismissal*, the significance is interpreted, but the operator decides not to perform the interrupting taks; (d) *preemptive integration*, the interrupting task is initiated immediately, intruding on the ongoing task, and performed to completion before resuming the ongoing task; and (e) *intentional integration*, the interrupting task and the ongoing task are considered as a set, and the operator rationally determines how to integrate performance of the interrupting task. The IMSM describes interruption management as stages: detection of the interruption annunciation, interpretation of the annunciation, integration of the interruption into the ongoing task set, and resumption of the ongoing task set. This model also defines four general effects of interruptions in terms of the information processing stages and suggests measurement constructs for evaluating these effects. These effects are *diversion, distraction, disturbance*, and *disruption.*

Diversion occurs when attention and possibly sensory apparatus are redirected from prior, primary focus, to the stimulus of the interruption annunciation. Distraction is the momentary redirection of attention to interpret an interruption annunciation. Disturbance results from efforts to triage the interruption and to immediately execute the associated performance, or schedule it for later performance. Effects of diversion, distraction, and disturbance may further propagate to disruption of downstream task performance due to the additional integration requirement imposed by the interruption. The extent of disturbance and disruption that an interruption induces depends on the interruption-management behavior used to integrate the interruption into the ensemble task flow.

The IMSM is also a basis for defining dependent measures to sensitively address the degree to which an interruption diverts, distracts, disturbs, and disrupts. Distractibility of the interruptions was measured by pilot acknowledgment times to an ATM interruption announcement. Disturbance of the interruption, the degree to which the presence of additional task influences performance at the interruption point, was measured by interrupting-task initiation time, interrupting-task performance errors, ongoing-task resumption time, and control inputs during the post-interrupt/pre-resumption interval. Disruption effects associated with having been interrupted or the propagative effects on an ensemble task set, was measured in the flight-deck example by procedure (interrupted task set) performance errors, time to complete the entire task set, and number of continuous control inputs during the procedure.

This IMSM is the first thorough model-based treatment of how people deal with interruptions. It provides a useful framework for hypothesizing task, operator, and environmental factors relevant to interruption management, for describing the effects of interruptions and behaviors for handling them, and for identifying dependent measures associated with stages of interruption management. These contributions are most directly applicable to situations commensurate with assumed characteristics of the interruption tasks and performance goals. Generalizability may be limited where interruption contexts are more complex and simultaneous, like human–human dialog.

4.2. Definition and Taxonomy of Human Interruption

McFarlane (1997, 1998)[6] proposed a general, interdisciplinary, theory-based definition and taxonomy of human interruption, which says that human interruption is "the process of coordinating abrupt changes in people's activities." Each part of the definition ties in with a useful body of existing literature. McFarlane's taxonomy identifies eight major dimensions of the problem of human interruption (Figure 3). The taxonomy was constructed from an extensive interdisciplinary base of theory about human interruption identified in a broad review of the literature from several domains. Each factor of the taxonomy represents an independent viewpoint for looking at the problem from some foundation of existing work.

Each factor creates a useful framework for discussing UI design for supporting human interruption. The design literature relevant to each is discussed here. The third factor from the taxonomy, method of coordination, is especially relevant to UI design, and this article addresses it separately in Section 5.

Source of Interruption

The computer as the source of interruption is the focus of this article, and an intelligent agent for management of e-mail is a good example (Lashkari, Metral, & Maes, 1994). Miyata and Norman (1986) distinguished between internal and external interruptions. Internal interruptions are side effects of internally backgrounded activities, that is, activities that people perform outside of their focus of conscious attention. External interruptions are side effects of externally backgrounded activities, that is, activities that people have delegated to other entities. Computers are one example of an external source of interruption. Other sources are people, animals, or noncomputer machines

6. McFarlane (1997, 1998, 1999): available online from the Naval Research Laboratory's HAIL Project homepage (Human Alerting and Interruption Logistics; http://www.aic.nrl.navy.mil/hail/).

Figure 3. **Taxonomy of human interruption (McFarlane, 1997, 1998).**

Factor of Human Interruption	Example Values
Source of interruption	Self [human], another person, computer, other animate object, inanimate object.
Individual characteristic of person receiving interruption	State and limitations of personal resource (perceptual, cognitive, and motor processors; memories; focus of consciousness; and processing streams); sex; goals (personal, public, joint); state of satisfaction of face-wants; context relative to source of interruption (common ground, activity roles, willingness to be interrupted, and ability to be interrupted).
Method of coordination	Immediate interruption (no coordination); negotiated interruption; mediated interruption; scheduled interruption (by explicit agreement for a one-time interruption, or by convention for a recurring interruption event).
Meaning of interruption	Alert, stop, distribute attention, regulate dialogue (meta-dialogue), supervise agent, propose entry or exit of a joint activity, remind, communicate information (illocution), attack, no meaning (accident).
Method of expression	Physical expression (verbal, paralinguistic, kinesic), expression for effect on face-wants (politeness),[a] signaling type (by purpose, availability, and effort), metal-level expressions to guide the process, adaptive expression of chains of basic operators, intermixed expression, expression to afford control.
Channel of conveyance	Face-to-face, other direct communication channel, mediated by a person, mediated by a machine, meditated by other animate object.
Human activity changed by interruption	Internal or external, conscious or subconscious, asynchronous parallelism, individual activities, joint activities (between various kinds of human and non-human participants), facilitation activities (language use, meta-activities, use of mediators).
Effect of interruption	Change in human activity (worth of this change is relative to the person's goals), change in the salience of memories, change in awareness (meta-information) about activity, change in focus of attention, loss of willful control over activity, change in social relationships, transition between stages of a joint activity.

[a](Brown & Levinson, 1987).

that a person uses to externally "background" activities. Also, some internal and external sources of interruption are unrelated to activities people have intentionally backgrounded, for example, having a hiccup (internal interruption) or being bumped into by a coworker (external interruption).

Individual Characteristic of Person Receiving Interruption

People have differences in their ability to multitask while being interrupted. Some critical jobs, like public safety "911" dispatch and air-traffic control, require people who can reliably perform these tasks. Joslyn and Hunt (1998; Joslyn, 1995) presented an empirically validated test called "The Puzzle Game" for predicting individuals performance on the dispatching task.

As we discussed briefly in Section 2, people's level of anxiety affects their ability to recall information about interrupted tasks (Husain, 1987). Their ability to maintain a constant level of arousal affects their performance on an interrupted vigilance task (Cabon, Coblentz, & Mollard, 1990). Level of motivation affects (a) people's ability to recall information about interrupted tasks (Atkinson, 1953) and (b) people's tendency to resume interrupted tasks (Weiner, 1965). Individuals have a degree of coordination ability that affects their ability to perform multitasks (Morrin, Law, & Pellegrino, 1994). Children's individual differences in ability on conservation tasks (discern violations in conservation of amount) and reversal shift tasks (distinguish pattern transpositions) predict their multitasking performance (Kermis, 1977). People show a measurable difference in their cognitive style relative to multitasking; this is called field dependence–independence (Jolly & Reardon, 1985). Their score on this ranking correlates with their success in quickly switching between tasks. People's level of apprehensiveness affects how often they initiate dialogue and how often they receive interruptions in human–human communication (Lustig, 1980). People's gender affects their initiation and management of interruption in human–human communication (West, 1982; Zimmerman & West, 1975).

Method of Coordination

Section 5 contains an in-depth discussion of this factor of the taxonomy of human interruption.

Meaning of Interruption

Computer systems are built to interrupt their users for different reasons. Sometimes interruptions are supposed to act as reminders to help people resume activities they had suspended or backgrounded. For example, the calendar application for the Macintosh named *In Control* (Attain Corporation) initiates beeps that interrupt the user to remind them of scheduled meetings. Taylor and Hunt (1989) said that interruption is a means of dialogue regulation—that, in human–human dialogue, people interrupt each other as a way to regulate dialogue turns. E-mail applications initiate interruptions to alert the user of the existence of new messages. Cars interrupt their users with beeps or even recorded voices to warn them when they leave the keys inside. Communication interruptions can indicate that another human in the system requires information available to you or has information the other assumes you require. "No meaning" is also valid. Some interruptions have no meaning other than as news that something has broken. Periodic failure of a communication channel (interruptions) has been observed to degrade the ability of Navy commanders to make tactical decisions (Callan, Kelly, Gwynne, & Feher, 1990).

Rouncefield et al. (1994) found in one office environment that the staff perceived interruptions as the "real work." "The 'interruptions' comprised those aspects of the work which the staff said they most enjoyed, namely, contact with customers, and that the work so 'interrupted' was the work they least enjoyed and considered a burden, namely, the paper work" (p. 281).

Method of Expression

Researchers have investigated useful ways of expressing interruptions. The goal of these efforts has been to discover methods of expressing interruption that can mitigate their negative effects on user performance. The interaction modality of the interruption task can conflict with the modalities the user is already using (Storch, 1992). Semi-transparency can be useful for graphical presentation of interruptions while the user is working on graphical tasks (Harrison, Ishii, Vicente, & Buxton, 1995). Spatial location can be an important expression choice for the UIs of interruption tasks (Osgood, Boff, & Donovan, 1988). Windowing and windowing focus cues can help disambiguate between concurrent tasks for task switching (Lee, 1992).

Obermayer and Nugent (2000) said that each incoming alert message had a degree of relevancy to the person's current task context. They suggested that the best method of expression was to make the degree of attention-getting cues relative to the importance of the alert to the overall task success. They said the appropriate expression method should be chosen based on how quickly the user must attend to the alert message to permit task success.

Channel of Conveyance

The channels of communication can affect human–human interruption behavior. Ochsman and Chapanis (1974; Chapanis, 1978) found that people who have a voice channel in their human–human communication system take control (interrupt each other) much more frequently than they give control. However, people who do not have a voice channel take and give control about equally. Chapanis and Overby (1974; Chapanis, 1978) found that the presence or absence of interruption capability in a communication channel—whether the human–human communication channel allowed people to interrupt each other—had no effect on how long it took people to perform cooperative tasks from remote locations, and had no effect on how many words they used. Participants compensated when they could not interrupt each other by changing how they formed their communication messages. When participants had interruption capability, they solved problems with many short messages. When participants did not have interruption capability, they solved problems with fewer but longer messages.

Latorella (1996b, 1998) found that interruptions had different effects on aircraft pilots, depending on whether the interruptions were delivered on the same or different visual or auditory channel as the ongoing task. Visual interruptions of auditory tasks resulted in the slowest performance times in starting the interrupting task. Auditory interruptions of auditory tasks resulted in the most errors on procedural tasks. Visual interruptions of visual tasks resulted in the best overall performance during interruptions. Auditory interruptions of visual tasks resulted in the most errors on interruption tasks.

Taylor (1989) summarized the tradeoffs between visual and voice channels for UI design of aircraft cockpit systems. Taylor found that visual channels were extremely useful for communicating spatial information, but that computer-initiated messages were better conveyed over the voice channel when pilots used their eyes for some other task. Taylor warned that the use of a voice channel is problematic, because people are very sensitive to bad design of voice-interrupt systems, and designs of such systems have frequently resulted in ineffective machine-initiated transactions and undesirable interruptions that were difficult to ignore. Karis (1991) found that imperceptible inefficiencies in a communication channel can affect people's interruption behavior. Karis found that (a) participants did not notice the existence of an added lag in message transmission times and (b) the inclusion of delays increased the frequency with which people interrupted each other.

Human Activity Changed by Interruption

Some research has looked at which aspects of multitasks affect the outcome of interruption on people's performance. As we discussed briefly in Section 2, Czerwinski, Chrisman, and Rudisill (1991) found an inverse relationship between task similarity—between the primary and the interruption task—and people's ability to remember information about the interrupted task after interruption. Gillie and Broadbent (1989) found that the similarity between the interruption and the current task and the complexity of the interruption task directly affected the disruptiveness of interruptions. Gillie and Broadbent (1989) also found that allowing users to review their foregrounded activity prior to handling an interruption did not necessarily help them recover that activity after interruption. They observed that the disruptive effects of interruption on people's memories were not caused by an inability to rehearse memory prior to handling an interruption; instead, the negative effect was caused by memory interference created by interruption tasks that were complex or similar to the pre-interruption task.

Effect of Interruption

People are generally very familiar with the subjective idea that interruptions affect their performance. These effects have been objectively observed in research, but results have been sometimes conflicting and have shown that understanding human performance with interruptions is a complex problem. Interruptions cause an initial decrease in how quickly people can perform post interruption tasks (Gillie & Broadbent, 1989; Kreifeldt & McCarthy, 1981). They also cause people to make mistakes (Cellier & Eyrolle, 1992; Gillie & Broadbent, 1989; Kreifeldt & McCarthy, 1981; Latorella, 1996a, 1996b). Interruptions also reduce people's efficiency (Latorella, 1996a, 1996b), and increase stress (Cohen, 1980). Field (1987) claimed to support the existence of interruption effects, but does not. Field's report of a pilot study does not contain an analysis for an overall effect of interruption. The experiment recorded four different measurements of participants' behavior following interruptions; however, no analysis was performed to determine if these data represented any meaningful interruption effect on the participants' task performances. Instead, an interruption effect was assumed and the analysis focused on the differences in performance caused by two alternative database-navigation tools in the post-interruption data. Interruptions do not always cause negative effects on human performance. Chapanis and Overbey (1974) found that interruptions had no affect on performance time, but they did affect the way participants accomplished those tasks. Hess and Detweiler (1994) found that training can suppress the negative effects of interruption.

4.3. Comparing Latorella's IMSM to McFarlane's Definition and Taxonomy

Latorella's IMSM (Section 4.1) and McFarlane's definition and taxonomy (Section 4.2) are different kinds of theoretical tools. The IMSM targets researchers' need to understand the process of human interruption in an important class of work environment. The IMSM shows the stages of cognitive-information processing that people exhibit and the kinds of management behaviors that merge to handle interruptions for a defined class of interrupting and interrupted tasks and performance objectives. The model structures a discussion of human-information processing to extract task, operator, and environment factors that will likely determine the degree to which an interruption will have deleterious effects. This information highlights where different kinds of performance problems can happen, and helps identify measures for assessing these effects. It also provides insights into the HCI process that can guide the design of human-interruption management support.

McFarlane's definition and taxonomy of human interruption targets UI designers' need to design systems that must interrupt their users. The definition and taxonomy are an attempt to map the total design space and identify a broad array of potential influences of user performance with tie-ins to relevant design literature for addressing these factors. The taxonomy shows areas of the problem, where specific technologies could be introduced to give people richer support for handling interruption.

McFarlane's definition and taxonomy are based on a broad, interdisciplinary, theoretical foundation, but they do not have the depth of process representation of Latorella's IMSM. The IMSM describes details of the interruption process in an important class of work context, and can help researchers make sense of observations about human behavior relative to handling interruptions. It can also be used to make useful design suggestions for work that are commensurate with the assumed circumstances, but the IMSM does not have the wide breadth of design space utility of McFarlane's definition and taxonomy. McFarlane's work can tie in with process-oriented literature, but the definition and taxonomy themselves do not contain sufficient depth of process information to help researchers understand much about human cognition in any specific work environment.

However, there is a useful common ground on support for interruption coordination in both Latorella's IMSM and McFarlane's definition and taxonomy of human interruption. Both works provide treatments of when to interrupt the user and what kind of user control should be supported in the UI design. This article asserts that this question is a paramount design topic for supporting human interruption. The theory says that people have innate coordination capabilities that are currently untapped because of poor UI design, and that better design may increase performance in handling interruptions. Malone and Crowston (1994), for example, said that such coordination is a central and ubiquitous human activity.

5. METHODS FOR COORDINATING INTERRUPTION

Latorella's IMSM identified five interruption-management behaviors suggest facets of UI support for coordinating interruptions. Oblivious dismissal and unintentional dismissal highlight the importance of exogenous attention cueing, and designing annunciation signals of appropriate salience. Intentional dismissal highlights the importance of embedding meaning (particularly priority information) in annunciation stimuli, and interface controls for placing an interruption "on hold." Preemptive integration, when the interruption is processed without reasoning that this is appropriate, requires support for resuming abruptly interrupted ongoing tasks, and indicates the need for reminders of both the need to resume and how to resume the interrupted task. Intentional integration, rational consideration of how to integrate performance of both interruption and interrupted task set, indicates the utility of scheduling support and support to evaluate effectiveness of, or develop, different integration plans. UI design solutions to coordinate interruptions determine when interruptions are presented to the user and what kind of control the user is given to deal with them. McFarlane's Taxonomy proposes four primary design solutions to coordinate user interruption: (a) *immediate interruption*, (b) *negotiated interruption*, (c) *mediated interruption*, and (d) *scheduled interruption* (or coordination by prearranged convention or explicit agreement). For example, a user may concurrently perform two tasks: (a) indirectly driving a car by supervising a robotic driver, and (b) conversing with another human passenger. Whenever the robot must initiate an interaction with its supervisor, it must first interrupt their conversation. An immediate solution would have the robot interrupt at any time in a way that insists that the supervisor immediately stop conversing and interact with it. A negotiated solution would have the robot announce its need to interrupt and then support a negotiation with its supervisor. This would give the human control over when to deal with the interruption. A mediated solution would have the robot indirectly interrupt and request interaction through the supervisor's personal digital assistant (PDA). The PDA would then determine when and how the robot would be allowed to interrupt. A scheduled solution would restrict the robot's interruption to a prearranged schedule, such as once every 15 min.

Driving errors are more serious than conversational errors. Therefore, a successful UI design for a robotic driver would ensure people's performance on the supervised driving task, regardless of side effects on other activities. It may be possible to guess that an immediate interruption solution would be best for this fictitious example. However, there is generally not enough design knowledge in the literature to determine which method of coordination would be best for specific work contexts, and different designers have very different intuitive answers. McFarlane (2002) empirically compared these four interruption coordination solutions for a dynamic, engaging desktop computer task. He found that negotiation was the best solution for all measures of user performance except where small differences in the timeliness of handling the interruptions is critical. In this case, the immediate solution is best.[7]

This section provides an interdisciplinary survey of literature on coordinating human interruption. The taxonomy of human interruption (McFarlane, 1997, 1998) provides a unifying framework for discussing the commonalties among works from diverse domains. McFarlane (1998, 1999, 2002) conducted a theory-based experiment to compare these methods of coordinating interruptions in a computer-based context. The results showed that differences in UI coordination solutions for human interruption caused large differences in user performance. The basic finding was that a negotiation-based method, which emphasized support for human control over the coordination process, was best for supporting all kinds of human performance, except where small differences in timeliness of handling interruption tasks were critical. The immediate solution produced the quickest reaction to interruption tasks. The results also identified other factors that impacted human performance, including individual differences in ability, perception of accountability for multitask success, perceived level of interruption/distraction, degree of predictability of occurrences of interruption, relative complexity of primary task at onset of interruption, and participant's degree of trust in their control over the multitask.

5.1. Immediate Interruption

Sometimes computer users cannot postpone handling interruptions but must handle them immediately. Many of the detrimental effects of interrupting people are related to people's difficulty resuming the original task after handling the interruption. Authors of HCI research have investigated UI design methods to support this error-prone activity. Ballas et al. (1992a, 1992b) discovered that UI design significantly affected people's ability to recover interrupted tasks in the airplane cockpit. When automated activities unexpectedly failed and users resumed a previously automated activity (externally backgrounded), they experienced a troublesome initial decrease in performance called *automation deficit.* Ballas et al. found that direct-manipulation design methods (low-semantic distance and direct engagement) allowed people to resume an externally backgrounded activity more successfully than text-based, indirect methods. Direct manipulation methods put meta-information into UIs in ways that allowed people to easily understand the structure and function of backgrounded activities (Shneiderman, 1992).

7. The experimental methods and results of this study are detailed in the other article in this issue (McFarlane, 2002).

The UI can be designed to present information about interrupted activity in ways that help people resume those activities more successfully than otherwise. One hypothesized approach relies on the benefits of rehearsal on memory retrieval; that is, if the user is warned before receiving the content of an interruption, then that person can cognitively rehearse the point of interruption in the ongoing task and more successfully resume it later after handling an interruption. Such mechanisms are proposed to help turn-taking dynamics in human communication (Duncan, 1972). Czerwinski, Chrisman, and Rudisill (1991) experimentally investigated this hypothesis. While warnings did improve performance, this improvement was not statistically significant. Their main finding was a strong negative relationship between task similarity and human performance. They speculated that warnings did not prove significantly useful because participants had not been told that they would be tested for recall, or perhaps because the size of delay used (30 sec) between warning and interruption was inappropriate. Czerwinski, Chrisman, and Schumacher (1991)[8] repeated the experiment but told participants that they would be tested for recall after interruption. They found that warnings had a significant positive effect. In fact, warnings largely mitigated the negative effect of task similarity.

Detweiler, Hess, and Phelps (1994) speculated that warnings may only be useful in high memory-load interruption tasks. In low load tasks, the user was able to interweave rehearsal of the pre-interruption task after switching to begin the interrupting task. Warning designs can include auditory signals and spoken messages (Latorella, 1996a; Nissen, 1974; Posner, Nissen, & Klein, 1976; Stanton, Booth, & Stammers, 1992), abrupt change in luminance (Müller & Rabbitt, 1989; Posner, Snyder, & Davidson, 1980), and proximity to current attentional focus (e.g., Posner et al., 1980).

Basic research in controlled psychological experiments has demonstrated the advantage of rehearsal on short-term memory retention (Peterson & Peterson, 1959) and of elaborative rehearsal on long-term memory recall (Wickens, 1984, pp. 232–233). Gille and Broadbent (1989) speculated that rehearsal may improve human performance when interrupted. This speculation arose as an explanation for experimental results that showed no interruption task-factor effects when rehearsal was possible but significant task-factor effects when rehearsal was prevented. Other experimental variables were changed in these two conditions, preventing convincing evidence of a rehearsal effect. Storch (1992) also suggested that the ability to rehearse when interrupted made a significant difference in how well interruptions were handled. Interruptions to a

8. The methodological details and full discussion of results for this experiment are described in another article in this issue of *HCI* (McFarlane, 2002).

data-entry task that were expressed as on-screen messages were significantly more disruptive than interruptions expressed as telephone calls or interruptions expressed as in-person human visitors. In fact, they found no distractive effect of telephone calls whatever. In the on-screen query condition, participants were forced to stop work immediately and begin doing the interruption task. However, in the telephone and walk-in conditions, participants had some control over when to stop the main task. The ringing phone may have been used as a warning support that afforded rehearsal. Participants could let the phone ring a few times while they mentally rehearsed the main task. The benefits of such warnings may only be significant when the interruptions are so absorbing that interleaved rehearsal is impossible (Detweiler et al., 1994), and the warning–interruption interval must be timed appropriately to encourage rehearsal (Czerwinski, Chrisman, & Rudisill, 1991).

Not leaving successful resumption to the frailties of human cognition, the Notepad program (Cypher, 1986) reminds users to resume interrupted activities by constantly displaying a list of interrupted activities. Lee (1992) found that expressing the active window with an animated border, instead of a static border, reduced the number of times people became confused about which window was active when resuming a task after an interruption.

Other studies have investigated the utility of embedding information into the UI to help people maintain awareness of the details of backgrounded tasks—the idea being that task resumption would be easier. Transparency is one design approach that can help users maintain awareness of backgrounded tasks (Harrison et al., 1995).

Gaver (1989) proposed that people gain important information from the sounds of backgrounded activities. For example, background sounds of a bottling factory floor were added to the Computer-Supported Cooperative Work (CSCW) team process-control system for a remote and distributed team (Gaver, Smith, & O'Shea, 1991). The previously unavailable factory sounds helped users maintain subconscious awareness of the various factory-control activities that they had externally backgrounded to floor workers. Robertson and others (Card & Robertson, 1996; Rao et al., 1995; Robertson, Card, & Mackinlay, 1993) successfully used peripheral information to help users maintain awareness of their location in information spaces by using spatial representations of informational relationships, for example, Cone Tree, Perspective Wall, Document Lens, Spiral Calendar, and the Hyperbolic Tree Browser. Awareness of location aids helped users to know when they had to resume the backgrounded activity of navigation. Shneiderman (1992) promoted embedding location structure into menus of windowing systems for similar navigational reasons.

Smith and Hudson (1995) found that audio information can be added to CSCW systems to help people maintain awareness of the interruptibility of other team members. This is an immediate-interruption design that helps people recover more easily from interruptions by allowing human interruptors to make intelligent decisions about when to interrupt their coworkers. Smith and Hudson's system allowed people to eavesdrop on filtered versions of coworkers conversations to determine others' interruptibility without invading their privacy. Coworkers' speech was automatically reduced to nonspeech signals that communicated only information about the speaker's tone of voice. This sound-based interface was less intrusive than similar video-based solutions for directly viewing coworkers to determine their interruptibility (e.g., Li & Mantei, 1992).

Gaver and Smith (1990) introduced action sounds (sonification of otherwise noiseless computer-based activities) into the CSCW system Shared ARK for shared virtual environments. Users could hear sounds associated with their own and everyone else's actions. Users found this useful for staying aware of each other's activities and for locating people within the information space. Pedersen and Sokoler (1997) combined the CSCW group awareness ideas of video and audio access of team-member activities with sonification. Privacy was maintained by presenting only an abstraction of other team members' physical and computer-based activities. Users saw each other as abstract images doing abstract things. Pedersen and Sokoler found that this was useful, but they said that building a natural and extensive abstract, semantic language for activity was beyond the scope of their article.

The way the interruption is presented can affect its level of perceived disruptiveness. Spatial location can also be an important design choice for the UIs of interruption tasks. Osgood et al. (1988) compared interfaces that interrupted users with a set of numbers during a tracking task. People performed better when the interruption was expressed as a rapid display of numbers in the same location than when the interruption information was displayed at the same time but spatially distributed on the screen.

Davies, Findlay, and Lambert (1989) discussed the merits of different UI designs for interrupting people with reminders of background and suspended activities. Reminders help people recover from interruptions by reminding them of the existence and sometimes the details of previously interrupted activities. Davies et al. applied theories of cognitive psychology and cognitive modeling to propose four categories of designs for reminders: *normal switch*, *minimum switch*, *micro-switch*, and *information at the fixation point*. These categories represented four different UI designs for reminders that required users to exert different cognitive efforts to get state information about interrupted tasks. The designs differed as to where the state information of the interrupted activity was available: (a) normal switch-off screen, (b) minimum switch-on screen but not in user's central viewing location, (c) micro-switch-on screen and in the user's peripheral vision in a way that did not require eye movement to get the state information, and (d) information at the fixation point and on screen at the user's current eye fixation point. Davies et al. concluded that the inclusion of reminders was a useful design method for recovering from interruption. They also found support for their proposed categories by showing that people could more easily maintain awareness of the editing mode of a word processor when the mode information was conveyed by the cursor shape (information at the fixation point design) instead of in a separate window (minimum switch design).

From the previous studies, it seems that the best way to help users recover from interruption is to design the UI to constantly present obvious reminders about the existence and state of interrupted activities. However, the constant portrayal of information about interrupted tasks can negatively affect people's performance on their foregrounded activities. Noy (1989) found that providing auxiliary displays for navigation-like secondary tasks in an automobile simulator caused degradation in people's performance on the driving task. Nakagawa, Machii, Kato, and Souya (1993) found that monitoring the computer's handwriting recognition of live pen-based handwriting was a separate activity that distracted users and negatively affected their performance on pen-based interfaces.

One approach that does not depend on loading the display with information about backgrounded and suspended activities is to include tools that help users quickly review the state of an interrupted activity when attempting to resume it. Field (1987) compared two different UI tools that allowed people to review their interaction histories when resuming previously interrupted computer-based activities. Field presented some weak evidence that people can resume their primary task more easily after an interruption, if they are provided with a selective retreat tool and not a restrictive retreat tool. A selective retreat tool allows users to quickly see a complete history of their previous interaction with the information system. A person can use this tool when they try to resume a previously interrupted task by reviewing their interaction history, and retreating, or jumping back to any of their previous contexts. The less powerful, restrictive retreat tool does not show people their interaction context, and it only allows them to retreat, or jump back to the previous context, or go to the main menu.

Malin et al. (1991) said that the UI should be designed to reorient users to previously interrupted activities when they try to resume them. If interruptions come from noncomputer sources, the machine is not necessarily able to detect when the interrupt happens. Malin et al. presented a design that specifically allowed users to suspend and resume activities. Users can explicitly mark the occurrence of interruptions. The computer can then generate appropriate recovery support. Malin et al. also presented a useful design that allowed users to orient themselves to the current state of the system when they took over a task from a previous user. A simple log of relevant, recent decisions was made easily available. This same design could be used to aid users in recovering from interruption. Rouncefield et al. (1994) also found marking to be a useful strategy for aiding resumption of tasks after interruption. When people in paper-based office environments received interruptions, they physically marked their work context before leaving it to handle the interruptions. These markers, then, facilitated recovery of prior work context when people returned to their prior tasks after handling interruptions.

5.2. Negotiated Interruption

Clark (1996) said that people normally negotiate human–human interruptions. Unlike the immediate-interruption method of coordinating interruption, people usually have choices of whether to allow interruptions and how and when to handle them. Clark said that in normal human–human language usage people have four possible responses to interruption: (a) take-up with full compliance, (b) take-up with alteration, (c) decline, or (d) withdraw (Clark, 1996, pp. 203–205, 331–334). It is useful to design UIs in ways that take advantage of people's innate ability to negotiate interruptions. An external entity that initiates an external interruption may do so in a way that gives the user control. The interface could afford the user four options of when or whether to handle the interruption: (a) handle it immediately (take-up with full compliance), (b) acknowledge it and agree to handle it later (take-up with alteration), (c) explicitly refuse to handle it (decline), or (d) implicitly refuse to handle it by ignoring it (withdraw).

Woods (1995) proposed that people have a natural ability to manage their own attention. While people concentrate on a single task with focused attention, they can also simultaneously process a huge amount of information about other peripheral events. This parallel processing happens quite subconsciously to the performance of the focused task, and people can accomplish it easily and naturally without significant negative effects on performance of the focused task under certain circumstances. Woods described how people use the information they process about peripheral tasks to effectively guide their focus of attention between competing tasks. If UIs could be designed to deliver subtle continuous information about background tasks, Woods argued that users could easily handle their own attention switching better than a computer. Woods asserted that alerts should be delivered in subtle ways that exploit users' natural power to schedule their own attention.

Wickens and his colleagues (Raby & Wickens, 1990, 1991; Raby, Wickens, & Marsh, 1990; Sega & Wickens, 1990, 1991) found that pilots naturally manage their own attention among the competing demands in multitasking situations. These experienced aircraft pilots were aware of their own level of workload and dynamically allocated attention to flight tasks, depending on their workload and task priority level. When workload was high, they spent a higher proportion of their time attending to the high-priority components of the piloting multitask than to the low-priority components. Humans were able to accomplish this complex scheduling while simultaneously performing a difficult multitask.

There are useful examples from commercial applications that support rudimentary negotiation of user interruptions. Several e-mail applications give users some level of control over when to read their incoming e-mail messages. For example, when a new e-mail message arrives, the program can get the user's attention by interrupting them with a signal notification, like a beep and a modeless dialogue box. The user then can decide to immediately allow the interruption or handle it later.

One design approach is to present user interruptions in ways that allow people to ignore them, if they choose. Lieberman (1997) implemented a version of this design in the Letizia autonomous interface agent. Letizia is an aid that runs in the background, and makes recommendations of possibly related web pages to its user while the user browses the web. Letizia's interruptions do not directly interfere with users' web browsing activity. Instead, users are left to pursue their browsing activity with a normal browsing tool (i.e., Netscape), and the Letizia agent displays its suggestions in a separate but visible window. Letizia automatically loads web pages that it decides may be of interest to the user. Because these automatically loaded pages are displayed in a visible window, the user must see those changes in their peripheral vision. When Letizia initiates one of these interruptions, users have a choice of four possible responses: (a) look at the Letizia window and decide to immediately read that page, (b) look at the Letizia window and decide to later read that page, (c) look at the Letizia window and decide not to read that page, or (d) ignore the Letizia window.

Oberg and Notkin (1992) investigated a similar design for interrupting users with error reports in a computer-programming environment. Oberg and Notkin generated a Pascal editor with a dynamic code debugger that ran in the background. While people used the computer to edit their computer program, the debugger continuously ran in the background. Whenever the debugger detected a programming error, it interjected an error message within the code near the user's cursor position. Oberg and Notkin specifically chose a UI design that gave users control over when or whether to address these interruptions. They created an interface that did not interfere with the coding activity, but instead used color to notify users of the locations of existing errors. The interface represented the age of existing errors by increasing the saturations of the text color over time. The notification marker for "important" errors got darker more quickly than those for "less important" errors.

This error coding alerted users to the existence of errors, but did it in an unobtrusive way so they had control over when and whether to handle these interruptions. Oberg and Notkin did not formally compare their unobtrusive design with other more disruptive alternatives; however, they said that their anecdotal evidence endorses its usefulness.

Any design solution that implements the negotiated interruption method for coordinating user interruptions must have a mechanism for getting users' attention while they attend some other activity. Users must be notified of incoming interruptions, so they can control when or whether to handle them. People's attentional focus is vulnerable to certain kinds of stimuli (Müller & Rabbitt, 1989). Shneiderman (1992) said, "Since substantial information may be presented to users for the normal performance of their work, exceptional conditions or time-dependent information must be presented so as to attract attention" (pp. 80–81). He presented the following techniques for getting users' attention: *intensity, marking, size, choice of fonts, inverse video, blinking, color, color blinking*, and *audio*. Preece et al. (1994, pp. 100–108) also presented guidelines for how to solve UI design for attacting users' attention. They said that the results of psychological studies of human perceptual grouping of spatial and temporal cues can be used to direct human attention. These cues include color, graphical flashing, reverse video, and auditory warnings. Visual movement within people's peripheral vision has also been found to be an effective attention-getting technique. Ware, Bonner, Knight, and Cater (1992) found an inverse relationship between the velocity of moving iconic interruptions and people's response time in detecting and handling them.

Rich (1996) investigated the utility of using a moving hand-shaped icon as an attention-getting technique for interaction with an intelligent agent. In one version of the agent interface, the agent did not interfere with the user, but waved its hand to get the user's attention. This gave the user control over when or whether to pursue the agent's interruption. A person's attention is also susceptible to another's eye gaze, that is, people looking at each other. Kendon (1967) said that gaze direction is one of the principle signals by which people manage interruption in human–human communication. For social reasons, people are predisposed to attend to any occurrence of another person looking at them.

Although it is useful to give users control over when and whether to handle interruptions, it is not a complete solution to the interruption-management problem. One effect of interruption is to disrupt people's memories of the details of pre-interruption tasks. It may seem reasonable to hypothesize that this negative effect is caused by people being caught off guard and beginning the interruption task without first rehearsing information associated with the pre-interruption activity, which is critical to its successful resumption after interruption. If this hypothesis were justifiable, then a negotiation design solution would successfully avoid this negative effect of interruption. However, this hypothesis has not yet been empirically supported. Gillie and Broadbent (1989) found that allowing users to review their foregrounded activity previous to handling interruptions did not necessarily help them recover that activity after interruptions. They observed that the disruptive effects of interruption on people's memories were not caused solely by people's inability to rehearse their memories before handling interruption. Other factors, like task complexity and similarity, also affected people's ability to resume interrupted tasks.

Katz (1995) found that negotiation design solutions have disadvantages and that users can sometimes prefer immediate-interruption UI designs. He compared two different interfaces for a kind of telephone Call Waiting termed *Caller ID on Call Waiting* (CIDCW). When a person is talking on the phone, CIDCW gives them information not only of the existence of incoming calls but also of the new caller's name and phone number. Katz conducted an experiment that compared two different UI designs for the CIDCW system: (a) automatic interruption—an immediate interruption solution, and (b) user-controlled—a negotiated interruption solution. The automatic interruption interface caused an immediate break of what the user could hear. A beep and then the information of the new caller (1.1 sec) occluded what the conversant could hear, then the system restored the audio connection and conversation resumed. The original conversant was unaware that a break had occurred. The user-controlled interruption interface announced the existence of a new call with a beep, and then the user had to press a button to hear the caller ID information. Katz found that participants preferred the automatic interruption interface threefold over the user-controlled interface. The participants said that the user-controlled interface was much more disruptive of their telephone conversation than the automatic interface.

Katz said that the automatic interface and the user-controlled interface design solutions for CIDCW systems have advantages and disadvantages. The advantages of the automatic interface are (a) users do not need to take any action to receive caller ID data, (b) users do not have to learn anything new to use the interface, and (c) users do not have to formally break their conversations, and excuse themselves to get the caller ID information. However, the automatic interface has two disadvantages: (a) people's conversations can be unexpectedly suspended for a second, and (b) people know that they could be interrupted at any time, regardless of what they are saying. The user-controlled interface has the advantage of not unexpectedly blanking out chunks of people's conversations or causing uncertainty in users' expectations. However, the user-controlled interface has the following disadvantages: (a) users might need to formally break their conversation to hear the caller ID information, (b) users have to learn a new interface, and (c) users have to take specific action, and might postpone it so long that the new caller tires of waiting and hangs up.

5.3. Mediated Interruption

The White House Communications Agency (WHCA) provides the president of the United States (and associates) the capability to make public speeches anywhere. There is a critical human-interruption problem that can affect WHCA's ability to successfully announce the president and other dignitaries at these public meetings. The WHCA uses a mediator to solve this problem. Whenever the president schedules a public speech, the WHCA sends a team in advance to prepare the site. They must set up a public-address system or contract for one locally, arrange the president's special podium and teleprompter, and prepare a ready communication link out. One WHCA team member is designated to sit in a van out of sight and announce the president and the other VIPs. The introduction must be done right the first time, because the professionalism of the introduction sets the stage for how the president will be received. The WHCA team plays "Hail to the Chief" (from a CD), and then the announcer says, "Ladies and Gentlemen, the president of the United States of America, George Bush; … the queen of Flagmanistan, Jane Janga Yyptemshep; … Senator Henry Joyce Jones from Virginia." If the announcer stammers or mispronounces an important name or fails to include someone, it could anger the audience or make the president look unprofessional.

The WHCA team is in place and ready at the airport speech site before the president arrives. The WHCA announcer has a prepared introduction card to read. However, when Air Force One actually lands, mad chaos often begins. The planned introduction must be immediately changed or amended to accommodate last-minute changes to the list of attendees and lots of aids and dignitaries come swarming over the WHCA announcer trying to give important new instructions. WHCA has solved this problem by assigning another team member to mediate between the chaos and the announcer. The mediator allows the announcer to concentrate while still being accessible for last-minute changes in a controlled way (Personal communication, WHCA, March 22, 1996).

Adding a mediator to the UI increases the separation between the human and the task and is not always a good solution for an interruption problem. Delegating the interruption problem to a mediator begets a new task of supervising the mediator. Kirlik (1993) observed that the costs of delegating a task to a task-offload aid (like a mediator) can sometimes outweigh the benefits. It is possible for a poorly designed mediator to be more disruptive than the interruptions they broker.

Most research on computer-based mediators in the current literature tries to find ways to reduce the supervision costs by increasing the mediator's ability to automatically accommodate people's cognitive limitations. Five main approaches are (a) predict people's interruptibility, and use the results to intelligently time interruptions; (b) investigate new UI methodologies for supervision; (c) automatically calculate users' cognitive workload, and use the results for dynamic task allocation; (d) categorize different human and computer abilities, and design supervisory control systems that exploit the different abilities of each; and (e) build and use a cognitive model, and use the results to guide UI design process.

Predicting Interruptibility

People's degree of interruptibility, or their vulnerability to the distraction effect of interruption annunciation signals, dynamically changes and is dependent on conditions of the person, their multitask, and the context. Miyata and Norman (1986) have identified several useful factors of human behavior that can be used to predict people's interruptibility: task dependency, relative priority, activity stages, user-specified interruptibility, and the difference between notification and description for reminding people of backgrounded activities. Related tasks in a multitask often have dependencies. If the computer can mirror the user's activities with a task model, then it can automatically determine when a backgrounded activity will be needed within the context of the foregrounded activity. Activities in a multitask may have different importance, and the relative importance of the interruption task and the foregrounded task can be used to quantify users' interruptibility. People's activities can be decomposed into stages relative to human cognition (Norman, 1986). People's interruptibility changes depending on the stage of their foregrounded activity. For example, people are more interruptible at the point where they transition between the last stage (evaluation) and the formation of a new goal or intention (Miyata & Norman, 1986, p. 278). Interruption initiation time was significantly longer when interruptions occurred between activities within a task, than when they occurred either between tasks or outside the task set (prior to starting or after ending the procedure; Latorella 1996b, 1998). People have a meta-cognitive awareness of their own interruptibility. This is why they sometimes turn off sources of interruption by shutting office doors, turning off telephones, or putting up "do not disturb" signs. There is a useful distinction between notification and description for reminding people of a backgrounded activity. People are more interruptible for a brief signal that announces the existence of an interruption than they are for the full interruption itself.

Czerwinski, Cutrell, and Horvitz (2000a, 2000b) found that the points between tasks or subtasks indicated optimal interruptibility, that is, that the degree of disruption on performance efficiency depended on the specific point in a task that an interruption was presented. They investigated the harmful effects of interruptions relative to those caused by Internet instant messaging. Instant messaging is like a phone call with another person, but the interaction is handled through a text channel. People initiate conversations with others by interrupting them with text messages that are delivered directly and not queued like e-mail. Czerwinski, Cutrell, and Horvitz (2000a, 2000b) concluded that the best UI design solution for human interruption exploited the utility of timing interruptions to coincide with people's natural task completions. They suggested that interruptions not be delivered immediately but be queued and delivered when the user was switching tasks. An interruption mediator would have to constantly observe user actions and be able to automatically determine when the people were between meaningful tasks or subtasks.

HCI for Supervision

Novel UI methods can support people conducting mixed-initiative interactions with their computer systems, including handling interruptions. Intelligent UI technologies, like intelligent interface agents, can provide representations of the computer "helpers" that give people a convenient way to interact with the system that is interrupting them (Chignell & Hancock, 1988; Lieberman, 1997). One example is a telephone-receptionist agent with an expert system to mediate all of a person's telephone calls (Gifford & Turock, 1992). The agent makes it so a user only has one telephone number, and is accessible anytime anywhere on that one number. People sometimes use telephone answering machines or caller-ID boxes as dumb versions of this kind of telephone mediation (Sullivan, 1993). A straightforward use of this kind of mediation is for a user to allow the answering machine to record their messages when they are away from their telephone. However, people also use these mediators to screen their calls when they are present, but unwilling to be interrupted except by specific people or topics.

Bannon (1986) said that people know how to give subtle signals of their interruptibility, for example, varying positions of a person's office door, and that this ability should be exploited for the design of systems that must interrupt people. Bannon investigated the "talk" facility in terminal-to-terminal communication in computer-mediated communication, and discovered that this technology is a potential source of interruption. While a user is typing a message, talk messages can intrude unexpectedly and interrupt. This is poor UI design.

Cognitive Workload and Dynamic Task/Function Allocation

Automatic cognitive-workload assessment (Gopher & Donchin, 1986; O'Donnell & Eggemeier, 1986) is another approach to reduce mediation costs. Authors who use the concept of workload ascribe to the idea that human brains are just another kind of machine and that the load on this machine can be measured. In studies of workload, people are often viewed as a kind of component (man in the loop) to be used in constructing important systems. Berger, Kamoun, and Millot (1988) proposed a measure of workload to be used to dynamically change automated assistance on continuous control tasks. Bergeron (1968) investigated the measurement of workload on tasks similar to piloting a lunar lander. Kuperman and Perez (1988) analyzed a team system for Air Force bomber missions, and used workload measurements to identify crew task choke points. The workload measure can be used to dynamically allocate decision tasks between a human decision-maker and computer-based, intelligent decision-maker. When the user has a light workload, then all decisions are allocated to them, but when they become overloaded, then a computer-based decision-maker is invoked and begins taking over some of the person's decision-making responsibilities. Authors base their dynamic allocation on different allocation theories: queuing (Chu & Rouse, 1979; Rouse, 1977; Walden & Rouse, 1978) and optimal control (Millot & Kamoun, 1988). Mouloua, Parasuraman, and Molloy (1993) found that adaptive-function allocation improved people's ability to monitor for system failures in simulated airplane flights.

Cook, Corbridge, Morgan, and Turpin (1999) said "Dynamic function allocation (DFA) refers to the variable distribution of functions in real time between the system and the operator(s) to achieve optimal system performance" (p. 388). They identify two main approaches for implementing DFA capability: (a) *implicit* DFA, where the computer dynamically distributes functions among people and computers; and (b) *explicit* DFA, where the human operator(s) themselves dynamically decide whether they or their computers will perform the required functions. (Note: UI support for *explicit* DFA is a negotiation-based coordination solution.)

Human Factors for Supervisory Control

Computers are sometimes built to control physical processes that people cannot or should not control directly. When such a system controls an important process, it is typically supervised by a person to ensure success. These systems support supervisory control (Moray, 1986; Sheridan, 1987), and embody a kind of mediation in which the computer serves as a mediator between a person and the physical world. Sheridan (1988) categorized human functions (human supervisory activities), and proposed that these categories be used to discover the human-attention requirements of the different supervisory activities.

Cognitive Modeling for Mediation

If a computer could magically know everything about what a user has, is, and will do, then it could always interrupt the user when and how they would best want to be interrupted. If such a system could be built, then the mediator would become invisible and require no user supervision, like in ubiquitous computing (Preece et al., 1994, pp. 149–151). This is an attractive and popular solution concept, and the literature reports on several applied models of human cognition for use in dynamic management of UIs for systems that support user multitasking. The Pilot's Associate program is a good example (Hammer & Small, 1995). Its designers incorporated applied user models and task models to try to automatically infer user intentions in the multitask of a tactical mission for a military, single-seat aircraft. Once the Pilot's Associate had predicted what the pilot would want next, it would interrupt the pilot with appropriate information and activities. Attempts to build such a system have not been adequately successful, because of the difficulty of accurately inferring users' intentions even within this limited task domain. Funk and Braune's (1999) Agenda Manager is a more recent implementation of this philosophy to manage flightdeck tasks.

Authors have applied several theoretical domains to human cognitive modeling. Some approaches emphasize that the human brain is an information-processing machine (Card, Moran, & Newell, 1983). Schweickert and Boggs (1984) investigated the utility of modern variants of the single-channel theory from computer science. Forester (1986) examined the usefulness of a multiple-resource model of human-information processing. Soulsby (1989) evaluated the utility of control theory and estimation techniques. Some approaches postulate that human cognition uses rational mechanisms and, therefore, other rational models can be generalized to modeling people; for example, Navon and Gopher (1979) investigated the utility of economic theories of resource allocation. The COGnition as a NEtwork of Tasks (COGNET) model is based on a network of local goals or tasks that the person must pursue (Ryder & Zachary, 1991; Zachary & Ross, 1991). COGNET has been applied to military multitask UI domains: anti-submarine warfare (Weiland, Cooke, & Peterson, 1992; Zachary, Zubritzky, & Glenn, 1988; Zubritzky, Zachary, & Ryder, 1989) and anti-air warfare (Zachary, Zaklad, Hicinbothom, Ryder, & Purcell, 1993). Other authors have created models of human attention to investigate UI design for user multitasks: managing supervisory control multitasks (Enstrom & Rouse, 1977; Pattipati, Kleinman, &

Ephrath, 1983; Tulga & Sheridan, 1980) and monitoring graphically displayed information (Senders, 1964).

With so many different modeling approaches from which to choose, it would be very useful to have some guidelines on how to evaluate competing models. Wickens, Larish, and Contorer (1989) evaluated the relative utility of five different cognitive models for predicting multitasking performance in a helicopter. The five models were as follows: Human Operator Simulator (HOS, v4.0), PROCRU, WINDEX, task network, and Wickens' multiple resource. Wickens said that the coding of demand level—how task performance is affected by the performance of other active tasks—was the most important question for evaluating the utility of competing models.

Interruption by Proxy

One interesting idea for mediation that has not been applied to UI design is that of interruption by proxy. Salter (1988) described a method to extract information from human experts for building expert systems. A human expert's knowledge can be recorded covertly with a version of interruption analysis. An expert is observed doing what they do best. In normal interruption analysis, the investigator interrupts the expert whenever the expert makes a significant decision, and the interviewer asks them about the details of that decision. However, interrupting experts has the detrimental side effect of stopping them from their normal operations. The researcher can avoid this by getting a second proxy expert. A second expert in the same field observes the first expert with the investigator. Whenever the investigator needs to interrupt the first expert to get information, they instead interrupt the proxy expert, and the proxy explains the decision processes of the first expert.

WHCA uses a form of interruption by proxy for controlling the teleprompter while the president is speaking. When the president gives a speech, he concurrently performs at least two activities: He delivers a speech (an external, foregrounded activity) and he reads the next part of the speech from the teleprompter (an internal, backgrounded activity). In addition, someone must also manually scroll the teleprompter. The president's first two concurrent activities are so demanding that he does not participate in the scrolling activity. The WHCA totally automates the scrolling task without interaction from the president. Once he begins speaking; they cannot interrupt him, and he cannot give them directions. The WHCA solution is for one of their team members to pretend to be the president, a proxy president, and try to scroll the teleprompter live as the real president gives his speech. Being the proxy president is a very difficult job for several reasons: (a) typically, the WHCA does not get the speech from the president's staff until within 15 min of its delivery; (b) there are several technical problems involved in preparing the teleprompter; (c) the president dynamically changes his rate of delivery and often makes unannounced deviations from the prepared text; (d) the teleprompter control system allows the WHCA team to only see what the president is seeing; (e) and the WHCA teleprompter controller is not in the same room with the president. The WHCA solution saves the president from being interrupted with the scrolling activity; however, speech time is high-stress time for the WHCA. One WHCA team member is the proxy president, and several other team members huddle about the proxy to help with the task of anticipating what the president will want to see next (Personal communication, WHCA, March 22, 1996).

There is at least one implementation problem blocking this design solution for coordinating user interruptions by computer: A computer-based proxy would have to be constructed with the capability to stand in for the human when they are busy. Artificial intelligence (AI) technology is not currently good enough to deliver a proxy that can stand in for a person in a general way. The proxy solution would only make sense for well contructed and highly predictable tasks that an AI application could do reliably.

5.4. Scheduled Interruption

If people could know the when-what-where-why-and-how of incoming interruptions, they could plan their other activities to minimize the negative effects of interruptions. However, to be able to know about interruptions before they happen, people would need some control over the initiation of those interruptions. Expert users can develop sophisticated dynamic models of their tasks and task environment, and they can begin to develop contextually defined expectations for the type and timing of externally induced tasks interruptions. To the extent that users have such a model, these externally induced tasks become less interrupting (immediate, mediated, or negotiated), and become more scheduled tasks. The UI design solution of scheduled interruption can provide users with the ability to transform some future interruptions into planned interrupting activities by giving them a kind of prearranged control over when the interruption are initiated.

One form of this control comes from studies of time management for organizational management of people's work time. Hall and Hursch (1982) found that time-management training had a large and significant effect on participants' ability to spend more time each day performing high-priority tasks. Applying the time-management techniques allowed people to avoid being constantly taken away from high-priority activities and the negative effect of interruption. Before training, one participant, a university physicist, complained that he had no time for his high-priority activities because of constant interruptions by his students working in a nearby lab. Hall and Hursch observed that this participant's average time spent on high-priority activities increased from 28 min a day to 2 hr 19 min a day following the time-management training; the experiment ran 8 weeks. The participant successfully applied the time-management technique of creating a daily schedule that indicated his interruptibility during different time periods in the day. He posted this schedule on his door and scheduled rules for conventional interruptions with his students, although these rules had to remain somewhat flexible, because of his need to participate in students' ongoing research. For example, his schedule indicated that 8 a.m. to 10 a.m. was for high-priority activity and 5-sec interruptions would be allowed; 10 a.m. to 12 p.m. was for quick problems and interruptions of 5 min or less would be allowed; 1 p.m. to 3 p.m. was time open for meetings on demand; and 3 p.m. to 5 p.m. was time for completing tasks and no interruption would be allowed. Other time-management professionals also promote the usefulness of this technique of scheduling dedicated time each day for performing high-priority activities (Covey, 1989; Des Jardins, 1998). They found it useful for people to plan and announce their pre-coordinated schedule for interruptibility. This technique can automatically change some kinds of would-be interruptions into ordinary planned activities.

Clark (1996) said that people are very familiar with two useful kinds of scheduling techniques for normal human–human activities: *explicit agreement* and *convention*. Explicit agreement is a technique that people use to prearrange the coordination of a one-time event, like a meeting for lunch at a particular restaurant on a particular day and time. Convention is a technique that people use to prearrange the coordination of a recurring event, like a group meeting that happens in the same place and time every week. Similarly, interrupting tasks can be explicitly handled according to a rule set, with the default condition having been defined by some convention. These familiar and useful methods for coordinating interruptions should be useful for solving some HCI design problems for user-interruption.

"Constant interruptions" are another form of scheduled work solution. If a person knows that they will receive a constant, unending, stream of interruptions, then none of these interruptions are a surprise. And none of the interruptions interfere with other work in unexpected ways. Rouncefield et al. (1994) found in one office environment that there were times of day and week that staff could reliably anticipate constant interruptions. Rouncefield et al. said, "Predictable interruptions interfered less with the work because a set of finely differentiated expectations had developed about the likely time taken to complete a task, or whether it could be completed without interruption" (p.281).

Formal literature on scheduling theory focuses on schedule optimization (French, 1982), and is typically applied to job sequencing and machine assignment in manufacturing assemblies (e.g., Sadowski & Medeiros, 1982). This literature is not generally concerned with the utility of providing users with predictable work events; however, it can be used to build UI support that does increase such predictability. Scheduling theory provides a normative model of task management (Moray & Hart, 1990) and may be extended to a normative model for intentional integration of interruption (Latorella, 1996b, 1998).

6. DESIGN DISCUSSION

There are five basic strategies to improve human performance on an interrupt-laden multitask: (a and b) *training* and *incentives* (Dismukes, Young, & Sumwalt, 1998; Hess & Detweiler, 1994; Linde & Goguen, 1987); (c) *personnel selection* (Joslyn, 1995; Joslyn & Hunt, 1998); (d) *completely replace person with automation*; and (e) *design HCI support.* Figure 4 summarizes specific interventions related to these fundamental approaches for improving human–system performance.

It can be debated which of the five approaches is most valuable. In real-world work contexts, however, leaders usually take a multipronged approach to improving interruption management. This is true in the aforementioned Aegis example. Navy leaders are already working to

1. Train Aegis operators in simulation and operational exercises with expert human tutors.
2. Promote operators who perform well to higher grades and pay.
3. Select people for jobs based on observed capabilities.
4. Introduce technological improvements to automate all functions that do not require human authority or decision-making.
5. Develop improved UIs to support future human operator requirements.

UI design has the most potential for improving human performance. The potential utility of training, incentives, and personnel selection are limited because human cognitive capabilities do not change. The utility of automation is also bounded by human cognitive capabilities, because these limitations restrict people's capacities for monitoring and providing supervisory control of such systems and for delivering accountability for actions. Further, poorly designed automation, that which does not consider possible environmental conditions, may fail in an ungraceful manner (Norman, 1986), thrusting the human operator into control without having been aware of ongoing processes. Human supervisory control and authority remain important to the extent that automation for a particular context cannot or does not fully embody important environmental conditionals.

Figure 4. **Approaches for solving performance problems caused by human interruption.**

Approach	Pros	Cons
Training	• Potential for measurable improvement	• Can be very expensive • Effectiveness is heavily dependent on training design and delivery • Doesn't produce consistent results across different people
Incentives	• Relatively easy to administer • Can cause quick improvements	• Unreliable effects • Potential to distract people from the real objectives • Can change the perceived meaning of work • Incentives may be difficult to design appropriately • Effectiveness degrades over time and incentives must be continually increased to remain effective motivators
Personnel selection	• Minimize variance in performance across different people performing the same task • Improve performance by selecting only those people least likely to make errors	• Can be extremely difficult to construct a valid and reliable predictive measure • Potential for work hiring discrimination issues especially if the predictive test tends to favor members of particular racial, ethnic, or cultural groups • Implementing a selection policy can have important effects on the work culture and work attitudes of team members • There are potential ethical, legal, and labor union issues in implementing a selection test in an already existing workforce

Completely replace person with automation	• Can be ideal if it is appropriate and actually works	• Many kinds of human tasks are inappropriate and unethical to delegate to automation because computers can not be accountable for failure
	• Upgradable	• Automation has to be supervised and that's a new task for some person • Automation has its own reliability problems • For team tasks, replacing a person can affect the capability of the rest of the team
Design HCI support	• Directly supports people as they actually work on real tasks	• Can be very expensive and complicated to develop and implement in a work context
	• Can prevent errors and increase effectiveness at the actual time and work context where this help is needed	• Can have validity and reliability problems associated with any kind of computer system
	• Consistent and continual presence of support	• May introduce meta-work for the user to manage the tool itself (Kirschenbaum et al., 1996)
	• Upgradable	• Can be difficult to design well and poor HCI design can actually degrade performance
	• Human retains necessary authority and accountability for success	• Support solutions may not scale well as tasks evolve over time
	• Potential to engage various kinds of people's vast innate cognitive processing that would not have been invoked otherwise	• May include hardware requirements that are not already present in the work place (Brown & Levinson, 1987)
	• Can improve the users perception of their responsibilities and attitude toward work	

Navy operational experts and system developers have identified UI design as the most promising intervention to improve overall performance in the Aegis system. Therefore, the remainder of this article focuses on methods for improving interruption management through UI design.

The IMSM defines stages of managing an interruption as detection, interpretation, integration, and resumption of the ongoing activity (Latorella 1996a, 1998). The following design discussion explores the nature and proposed utility of computer-based support for these phases to achieve *interrupt resilient* (Latorella, 1996a, 1998) interfaces, that is, interfaces that gracefully allow the integration of interruptions and resumption of ongoing activities as appropriate to the optimal prioritization of these tasks. It is important at this point to recall the form of an interruption defined for this model (Section 4.1); an interruption is composed of an annunciation stimulus and an interrupting task.

6.1. The Three Phases of Human Interruption

IMSM leads to the identification of three phases of human interruption relative to the requirement that a person must switch from their current task to the interruption task and then back. The three phases are (a) *before switch,* (b) *during switch*, and (c) *after switch.* Before switch is what happens before the user starts working on the interruption task. During switch is what happens while the user addresses the interruption. After switch is what happens after the user finishes adressing the interruption and resumes the previous task. The following three subsections describe the objectives of UI support for each phase and identify potential UI design approaches. Tables in each section identify specific UI support ideas suggested by Latorella's IMSM and McFarlane's definition and taxonomy of human interruption.

6.2. UI Support for the Before Switch Phase

The objective of UI support for the before switch phase is to make sure people are interrupted the best possible way to ensure overall task success. A primary method for minimizing diversion caused by interruption is to increase the predictability of the interruption. This can be done with visualization–sonification support for increased situational awareness of backgrounded tasks (those that might cause interruptions) and visible clocks and countdown timers where appropriate. UI support should facilitate appropriate communication for interruption announcements by intelligently matching the salience of interruption annunciation to the importance of the interruption relative to the user's overall task objectives. Warnings can be delivered to allow users to implement cognitive memory strategies, like rehearsal, for easier recovery and resumption after interruption. The UI should deliver the appropriate kind, or mix of kinds, of interruption coordination support. This should include negotiation support as central to any solution that includes human accountability for task success. Intelligent determination of coordination solution depends on dynamically changing information about the work context. Domain-specific task modeling (e.g., Funk & Braune, 1999) can identify relative prioritization of the interrupting and ongoing tasks. UI support should also facilitate integration of the interruption task into the ensemble task set, while minimizing disturbance of the ongoing task set (Figure 5).

6.3. UI Support for the During Switch Phase

The objective of UI support during an interruption is maximize the overall performance on both interrupting and interrupted tasks. Support can take the form of thread-tracking software, such as smart checklists, to ensure that all activities of an initiated task are completed, or the user explicitly communicates incomplete termination of the task. Presentation of these registers would improve situation awareness of the state of all tasks under a user's responsibility. This is particularly important when a user has delegated completion of a task to an automated agent or a fellow human operator. UI controls should facilitate easy switching between tasks and explicit markers of progress on individual tasks and toward system level goals (Figure 6).

6.4. UI Support for the After Switch Phase

The objective of UI support for the post-interruption interval is to facilitate resumption of interrupted tasks and minimize the disruption caused by the interruption. Good support during the before switch phase can make this much easier. Recovery support can include reminders and replay capabilities (Figure 7).

7. CONCLUSION

This article identified why human interruption is an important HCI problem, and why it will continue to grow in ubiquity and importance. Scientific research and observations from a variety of disciplines indicated that humans are prone to interruption, and are error-prone in these circumstances. We have reviewed specific examples of this problem in complex systems, and indicated the breadth of applications to which the general problem of interruption management applies. Further, incident and accident studies provide evidence that the consequences of poor handling of interruption can have catastrophic results. We reviewed existing guidance for recommending spe-

Figure 5. **UI support for the before switch phase.**

Process model–interruption management stage model

- Facilitate appropriate exogenous cueing to interruption by designing annunciation stimulus salience commensurate with relative importance/urgency of interrupting task.
- Mininmize deleterious effects by announcing interruptions at cognitively appropriate points (e.g., between tasks rather than between activities) in an ongoing task set.
- Minimize deleterious effects by designing modalities of interruption annunciations in consideration of interrupted task modality.

Design space–definition and taxonomy of human interruption–coordination

Immediate	Semantically loaded warnings, brief delay to allow cognitive preparation, contextual bookmarking, multimodal interaction redundancy, maximize predictability of interruption. Explicitly mark task context where interrupted.
Negotiated	Maximize efficiency of user control in negotiating interruption by supporting (a) instant communication of meaning and requirements, (b) decision support for relevancy to current task, and (c) effortless quick command of negotiation interaction. Select appropriate channels, multimodal redundancy, maximize predictability and trust of interaction support.
Mediated	Maximize the intelligence of the automation to accurately infer useful ways to broker interruptions.
Scheduled	Visible clocks or other tools for increasing the predictability of scheduled transitions.

Figure 6. **UI support for the during switch phase.**

Process model–interruption management stage model

- Minimize the long-term memory access time and errors by providing associations of annunciation with required interrupting task performance requirements.
- Provide support for rationally determining how best to integrate performance of interruptiong task and interrupted task set.

Design space–definition and taxonomy of human interruption–coordination

Immediate	Maximize UI support for interruption task to allow the user to get it done quickly; and maximize support for situational awareness (SA) of backgrounded tasks.
Negotiated	<same support as immediate>; and easy interactive controls for switching back to original task as needed.
Mediated	Maximize trust in automation through meta-information about status of expected services and accuracy levels of inference services.
Scheduled	<same support as immediate>; and status information about performance levels related to timing.

Figure 7. **UI support for the after switch phase.**

Process model–interruption management stage model

- Enhance memory of interruption position by external markers or by allowing rehearsal.
- Provide overview status of backgrounded taks.

Design space–definition and taxonomy of human interruption–coordination

Immediate	Bookmark recovery, context restore; replay capability with flexible user control; time compression summarization for replay; reminders of objectives and previous activities.
Negotiated	<same support as immediate> Display information verifying that interruption task was completed successfully.
Mediated	Intelligent constraints on user actions to enforce error-free resumption of original task.
Scheduled	<same support as immediate> Summary of amount of time spent away from original task.

cific interface designs to ensure appropriate resilience to and handling of interruptions in complex human–machine systems. Finding this lacking a principled approach to improving interface design for interruption management, we proposed two theoretical frameworks that form a foundation for such guidance. We concluded with a discussion of interventions that can improve interruption management, and focused on interface design as the most promising of these. Specific recommendations for interface design features are provided to improve management of human interruption in complex systems. A good design process must include iterative testing in representative environments that include realistic interruptions.

This article's proposed guidance for interface design derives from theoretical assimilation of primarily basic research in *attention, memory, linguistics, situated cognition*, and *workload management.* Actual design of these features in a particular domain interface will require empirical assessment to address the degree to which interruptions divert, distract, disturb, and disrupt ongoing task performance, and the IMSM interruption management behaviors and methods of interruption management (immediate, negotiated, mediated, scheduled) that are afforded and encouraged by these features. We encourage the designers of interfaces to explicitly consider the interruption-management problem in design and evaluation and to report successful design strategies. Such valuable design experience will further define guidelines to develop supportive UI's for ubiquitous, interrupt-laden environments.

NOTES

Background. This article contains revised and/or broadened pieces from McFarlane (1999) and MacFarlane's doctoral dissertation (McFarlane, 1998). The majority of the results and discussion in this article, however, are unique to this document. MacFarlane's research was conducted as part of the Naval Research Laboratory's Human Alerting and Interruption Logistics (HAIL) project. The URL for the HAIL homepage is http://www.aic.nrl.navy.mil/hail/. The article is also based on work done for Latorella's doctoral thesis at the Industrial Engineering Department, State University of Buffalo (1996). Publications resulting from this research are available at http://zethus.larc.nasa.gov/~kara.

Acknowledgments. Portions of this work were performed as part of MacFarlane's doctoral dissertation at George Washington University (GWU) under John Sibert. Editing contributions for this article were made by James Ballas, Astrid Schmidt-Nielsen, Susan McFarlane, Derek Brock, Justin McCune, William Lawless, Paul Berger, and Steve O'Neill. Latorella's work significantly benefited from commentary by Colin Drury, Valerie Shalin, and Joseph Sharit. Implementation and data reduction significantly benefitted from the efforts of Paul Schutte, Regina Johns, John Barry, and simulation staff at NASA Langley. Latorella (1996b, 1998) more fully describes the contributions of the many helpful contributors who made this work possible.

Support. Major funding for MacFarlane's work was provided by James Ballas, Naval Research Laboratory. Additional funding was provided by Michael Shneier, Office of Naval Research; John Sibert, GWU; and Gerard Mayer, Lockheed Martin Advanced Technology Laboratories. Latorella's work was supported by Industrial Engineering Department, State University of Buffalo, under Colin Drury; and a NASA Graduate Student Research Program Fellowship under the sponsorship of Paul Schutte (Grant NGT–50992) at NASA Langley.

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HCI Editorial Record. First manuscript from Daniel McFarlane received on July 6, 1999. Revision received August 7, 2000. The *HCI* editors decided to split the submission into two manuscripts; this manuscript included Kara Latorella as co-author. First version of this manuscript received September 3, 2001. Revision received October 2, 2001. Accepted by Ruven Brooks. Final manuscript received November 6, 2001. — *Editor*

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