Designing for Human-Agent Interaction

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■ Interacting with a computer requires adopting some metaphor to guide our actions and expectations. Most human-computer interfaces can be classified according to two dominant metaphors: (1) agent and (2) environment. Interactions based on an agent metaphor treat the computer as an intermediary that responds to user requests. In the environment metaphor, a model of the task domain is presented for the user to interact with directly. The term *agent* has come to refer to the automation of aspects of human-computer interaction (HCI), such as anticipating commands or autonomously performing actions. Norman's 1984 model of HCI is introduced as reference to organize and evaluate research in human-agent interaction (HAI). A wide variety of heterogeneous research involving HAI is shown to reflect automation of one of the stages of action or evaluation within Norman's model. Improvements in HAI are expected to result from a more heterogeneous use of methods that target multiple stages simultaneously.

Interacting with a computer requires adopting some metaphor to guide our actions and expectations. Most human-computer interfaces can be classified according to two dominant metaphors: (1) agent and (2) environment. Interactions based on an agent metaphor treat the computer as an intermediary that responds to user requests. In the environment metaphor, a model of the task domain is presented for the user to interact with directly.

Command-line and screen editors illustrate a simple contrast between these approaches. To change a word in a command-line editor such as *ex*, you must (1) instruct the editor to move to the appropriate line number, then (2) enter some command such as s/old/new (locate string *old*, then substitute for string *old* string *new*). To view this change in the context of the surrounding text would then require composing a command such as p .–10,.+20 (print from 10 lines before to 20 lines after the current location). This same task is far easier with a screen editor where you simply move the sprite- using mouse or cursor key to the offending word, delete it perhaps by backspacing over it, and type in the replacement. This keystroke superiority of screen over command-line editing is a well-known human-computer interaction (HCI) (Card, Moran, and Newell 1983) result. If the task were changed to "change every occurrence of old_word to new_word," the relative advantage is reversed: An instruction to an agent such as "g/old/s/old/new" (locate string *old*, then substitute for string *old* string *new* for *g* = every occurrence of string *old*) is far simpler than scouring the surrogate document for occurrences of *old_word*, erasing each, and typing *new_word* in its place. For this example, the character of predictable errors will differ as well; the subject interacting directly with the document is likely to miss some occurrences of *old_word*, but the subject issuing the global command can suffer unintended consequences such as changing *not_old_word* to *not_new_word*.

In practice, the better features of line editors such as string searching and global replace have almost always been retained in screen-oriented editors, leading to interfaces in which indirect requests can be issued to perform tasks for which direct manipulation proves too cumbersome. The distinction between agent and environment metaphors is not identical to the distinction between agent-based and direct manipulation-based interfaces that has been much debated (Shneiderman and Maes 1997). The agent-environment distinction reflects the semantics (action versus request) of the interaction rather than its syntax (command line versus button press). The binocular icon search button found on NETSCAPE browsers, for example, uses a pushable button to advertise its availability and means for initiating search but leaves the task of locating a string to an agent rather than require the user to search the text line by line. Task actions communicable using an environmental metaphor are a proper subset of those that could be specified to an agent and are just those tasks such as iconic desktops, text editing, draw programs, or geographic information systems that can provide clear, literal correspondences between the task domain and the on-screen representation.

The power of this approach, which provides advertisement and unique identification and selectability of available objects and actions, is reflected in the ascendance of graphic user interfaces (GUIs). The value of the agent metaphor to interaction only becomes apparent when objects are not present or fully visualizable, and actions are repetitive, delayed, or poorly specified. The distinctions between agent- and environment-based HCI are similar to those between manual and automated action in the physical world. It is much simpler for us to drive a car or set a table than instruct a robot to do so, but we would rather adjust a thermostat or program a milling machine than repeatedly perform these actions by hand. Although the computer offers the ultimate in flexible automation, instructing it do what we want can be arbitrarily hard for humans, as demonstrated by the difficulty experienced in using traditional programming and scripting languages. The growing popularity of agent-based interaction reflects the emergence of an increasingly powerful and complex computing environment, bringing with it desires to perform flexible tasks involving multiple or unknown objects by users who do not want or might not have the ability to program.

Norman's (1988) ecological model of HCI is reviewed and utilized to organize research in human-agent interaction (HAI). Our premise is that software agents are intended to automate repetitive, poorly specified, or complex processes by bridging the gulfs between a user's desires and the actions that could satisfy them. Tasks, domains, and interaction methods are categorized according to the uncertainties they bring to, or reduce at, stages in this model. A maturing paradigm of HAI is envisioned in which adaptation, user profiles, demonstration, and scripting are used, as appropriate, to facilitate HAIs.

Reference Model

Don Norman (1986) characterizes HCI as the problem of bridging the twin gulfs of execution and evaluation. The *execution side* of the cycle involves translating a goal into a sequence of actions for achieving the goal. The *evaluation side* involves using feedback from the domain to compare the result of the action to the goal. The model is cybernetic, rather than logical, in that it emphasizes feedback and incremental action rather than problem space search or planning. A crucial feature of this model is that tampering with either side of the loop can lead to detrimental or unanticipated results. If the execution side is automated, the human might fail to observe effects of actions and be unable to correct errors or modulate ongoing behavior. If the evaluation side is automated, the human might be unable to track the effect of actions and adjust to their results.

Norman proposes seven stages of action in this model to link the user's goals to the world. The stages of execution are (1) forming an intention to act, (2) translating this intention into a planned sequence of actions, and (3) executing this sequence. The stages of evaluation are (1) perceiving the state of the world, (2) interpreting this perception in light of prior action, and (3) evaluating this change with respect to the initial goal. The gulfs refer to the interface-metaphor that separates the user's goals from the application domain in which they must be realized. An example of this form of analysis is shown in table 1.

Although approximate, rather than precise, and proposed in the context of early GUIs, Norman's model provides a useful reference for analyzing HCIs of all forms because it identifies the cognitive processes and the linkages between them that must be supported for HCIs to succeed.

We define an *agent* to be a program that automates some stage(s) of this human-information–processing cycle. This definition does not apply to software-only agents found in multiagent systems and excludes HCIs involving simple direct-manipulation actions or explicit command-line requests.

Figure 1 shows the Norman reference model and the ways in which the involved cognitive processing might be automated. Automated processes are indicated in italics within dashed boxes. Serial (nonlooping) automation strategies range from direct aiding, such as action sequencing or attentional filtering, to executive functions, such as anticipatory action or prioritized filtering. Agents that interact continuously with the domain can be semiau-

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Goal	Improve the appearance of the letter.
Intention	Change the paragraph style from indented to blocked; replace all new-paragraph commands with skip-line commands.
Action specification	Specify sub/.pp/.sp/whole.
Execution	Type "sub/.pp/.sp/whole."
Perception	Each line of text begins at left margin.
Interpretation	The paragraphs are blocked.
Evaluation	The letter now "looks better"?

Table 1. Changing the Format of a Letter (Norman 1986, p. 44).

tonomous with or without feedback or can perform their assistive functions completely independent of the user. These categories could be elaborated to incorporate the transparency of automated processes and other aspects likely to affect HAIs, but these nine should suffice to suggest some of the structural complexities and concerns that should inform the design of agents to assist human users. A rule of thumb would be that any serial configuration that automates a complete side of the loop isolates the user and can lead to breakdown, as can semiautonomous configurations that do not explicitly supply appropriate feedback.

As shown in figure 1, automation can occur either through semiautonomous processes set in motion by the user or by the bypassing of stages of execution or evaluation that the user must otherwise perform. An agent that searches several databases for a favorable price is an example of a semiautonomous process. This form of closed-loop automation is found in process industries where operators establish a variety of set points for valves, breakers, and proportional controllers. For automation of this sort to succeed, the user needs a relatively detailed mental model of the domain and what the automation is to do to program it (transparency) and, subsequently, would benefit from good displays and methods for monitoring its performance (feedback).

An adaptive agent that volunteers *ls –t* after learning that a user invariably types *ls –t* to see what the current paper is after changing directories to Papers automates stages involved in instantiating a goal, forming intent, and planning a sequence of actions. An attentional filter that rings a bell and raises the flag on a mailbox icon whenever there is mail from members of the work group (but no one else) automates the stage involved in perceiving the domain. Examining other behaviors attributed to software agents will establish that this model of closed loops and bridged stages accommodates most.

Equating software agent with programs that automate aspects of interaction agrees with many popular definitions: Shneiderman (1995, p. 14) lists adaptive behavior, accepts vague goal specification, gives you just what you need (automating execution-evaluation), works when you don't, and works where you aren't (semiautonomous processes) to characterize agents. On the other side of the argument, Patti Maes (Shneiderman and Maes 1997) identifies an agent's characteristics as removed in time and place (semiautonomous) and adaptive to user's habits, performance, and interests (automating execution-evaluation). Anthropomorphism, a target of Shneiderman's criticisms, is not considered an essential feature of agents by either Maes or the present model. She goes on to deny the necessity of personifying or anthropomorphizing agents and proposes the reliance on user programming or machine learning, rather than traditional AI techniques, as an additional distinguishing characteristic of successful agents. Maes (1994) argues for indirect management (semiautonomous process) alone as distinguishing HAIs.

Other theorists (Laurel 1997; Payne and Edwards 1997; Negroponte 1995) stress the agent's assistance in common tasks, rather than mechanisms used to assist, as the defining char-

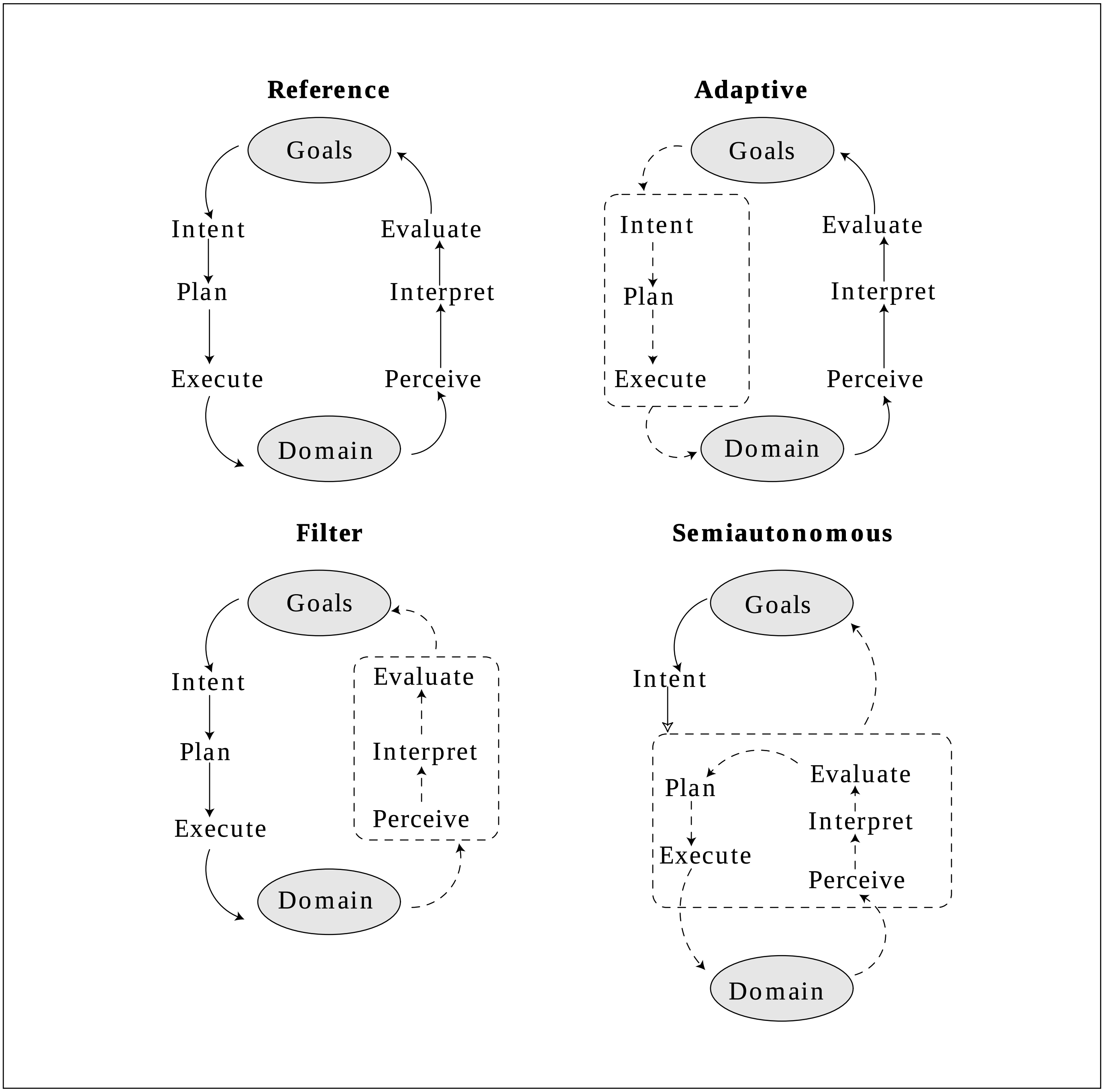

Figure 1. The Norman Reference Model.

acteristic. Finally, there are broad and ambitious taxonomies of agents based on laudatory characteristics such as inferential capability (Bradshaw 1997; Milewski and Lewis 1997); degree of agency, mobility, and intelligence (Gilbert 1997); degree of autonomy, cooperation, and learning (Nwana 1996); and place within the universe of biological, robotic, and digital entities (Franklin and Graesser 1996).

My objective is not to add to these proliferating typologies of software agents but instead to examine the potential of agent automation to facilitate HCI. The basic premise of this approach is that the greatest impediment to assisting human users lies in communicating their intent and making results intelligible to them.

Today, in almost all cases, the limiting factor in HCI is not computing cycles or connectivity to information sources or characteristics of peripherals (the machine side) but the user's ability or willingness to communicate these desires and sift, organize, and represent the machine's response to satisfy them (the human side). For example, although I have a PERL interpreter for which I could, in principle, write a script that would visit a list of web sites, extract particular information from each, perform comparisons, and return the result to my in box, I will almost certainly not do so. The effort of prescribing how to navigate, how to parse HTML at each of the sites, and how to analyze and return the results is infinitely more difficult than pushing buttons and following links on my browser myself. It would probably remain more difficult even if I had to repeat the search 10 or 15 times. Even when the time to search repeatedly equaled the time to program, I would still prefer the manual search because of the lower cognitive effort. As this example suggests, scripting languages might fit the definition as maximally powerful instructable agents, yet they fail miserably in satisfying Negroponte's (1995) desire for an implacable butler or mine for a no-hassle autonomous web searcher. The problem is a human variant of a Turing equivalency. Scripting languages or, for that matter, assembly code might meet the letter of a definition of agents, but the spirit clearly lies in the ease with which our desires can be communicated.

As this example suggests, there is considerable merit in the vaguer definitions, such as "assistance at common tasks," which implicitly incorporate ease and utility. To reflect this insight, the definition of *software agent* is amended to a program that automates some stage(s) of the human information-processing cycle, leading to a significant decrease in human effort. This conception is consistent with Shneiderman and Maes's (1997, p. 53) notion that "an agent basically interacts with the application just like you interact with the application" in that the locus of agent automation is on the executive tasks otherwise performed by the human. As in other instances of pervasive automation, software agents will disappear from notice as their behavior becomes sufficiently familiar, just as we no longer think of elevators as automated but instead as directly controlled.

Tasks and Constraints

As the script versus interpreter contrast suggests, any constraint on the agent's behavior from outside reduces both the generality of possible tasks and the human effort of initiating them. The arguments for the superiority of direct-manipulation interfaces (Shneiderman and Maes 1997; Lanier 1995) rest on just this point. The presence of buttons, toolbars, drop-down boxes, and other visible controls makes the set of possible action goals perceptually available without relying on memory or other cognitive resources. In the point-and-click environment, the problem of planning and executing sequences of actions is trivialized to selecting a visible object and executing the action associated with it. Immediate feedback is typically provided for selection and operation, short circuiting the problems of perceiving and interpreting the action's effect, leaving only evaluation as a task for the user. Any less constrained task becomes a candidate for automation. Because stages of execution involving the translation of a goal into an intention to act and the translation of this intention into a set of internal commands are unobservable until commands are executed, most automation of execution bridges all three stages. Automation of execution, therefore, is primarily a matter of goal recognition. The other class of agent aiding lies in automating the entire loop, which can be as simple as the independent execution of a loop or as complex as the interplay of guidance and execution.

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Automating Execution

Hypothesized agents such as Negroponte's (1995) digital butler or the smiling, bow tie–wearing Phil portrayed in Apple's 1977 KNOWLEDGE NAVIGATOR video achieve their effect by accurately anticipating their users' desires, that is, automating goal instantiation. To successfully anticipate a user's desires and needs, there must be few, preferably a single goal that can be satisfied by a stereotyped sequence of actions associated with particular states and events. Automation of this sort is open loop, leaving evaluation to the user. The user initiates actions under ambiguous conditions that are interleaved with agent-initiated actions where appropriate goals can be identified. This form of automation can be achieved by matching a user's characteristics to those of a sample or demographic group with known goals and actions, observing and replicating the user's own state -> action sequences, or by providing explicit instruction, such as log-in scripts or resource files.

Automating the Cycle

Any process for which evaluation can be separated in time, space, or representation from initiating action is a candidate for automation of this sort. Conventional computer applications, such as a payroll program, that are set in motion and later return confirmation of success or failure are examples of this type of interaction. With closed-loop automation, sequences of actions, comparisons of results, and adjustment of activity all must be coordinated with a user's intentions. Although ordinary programming meets the automation requirement, it does not satisfy the flexibility and ease of expressive effort expected from software agents. Most examples of agents of this sort are only distinguishable from conventional programs in that they can be scheduled in advance, they can interact with other programs or information sources as scripts do, or they anthropomorphize the interaction to be perceived as intelligent or believable.

The problem of bridging the gap between human intent and complex environmentally guided action by software agents remains open. Put broadly, this question is one of how to make the programming of computers easy and the knowledge accessible to the general public. The problem is not solved, but various techniques, including programming by demonstration, visual languages, context sensitivity, forms, and direct manipulation, might offer partial solutions.

Constraining Expectation and Interpretation

A key factor in the success of direct manipulation is its ability to constrain intent (you can only select objects you can see) and action (you can only click on what you see) so that there is little ambiguity about what can be done or how to do it or what has been done. The asynchronous, semiautonomous behavior of a closed-loop agent by contrast offers little in the way of affordances or feedback to constrain a user's expectations or evaluations. As a consequence, the designer not only has the problems of automating actions but also of conveying to the user what actions are available, what goals they might satisfy, how to know that they have been performed, and how to verify that they have been performed successfully. These problems can be ameliorated by efforts to make the control of behavior apparent, understandable, or justifiable to the user. Anthropomorphism, mental models of agents, and explanation facilities can aid in reducing these ambiguities.

These problems of expectation are shared in common with human interaction in earlier forms of automation and intelligent systems and should benefit from accumulated experience in these areas.

Conventional Automation

Many issues affecting human interaction with software agents have already been explored in the context of conventional automation. Just as e-mail, the web, and burgeoning information overload are making the development of software agents necessary to allow information workers to continue to perform their jobs, increasing complexity in industrial systems such as nuclear power plant control rooms and aircraft cockpits long ago made them uncontrollable without automation. The point is that in excessively high work-load domains, we delegate tasks to machines not merely as a labor-saving convenience but because of necessity. The model of a subservient, if intelligent, machine waiting at our beck and call might not fit these high–work-load environments in which a human failure to initiate automated action can be just as detrimental as an inappropriate action taken by a machine.

Autonomy

The broadest issue raised by necessary automation involves the relative autonomy of the human and machine. Relative autonomy has effects in areas ranging from acceptance and willingness to use automation to the stability and effectiveness of the resulting human-machine systems. Although at least one party needs autonomy, systems in which the machine has the autonomy, or both human and machine act independently, are possible.

Two basic issues affect trade-offs in autonomy:

First is the degree to which automation requires explicit initiation (machine autonomy). Starter and Woods (1995) classify errors involving automation as errors of commission or omission. Their error of commission refers to events in which the human fails to engage automation, engages it in the wrong mode, or engages it with inappropriate settings. The failure to spell check a document, the unintended change of *not_old* to *not_new*, or the UNIX command rm –r * (recursive delete) issued in lieu of rm –f that merely suppresses commentary are examples of errors of commission.

Second is the degree to which automation provides explicit feedback. The problem of adequate feedback is the complement of that of control. A basic precept of human engineering is that human errors cannot completely be eliminated. The reliability of human-machine systems therefore depends crucially on providing opportunities for humans to recover their mistakes. When automation intervenes between the human and the domain, the ability to detect and, hence, correct errors can be impaired or eliminated.

If a situation has high work load and the user needs to delegate tasks to automation, the detail and timing with which the automation provides feedback needs to be established. One approach followed in process control and aviation is to have automation report back only when and if some predetermined set point is exceeded. This approach has worked well in process control where engineers can carefully predetermine the thousands of set points. In aviation, where response times are shorter and programming more flexible, results have been less pleasing with numbers of controlled flights into terrain (Starter and Woods 1994; Corwin et al. 1993) attributable to failures of pilots' interactions with their automated servants. Errors caused by omission (Starter and Woods 1995) of feedback about initiation are becoming increasingly evident in highly automated modern environments, such as the glass cockpit of the Airbus A-320. In errors of omission, the automation initiates action without alerting the human, the human fails to recognize what the automation has done, and failures occur because of this loss of situational awareness.

Jones and Mitchell (1995) propose a

set of prescriptive principles for resolving these issues in the human's favor: (1) human authority, where the human retains authority and responsibility; (2) mutual intelligibility, where human and machine maintain an accurate model of one another and the domain; (3) openness and honesty, where the machine's behavior is observable, the machine communicates intentions, and the machine's capabilities and limitations are made explicit; (4) management of trouble, where the machine possesses strategies to recognize and repair losses of mutual intelligibility; and (5) multiple perspectives, where the machine provides multiple perspectives to support alternate human problem-solving strategies.

Although this list begins with a nod to human sovereignty, it quickly makes clear that the basic problem afflicting our interactions with automation is not a struggle over authority but a lack of understanding and predictability of the automation. The primary concerns involving autonomy, initiative, and feedback also reflect this problem of human-machine domain coherence. Referring to our reference model, we can see why these problems arise. When automation is imposed between the user and the domain, it exacerbates both the gulfs of action and evaluation. Where automation is allowed initiative (adaptive agents), the user's evaluation becomes problematic because it can be difficult or impossible to disentangle the effects of the machine's actions from his/her own. Even more troubling, the attentional tuning between actions and their effects is lost; so, the user might utterly fail to notice significant changes in the domain. Even when the user retains initiative (semiautonomous agents), he/she is cut off from the domain by the intervening action-evaluation loop of the automation. The task is now not simply to plan, execute, monitor, and interpret but to express these behaviors as an intention and then monitor performance indirectly. The alarm systems of a nuclear power plant or the return message from an executing shell script are examples of this sort of second-order monitoring.

Trust

Many of the complex issues involving mutual human-machine modeling, awareness, and coordination are captured by the anthropomorphic term *trust*. If we examine the considerations that enter into our decision to delegate a task to a subordinate, instruct the subordinate in how to perform the task, monitor the performance, or authorize some class of tasks without follow-up, our trust in the subordinate will almost certainly play an explanatory role. Closer consideration will show our use of the term to be multidimensional. The trust we have that our secretary will remember to pick up the mail is distinct from our trust that he/she will compose a postable business letter, which, in turn, is distinct from our trust in the lawyer who assures us that the letter is not actionable.

Bonnie Muir (1996, 1994, 1987) adopted a taxonomy of trust for human-machine relations from sociologist Barber (1983), giving a nod to social psychologists (Rempel, Holmes, and Zanna 1985) for a complementary taxonomy and a source of conjectures about the dynamic character of trust. Barber (1983) defines trust in terms of three specific expectations: (1) persistence of natural, biological, and social "laws," for example, gravity, pain following injury, and parents protecting their offspring; (2) competence of others to perform their technical roles, for example, our trust that a bus driver will take us safely to our stop; and (3) fiduciary responsibility of others to fulfill their obligations, for example, our trust that a lawyer will administer an assigned estate without theft.

Rempel, Holmes, and Zanna (1985) propose a similar taxonomy to account for couples' attributions about one another's behavior. Initially, trust in a partner depends on predictability in his/her behavior, such as a preference for seafood or punctuality for dates. As the relationship matures, trust extends to the longer-term traits of dependability in matters such as remembering birthdays or picking up the laundry. In its final phase, trust extends to faith in the partner's affections and allegiance. As trust deepens, its bases and expectations shift from the instrumental and observable traits to the attributable and unobservable traits. Rempel, Holmes, and Zanna (1985) are concerned with both the acquisition and the resistance to extinction of these forms of trust. The faith in an alcoholic partner's affections, for example, might last long after any hopes of consistency or dependability are gone. The two taxonomies can be merged approximately, as advocated by Lee and Moray (1992), to distinguish (1) trust that is based on observed consistency of behavior (persistence or predictability), as in "I trust my watch to keep relatively accurate time"; (2) trust that is based on a belief in competence or well-formedness (competence or dependability), as in "I trust Martha Stewart's recipe for hollandaise"; and (3) trust that is based on faith in purpose or obligation (fiduciary responsibility or faith), as in "I trust my physician to monitor my health."

The match up is somewhat inexact with Barber (1983) breaking out competence into expert knowledge, technical facility, and everyday routine performance, which are essentially the same as our higher-level synthetic categories. Muir (1987) goes on to equate these three levels of competence with Rasmussen's (1983) taxonomy of skill-based, rule-based, and knowledge-based behaviors. Lee and Moray (1992) propose an additional correspondence to Zuboff's (1988) stages of trial-and-error experience (consistency), understanding (competence), and leap of faith (fiduciary responsibility) in developing operators' trust in new technology. A further analogy can be drawn to Dennet's (1987) description of three stances people can adopt to predict the behavior of systems: (1) physical-stance prediction based on physical characteristics and laws (persistence and predictability), (2) design-stance prediction based on what a system was designed to do (competence and dependability), and (3) intentional-stance prediction based on an assumption of rationality (fiduciary responsibility or faith). The convergence of five independent taxonomies purporting to describe how humans or machines behave or can be predicted to behave supports the appeal of this approach.

As bases for human modeling of machine agents, these taxonomies suggest that agents can be made predictable by (1) consistently pairing simple observable actions with input; (2) making the causes and rules governing an agent's behavior transparent; or (3) making the purpose, capability, and reliability of the agent available to the user. Muir (1996, 1994, 1987) refers to the process of acquiring predictive models of these sorts as *trust calibration,* the idea being that performance will be better for human-machine systems in which trust is accurately calibrated because the human's model will allow more accurate predictions. Disregarding issues of acquisition and extinction trust based on observable consistency or competence should yield more accurate prediction than faith in a black box's performance. The greater predictability of consistent or competent agents should also make boundary conditions and brittleness more apparent and remediable. Agents trusted on faith, by contrast, would require a high degree of reliability across their range and more communication to maintain accurate coordination. Experiments in our laboratory (Sycara et al. 1998; Lenox, Roberts, and Lewis 1997) support these hypotheses, finding that although subjects interacted more extensively with an opaque agent requiring faith, an agent of observable competence led to substantially better target identification and resolution of encounters.

Trust and Experience

Miur's (1996, 1987) and Lee and Moray's (1992) experiments address the effects of errors on ratings of trust and willingness to use automation. Muir (1996, 1987) reports a large constant error (predictable) had approximately the same impact on ratings of trust as a much smaller variable error than the level-of-trust model would suggest. Both Muir (1996, 1987) and Lee and Moray (1992) found correlations between ratings of trust and reliance on automation; however, recent studies of pilots (Reiley 1996; Singh, Molloy, and Parasuraman 1993) found no relation between attitudes toward automation and reliance on automation in a laboratory task. Time limits on laboratory experiments make it difficult to test Rempel, Holmes, and Zanna's (1985) and Zuboff's (1988) hypotheses about developmental stages of trust. Observation of new and experienced users of real systems, however, provides an opportunity to examine these predictions.

Contrary to conventional wisdom, human autonomy and control is not always preferred by experienced users of automation (Parasuraman 1997). Reiley (1994), for example, found that pilots were more reliant on automation than college students. In the past year, I have conducted a series of surveys of University of Pittsburgh students, examining their use of automated features of popular software. Contrary to our expectation that experienced users would prefer options giving them greater control, I have found that it is the beginning users who prefer high levels of control, but the more experienced users prefer to relinquish control to the system. With Microsoft WORD's "replace text as you type" spell-correction option, for example, I found that over half of the experienced users chose it, but only 22 percent of the less experienced users left it on. In agreement with our conjecture that successful black-box automation requires explicit attention to feedback, the experienced users overwhelmingly chose the message for confirming changes, but the inexperienced users rejected it. Use of the printer icon in preference to the menu print option that brings up a dialog box allowing customization of a job showed similar results. Approximately 70 percent of the experienced users chose the icon, but a similar proportion of the novices preferred the control offered by the menu selection. Although nonlongitudinal observations of this sort cannot trace the development of trust, the preference for control by new users and the willingness to relinquish it by the experienced suggests such a progression.

Effort and Individual Differences

Return on investment is a recurring theme in human use of automation. Often, the functions most easily automated, such as level flight, are those that need it the least. In fact, automation is often perceived as increasing, not decreasing, work load. Wiener (1989, 1985), for example, investigated pilots' attitudes toward cockpit systems. He found that only a minority agreed with the statement "automation reduces work load," but a substantial proportion felt that automation, especially programmable systems such as the FLIGHT MANAGEMENT SYSTEM, increased their work load. Early expert systems provide another example of automation that increases work. Miller and Masarie (1990) report that INTERNIST-1 often required 30 to 90 minutes of data gathering and interaction to complete a single diagnostic consultation. Almost any form of procedural instruction has the potential of becoming more work than doing it by hand, and in a choice environment where automation is optional or can be turned off or disabled, it often will be.

In a recent review of human use of automation, Parasuraman (1997, p. 48) identifies three strategies for better using automation. The first of these—"better operator knowledge of how automation works"—deals with the predictive model that we have discussed in terms of trust. The second strategy requires anticipating and designing for "large individual differences (which) make systematic prediction of automation use…difficult." The third strategy holds that automation must not require a high level of cognitive overhead.

Extending this guidance to agents is a daunting task. Supporting trust requires that the agents either be very simple and observable, be intelligible and make their interior processes and products visible, or be highly reliable with explicitly managed communications. Agents must be designed at varying levels of sophistication to accommodate interindividual and intraindividual differences and must be so easy to instruct that it is no more difficult than doing the task ourselves. These same key points—cost, modeling and trust, and adaptivity—are stressed by Milewski and Lewis (1997) in their review of the human automation and agent literature.

One clear conclusion of this review

of psychological literature involving human trust of automation is that anthropomorphism can do little to improve HAI in the near term. Faith, the only form of trust that can be associated with a presentation mimicking human behavior, is the least helpful in terms of coordinated behavior and the most difficult to acquire. Transparent forms of presentation that make the competence and rules of agent behavior apparent are more promising for improving performance and establishing trust.

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Human-Agent Interaction

Norman's human reference model organizes agents into three broad classes: (1) anticipatory, (2) filtering, and (3) semiautonomous. Each class presents its own design challenges to promoting effective human interaction. In this section, representative examples of each of these classes are discussed.

Anticipatory and Filtering Agents

Anticipatory agents are classified by our model as those that automate some portion of the action-execution cycle. Although an anticipatory agent can have significant information-gathering interactions with the domain, this information is gathered to determine a context used to infer the user's likely intent. Anticipatory agents are a sort often portrayed in fiction and typified by an intimate acquaintance with their user's intentions and preferences, such as an experienced butler. Because these intentions and preferences can be quite idiosyncratic, complex, and difficult to express, anticipatory agents are often constructed as learning agents. As such, their task is not only to act in accordance with what is probably their user's intention but to learn mappings from the software context and sequences of user actions to the subsequent action.

Our distinction between action anticipation and filtering is somewhat artificial because the learning methods used and actions learned can be similar. This similarity emphasizes the cyclical character of human relations to domains and the inseparability of action in directing attention and evaluation in determining subsequent actions. Anticipatory agents can be grouped into two broad classes: (1) those that perform a simple concept-learning task to mimic a human user's categorization scheme and (2) those that seek to infer a user's plan of action by observing a more complex sequence of actions to recognize the plan they are instantiating. Lesh and Etzioni (1995) attack this second sequential decision problem of plan recognition for performing simple tasks using the UNIX operating system, such as finding and printing a file. After each observed command, the set of possible plans supported by the sequence decreases. This problem, which is exponentially large in the number of goal predicates, illustrates just how difficult tasks that appear easy to humans can become. Deployed and tested agents that learn a user's "intention" are overwhelmingly of the simple concept-learning sort.

CAP (CALENDAR APPRENTICE) (Mitchell et al. 1994), an agent that learns room scheduling preferences, exemplifies the action-learning approach. CAP assists the user in managing a meeting calendar by providing an online calendar and e-mail facility. Users can enter and edit meetings on the calendar and instruct CAP to send invitations. CAP observes user actions "over the shoulder" and, as it acquires a rule set for predicting durations, locations, times, and weekdays of meetings, begins making suggestions to the user. Performance of learned rules is tracked, and as they are validated and new and hopefully more robust rules are learned, the agent will be able to make increasingly useful suggestions. Even in the relatively stable environment of Carnegie Mellon University, room scheduling had enough variance to stymie CAP a good deal of the time. Plots of prediction accuracy show a clear term-to-term periodicity with accuracy falling to the fortieth percentile at term transitions and rising to 60 percent or above by the middle of the term. Based on the reference model, CAP is an agent that automates the processes of intention formation and action planning. It is not autonomous because it requires a human action to initiate its suggestion process. The go–no go option given the user for executing CAP's plan is appropriate given the observed accuracies. CAP's users can tolerate this level of unreliability because the system is consistent and relatively transparent and provides explicit feedback (the suggestion). A similar meeting scheduling agent that doesn't specify the room to be used is reported by Kozierok and Maes (1993). Their calendar agent explicitly displays certainty factors providing more detailed feedback and a more favorable basis for reliability judgments.

The most popular task for anticipatory agents is the simple concept-learning problem of learning a human's categorization scheme. Using a feature vector extracted from a source such as e-mail headers, a concept-learning algorithm such as ID3 is used to replicate this categorization. New instances can then be sorted into the learned categories. Agents of this sort frequently bridge the gap between *anticipation* (automation of action) and *filtering* (automation of evaluation) because after classifying (matching the user's intent), they can go an addition-

> *A common thread across these varied systems is the use of inductive learning and feedback to automate the process of expressing our goals and intentions to the computer.*

al cycle by accepting this implicit evaluation and executing a subsequent action such as deleting the message. It makes no difference to the concept- learning algorithm that can as easily categorize incoming messages such as "buy IBM" or "invade Iraq" as the prototypical classification "file in folder A or B." The difference comes on the other side of the interface where a user might need explicit feedback or transparent justification for automating actions to adapt to the agent without concern.

The classic concept-learning agent is the mail or news agent that learns to file, delete, prioritize, and notify a user of incoming mail. MAXIMS (Lashkari, Metral, and Maes 1994), for example, performs all these functions after observing how a user chooses to deal with e-mail using the same mechanisms as the Massachusetts Institute of Technology scheduling agent (Kozierok and Maes 1993). Other systems of this sort include MAGI (Payne and Edwards 1997), a learning agent that runs behind the X-MAIL reader, and a news-story categorizer used with an online edition of a campus newspaper (Gustafson, Schafer, and Konstan 1998).

Although agents discussed to this point have used learning to adapt to and anticipate the intentions of an individual user, a similar class of systems does just the opposite. If one presumes that an individual's preferences will be similar to that of similar individuals, a system can learn from a large sample of interactions (for robust learning) with different individuals without extensive and error-prone trials for any one person. This approach, known as *collaborative filtering,* has spawned a variety of systems. Some filter manually by making available comments and ratings, for example, helping people select corporate documents by annotating their reactions (Goldberg et al. 1992) or rating articles in NETNEWS (Resnick et al. 1994). Others act as learning agents by comparing a user's profiles with those on file and estimating preferences on this basis, for example, Ringo Maes's (1994) music-recommendation system. Krulwich's (1997) LIFESTYLE FINDER takes this approach to its logical conclusion by using 62 demographic clusters identified by market researchers as a starting point.

A common thread across these varied systems is the use of inductive learning and feedback to automate the process of expressing our goals and intentions to the computer. The results are both impressive and humbling. When learning agents are expected to do more than recommend movies and music, their inaccuracies become apparent. Mechanisms such as Maes's user-selectable tell-me and do-it thresholds or displayed certainty factors provide opportunities for partial learning to put its best foot forward. As a consequence, for a given degree of learning, agent reliability is improved, and trust is more easily granted. Strategies of suggestion, rather than action, such as followed by CAP are another adjustment necessary at these levels of reliability.

Instructions and Semiautonomous Agents

Just as friends and spouses cannot always guess what we want unless we tell them, it is unreasonable to presume that primitive inductive-learning methods will empower agents to do so. Many of the routine cognitive tasks we would like to delegate to agents involve relatively complex sequences of behaviors, such as extracting particular information from a site on the web, monitoring a news group for a recent topic, or performing some set of conditional actions. What is significant about this list is that these requests all involve sequences of actions that, although individually constrained, combine to form unlearnable wholes. The problem of communicating these desires directly, however, is precisely the problem of end user programming that intelligent agents were supposed to resolve.

Actions that are removed in time and place from the user cannot be learned by observing and must explicitly be requested. The most commonly encountered instructable agents of this sort are the notification agents found at many web sites. These agents typically use a form-based interface to allow a visitor to enter an event that he/she wants to be notified about, such as a sale on airfares. When the event occurs, the agent is triggered, and notification is sent by e-mail.

Potential remedies for more sophisticated instructions are the usual suspects: high-level scripting languages, forms and direct-manipulation interfaces, programming by demonstration, and visual languages. Each approach has limitations that make it difficult for use in instructing semiautonomous agents. Scripting languages are difficult to learn and use. Many of the functions of branching, looping, and running asynchronously needed by semiautonomous agents are expressible but take too much effort. Scripting languages are far more general than the constrained sets of tasks one might want performed by an agent, but if all the scripts likely to be needed were written, a long reference manual and commands with too many parameters to understand would result. If direct manipulation were chosen, the accessibility problems would be solved but at the cost of an impoverished language with deficits in just the areas needed—branching, looping, and asynchrony.

A notable approach combining the power of scripting and the accessibility of direct manipulation and form filling is Etzioni and Weld's (1994) SOFTBOT. The user interacts through a form-based interface with a planning program that, taking the user's goal as an input, searches a library of action schema to generate a sequence of actions achieving the goal. The use of goals as input and action schemata as agent primitives makes this agent consistent with our reference model and consistent with our definition of an agent as a process automating stages of this model.

Programming by demonstration also appears a good candidate for instructing agents, although not in the programming of animation, as in KIDSIM (Smith, Cypher, and Spohrer 1997) or BITPICT (Furnas 1991). With Maes's (Shneiderman and Maes 1977, p. 53) characterization that "an agent basically interacts with the application just like you interact with the application," programming by demonstration in the fashion of EMACS macros would achieve just this effect. This is similar in spirit to over-the-shoulder learning but not subject to the pitfalls of inductive learning.

The final option, a visual language, seems particularly promising for instructing semiautonomous agents. Specialized applications in which programs can be assembled from modules (such as the action schema and goals from Etzioni and Weld [1994]) are particularly suited to visual languages. LABVIEW provides such a programming environment for signal processing, where logic and signal processing can be specified by laying out and connecting icons. A visual language for semiautonomous agents might allow the user to associate reusable behaviors, such as communications, remote accesses, or asynchronous responses, with appropriate goals in a similar fashion. Based on the reference model, this explicit specification of the relation between goals and actions allows a nearly transparent means of instruction.

Two current systems—the AGENT editor of the RETSINA system (Sycara et al. 1996) and Thurman, Brann, and Mitchell's (1997) APPRENTICE extension to OFMSPERT (OPERATOR FUNCTION MODEL)—follow this approach. The key component of the RETSINA reusable agent architecture is a hierarchical representation of task-subtask relationships. Temporal constraints between nodes are used to handle task planning and execution. The agent's plan library contains skeletal plans and plan fragments (cases) that are indexed by goals and can be retrieved and instantiated according to the current input parameters. The retrieved and instantiated plan fragments are used to form the agent's task tree that is incrementally executed. The formalism can also handle sophisticated control structures, such as deadlines, looping, and periodic tasks. The scheduling module schedules each of the plan steps, taking as input the agent's current set of executable action and deciding which action, if any, is to be executed next. The communication module accepts and interprets messages from other agents. The agent editor allows its user to visually construct and manipulate task trees to assemble agents having customized capabilities and behaviors.

The OFMSPERT APPRENTICE used a similar mechanism for editing the relation between goals and actions to allow a user to improve the performance of an expert system. The system performs the task until it encounters some impasse or error condition, at which time it summons its operator. The operator solves the problem and programs the system to deal with similar impasses. The OFMSPERT operations model consists of a model of the system being controlled, an activity model of operator activities, and a plan archive indexing activity trees. The OFMSPERT APPRENTICE is a computational implementation of the operations model. It is designed as a vehicle for incremental automation of the control task. The plan executor and monitor enable an operator to observe the plan in action and repair minor problems that arise by making changes to displayed activity trees. APPRENTICE is being developed to support operations automation in satellite ground control.

Both the RETSINA editor and the OFMSPERT APPRENTICE have the properties identified as desirable for human interaction with powerful agents. Both visually specify actions through goal-based trees and allow users to instruct the agent at this level. Despite their sophistication, both agents are transparent, and their competence and predictability can be inspected from the activity trees. Rather than relying on anthropomorphism faith and uncorrectable behaviors, these agents present themselves as they are and promise to be more useful as a result.

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References

Barber, B. 1983. *The Logic and Limits of Trust.* New Brunswick, N.J.: Rutgers University Press.

Bradshaw, J. 1997. *Software Agents.* Menlo Park, Calif.: AAAI Press.

Card, S.; Moran, T.; and Newell, A. 1983. *The Psychology of Human-Computer Interaction.* Hillsdale, N.J.: Lawrence Erlbaum.

Corwin, W.; Funk, H.; Levitan, L.; and Bloomfield, J. 1993. Flight Crew Information Requirements. Contractor Rep. DFTA-91-C-00040. Washington, D.C.: Federal Aviation Administration.

Dennet, D. 1987. *The Intentional Stance.* Cambridge, Mass.: The MIT Press.

Etzioni, O., and Weld, D. 1994. A Softbot-Based Interface to the Internet. *Communications of the ACM* 37(7): 72–76.

Franklin, S., and Graesser, A. 1996. Is It an Agent or Just a Program? A Taxonomy for Autonomous Agents. In *Proceedings of the Third International Workshop on Agent Theories, Architectures, and Languages.* New York: Springer-Verlag.

Furnas, G. 1991. New Graphical Reasoning Models for Understanding Graphical Interfaces. In Proceedings of Human-Computer Interaction '91, 71–78. New York: Association of Computing Machinery.

Gilbert, D.; Aparicio, M.; Atkinson, B.; Brady, S.; Ciccarino, J.; Grosof, B.; O'Connor, P.; Osisek, D.; Pritko, S.; Spagna, R.; and Wilson, L. 1995. IBM Intelligent Agent Strategy, White paper, IBM Corporation, Research Triangle Park, North Carolina.

Goldberg, D.; Nichols, D.; Ok, B.; and Terry, D. 1992. Using Collaborative Filtering to Weave an Information Tapestry. *Communications of the ACM* 35(12): 61–70.

Gustafson, T.; Schafer, B.; and Konstan, J. 1998. Agents in Their Midst: Evaluating User Adaptation to Agent-Assisted Interfaces. In Proceedings of the 1998 International Conference on Intelligent User Interfaces. New York: Association of Computing Machinery.

Jones, P., and Mitchell, C. 1995. Human-Computer Cooperative Problem Solving: Theory, Design, and Evaluation of an Intelligent Associate System. *IEEE Transactions on Systems, Man, and Cybernetics* 25(7): 1039–1053.

Kozierok, R., and Maes, P. 1993. A Learning Interface Agent for Scheduling Meetings. In Proceedings of the ACM SIGCHI International Workshop on Intelligent User Interfaces, 81–88. New York: Association of Computing Machinery.

Krulwich, B. 1997. LIFESTYLE FINDER: Intelligent User Profiling Using Large-Scale Demographic Data. *AI Magazine* 18(2): 37–45.

Lanier, J. 1995. Agents of Alienation. *Interactions* 2(3): 66–72.

Lashkari, Y.; Metral, M.; and Maes, P. 1994. Collaborative Interface Agents. In Proceedings of the Twelfth National Conference on Artificial Intelligence, 444–450. Menlo Park, Calif.: American Association for Artificial Intelligence.

Laurel, B. 1997. Interface Agents: Metaphors with Character. In *Software Agents*, ed. J. Bradshaw, 67–77. Menlo Park, Calif.: AAAI Press.

Lee, J., and Moray, N. 1992. Trust, Control Strategies, and Allocation of Function in Human-Machine Systems. *Ergonomics* 35(10): 1243–1270.

Lenox, T.; Roberts, L.; and Lewis, M. 1997. Human-Agent Interaction in a Target Identification Task. In Proceedings of the 1997 IEEE International Conference on Systems, Man, and Cybernetics, 2702–2706. Washington, D.C.: IEEE Computer Society.

Lesh, N., and Etzioni, O. 1995. A Sound and Fast Goal Recognizer. In Proceedings of the Fourteenth International Joint Conference on Artificial Intelligence, 1704–1710. Menlo Park, Calif.: International Joint Conferences on Artificial Intelligence.

Maes, P. 1994. Agents That Reduce Work and Information Overload. *Communications of the ACM* 37(7): 31–40.

Milewski, A., and Lewis, S. 1997. Delegating to Software Agents. *International Journal of Human-Computer Studies* 46:485–500.

Miller, R., and Masarie, F. 1990. The Demise of the "Greek Oracle" Model for Medical Diagnostic Systems. *Methods of Information in Medicine* 29:1–2.

Mitchell, T.; Caruana, R.; Freita, D.; McDermott, J.; and Zabowski, D. 1994. Experience with a Learning Personal Assistant. *Communications of the ACM* 37(5): 81–91.

Muir, B. 1994. Trust in Automation: Part I. Theoretical Issues in the Study of Trust and Human Intervention in a Process-Control Simulation. *Ergonomics* 39(3): 429–460.

Muir, B. 1987. Trust between Humans and Machines and the Design of Decision Aids. *International Journal of Man-Machine Studies* 27:527–539.

Negroponte, N. 1995. *Being Digital.* New York: Alfred Knopf.

Norman, D. 1988. *The Psychology of Everyday Things.* New York: Basic.

Norman, D. 1986. Cognitive Engineering. In *User-Centered System Design: New Perspectives on Human-Computer Interaction,* ed. D. Norman and S. Draper. Hillsdale, N.J.: Lawrence Erlbaum.

Nwana, H. 1996. Software Agents: An Overview. *Knowledge Engineering Review* 11(3): 205–244.

Parasuraman, R. 1997. Humans and Automation: Use, Misuse, Disuse, Abuse. *Human Factors* 39(2): 230–253.

Payne, T., and Edwards, P. 1997. Interface Agents That Learn: An Investigation of Learning Issues in a Mail Agent Interface. *Applied Artificial Intelligence* 11(1): 1–32.

Rasmussen, J. 1983. *Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering.* New York: North-Holland.

Reiley, V. 1996. Operator Reliance on Automation: Theory and Data. In *Automation and Human Performance: Theory and Applications,* eds. R. Parasuraman and M. Mouloua, 19–35. Hillsdale, N.J.: Lawrence Erlbaum.

Rempel, J.; Holmes, J.; and Zanna, M. 1985. Trust in Close Relationships. *Journal of Personality and Social Psychology* 49:95–112.

Resnick, P.; Iacovou, N.; Suchak, M.; Bergstrom, P.; and Riedl, J. 1994. GROUPLENS: An Open Architecture for Collaborative Filtering of NETNEWS. In Proceedings of the ACM 1994 Conference on Computer-Supported Collaborative Work, 175–186. New York: Association of Computing Machinery.

Shneiderman, B., and Maes, P. 1997. Direct Manipulation versus Interface Agents. *Interactions* (4)6: 43–61.

Singh, I.; Molloy, R.; and Parasuraman, R. 1993. Individual Differences in Monitoring Failures of Automation. *Journal of General Psychology* 120:357–373.

Smith, C.; Cypher, A.; and Spohrer, J. 1997. KIDSIM: Programming Agents without a Programming Language. In *Software Agents*, ed. J. Bradshaw, 165–190. Menlo Park, Calif.: AAAI Press.

Starter, N., and Woods, D. 1995. From Tool to Agent: The Evolution of (Cockpit) Automation and Its Impact on Human-Machine Coordination. In Proceedings of the Human Factors and Ergonomics Society Thirty-Ninth Annual Meeting, 79–83. Santa Monica, Calif.: Human Factors and Ergonomics Society.

Starter, N., and Woods, D. 1994. Pilot Interaction with Cockpit Automation II: An Experimental Study of Pilot's Model and Awareness of the FLIGHT MANAGEMENT SYSTEM. *International Journal of Aviation Psychology* 4:1–28.

Sycara, K.; Decker, K.; Panu, A.; Williamson, M.; and Zeng, D. 1996. Distributed Intelligent Agents. *IEEE Expert* 11(6): 36–46.

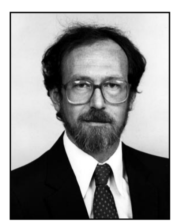
Sycara, K.; Lewis, M.; Lenox, T.; and Roberts, L. 1998. Calibrating Trust to Integrate Intelligent Agents into Human Teams. In Proceedings of the Hawaii International Conference on Systems Science, 263–268. Washington, D.C.: IEEE Computer Society.

Thurman, D.; Brann, D.; and Mitchell, C. 1997. An Architecture to Support Incremental Automation of Complex Systems. In Proceedings of the 1997 IEEE International Conference on Systems, Man, and Cybernetics, 2702–2706. Washington, D.C.: IEEE Computer Society.

Wiener E. 1989. Human Factors of Advanced Technology ("Glass Cockpit") Transport Aircraft, Rep. 177528, NASA Ames Research Center, Moffett Field, Calif.

Wiener, E. 1985. Beyond the Sterile Cockpit. *Human Factors* 27:75-90.

Zuboff, S. 1988. *In the Age of the Smart Machine: The Future of Work and Power.* New York: Basic Books.



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