Performance considerations for people with cognitive impairment in accessing assistive technologies

A wide range of assistive or rehabilitation technologies has been used to assist people having a variety of disabilities with mobility, communication, environmental control, daily living, and other activities. These technologies require certain motor, cognitive, and perceptual skills in their operation. The focus of this article is on the performance effects of the cognitive and perceptual requirements for operation of assistive technologies. To this end, the effects on human performance of the cognitive deficits commonly seen in traumatic brain injury are first reviewed. Examples of assistive technology techniques are presented with a focus on the cognitive and perceptual requirements for their operation. A model of performance for a specific assistive technology system is described, to demonstrate how an analytic approach can aid in understanding the effects of cognitive and perceptual requirements on performance. The examples and model illustrate the premise that as the assistive technology interface changes to accommodate increasing motor impairment, performance can be substantively affected by the increased cognitive and perceptual loads placed on the user. Improved understanding of performance effects related to cognitive and perceptual requirements for assistive technology operation is important for improving both selection criteria and the design of such systems.

Simon P. Levine, PhD
Associate Professor and Director
Rehabilitation Engineering Program

Heidi M. Horstmann, MS
Research Associate
Rehabilitation Engineering Program

Ned L. Kirsch, PhD
Director
Rehabilitation Psychology and Neuropsychology
Department of Physical Medicine and Rehabilitation
University of Michigan
Ann Arbor, Michigan

ASSISTIVE OR REHABILITATION technologies are designed to help people with disabilities perform a variety of daily activities. These technologies have been applied to a number of functional areas that include, but are not limited to, powered mobility, environmental control, augmentative communication, and computer access. The focus of this article is on the cognitive and perceptual requirements for using assistive technologies.

Many of the technologies discussed here specifically address limitations stemming from motor impairment. Such systems are usually designed with a primary emphasis on the motor abilities of the intended user. Frequently, only secondary consideration is given to the cognitive and perceptual requirements of the system and how well they match the user's abilities. This is an important point of concern even for users with purely physical impairments,[1] but for people with cognitive impairment, the cognitive and percep-

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tual requirements for operation are especially critical.

An underlying premise of this article is that the cognitive and perceptual requirements for system operation usually increase as the design of an assistive technology changes to accommodate increasing motor impairment. The task of computer text entry is a good example of this trade-off. One type of assistive interface that has been designed for people with very slow text entry rates is called "word prediction." These systems automatically present lists of words (based on previous character entry) in a screen window. The user can then select an entire word by choosing a single additional character. The intent of this system is to reduce the number of characters that must be entered. While this goal may be satisfied, this type of word prediction system requires that an individual be able to visually search the word list, decide if the desired word is in the list, and then enter the appropriate character to select the chosen word. These additional requirements may make the use of a word prediction system impossible for some cognitively impaired users or may require enough additional time for the associated cognitive and perceptual activities that the efficiency of the word prediction interface is lost.

In addition to assistive technologies that focus on motor impairment, there are many that specifically address limitations stemming from cognitive and perceptual deficits. These include cognitive remediation software, activity guidance systems,[2-4] and other software packages. The concepts developed in this paper should readily apply to these rehabilitation approaches as well.

To explore the effects of cognitive and perceptual requirements for operation of assistive technologies, this article is divided into three sections. First, a brief review of cognitive and perceptual deficits associated with traumatic injury and disease is presented. The purpose of the review is to introduce the ways in which cognitive deficits can affect user performance. Second, specific examples of assistive technology techniques are described along with discussion of the cognitive and perceptual abilities that are needed for effective utilization of these systems. Third, a simple model of user performance with a word prediction system of the type described above is presented. The purpose of this final section is to demonstrate the need and usefulness of analytic approaches in understanding the performance effects of cognitive and perceptual requirements for assistive technology operation. Together, the sections of this article are intended to highlight aspects of human performance in order to foster the development of improved criteria for both the selection and the design of assistive technologies.

REVIEW OF COGNITIVE AND PERCEPTUAL CHANGES FOLLOWING BRAIN INJURY OR DISEASE

People who sustain brain trauma or disease can experience a wide range of cognitive and/or perceptual impairments, in addition to motor impairment, which can directly affect their abilities to operate assistive technologies. These deficits can affect various areas of cognition, including attention, orientation, memory, verbal reasoning and problem solving, perceptual and analytic abilities, social reasoning, and executive abilities. All of these can have a direct impact on performance with an assistive technology system.

Attention

Attention is the ability to maintain cognitive effort, free from distraction or interference. There are three major types of attentional skills that are typically affected by injury or disease: sustained attention, selective attention, and alternating attention. Sustained attention (which may be affected by fatigue) is the ability to maintain effortful and/or deliberate activity, free from distractibility. Selective attention is the ability to filter out irrelevant or competing influences in the environment. Alternating attention is the ability to shift rapidly between competing environmental stimuli or conceptual lines of thought. Attentional deficits may impair an individual's ability to learn to use an assistive technology system, as attention is a critical first step in memory storage. Attentional deficits may also limit the level of skill that can be achieved; for example, the ability to attend consistently to salient aspects of the environment is necessary for a person to drive a power wheelchair independently and safely. Some assistive technology systems, such as the scanning interface discussed below, require the ability to respond in a rapid and timely fashion. This type of system is not likely to be successful for a person whose attentional skills are significantly impaired because such deficits often produce delayed reaction time.

Orientation

Orientation, like attention, is a fundamental neurocognitive skill that represents the individual's appreciation of the passage of events, the self, and the self as an element of the environment. It too is a prerequisite to the purposeful, goal-directed behavior that is necessary for both the use of and the motivation to use an assistive technology system.

Memory

While many classification systems for memory have been proposed, memory is often considered to be made up of three major components: the short-term sensory store (STSS), the working memory (WM), and the long-term memory (LTM). Deficits in any one of these systems affect an individual's ability to learn to use an assistive technology system, although it is often possible to compensate for mild deficits by supplying external aids such as a list of steps for common procedures. Memory deficits will also affect performance. For example, an individual who is entering a message into an augmentative communication system may forget what the message is before completing it, especially since completion of the message may take several minutes. Individuals whose memory deficits involve nonverbal or spatial information may have difficulty developing skilled use of a powered mobility system, as even frequented environments will always seem brand-new.

Verbal reasoning and problem solving

Deficits in the area of verbal reasoning and problem solving involve any skill in which the manipulation and use of verbal concepts is required. For example, limitations in logical thinking and problem solving can severely affect an individual's ability to recover from simple errors while using an assistive technology system and will therefore limit the degree of independence that can be achieved with the system. Limitations in understanding conceptual relationships (eg, similarities, differences, category membership, analogic or metaphoric relationships) affect an individual's ability to learn and use assistive technologies. Learning may be affected, because an individual may not recognize situations in which prior knowledge can be applied. This is particularly true with computer access and augmentative communication systems for which encoding techniques are used that require the user to recognize the relationship between an abbreviation and its expansion. Choice of such a system for an individual with difficulties in verbal relationships must be made with care, as it may present an unnecessary or insurmountable learning barrier.

Difficulty with specific skills such as letter recognition or reading comprehension have a clear impact on choice of system. Depending on the degree of the deficit, it may be necessary to select a system that uses pictorial or other nonverbal forms of information in all communication with the user.

Perceptual and analytic abilities

Perceptual and analytic abilities include nonverbal thinking skills that require a meaningful appreciation, interpretation, or manipulation of spatial and configural information about the environment, the body, or the body in relation to the environment. Perceptual and analytic deficits may be accompanied by, but are not synonymous with, sensory change. Deficits in this area may, for example, affect an individual's ability to maneuver a power wheelchair safely through the environment, as the individual's "map" (perception) of the spatial environment may be inadequate. As another example, these deficits might affect the individual's ability to find and select characters or pictures on the display of an augmentative communication system.

Social reasoning

Social reasoning skills are a complex set of abilities that are necessary for effective interpersonal relationships. While the specific definition of these skills varies from culture to culture, they generally include the ability to recognize and/or engage in socially appropriate behavior in common situations, the ability to see things from another person's point of view, sensitivity to another's emotional expression, and the ability to respond differently to particular social behaviors according to the context in which they have occurred. These skills are important to the operation of many assistive technologies. For example, they provide the basis for linguistic pragmatics and as such are necessary for fully effective use of an augmentative communication system. Social reasoning also affects performance with powered mobility systems, providing a way for the individual to judge, for example, when driving very close to another person is fun and when it is dangerous or annoying.

Executive abilities

Executive cognitive abilities are those that permit effective adaptation and accommodation to changing environmental demands through the appropriate and efficient integration of more basic cognitive skills. These skills include flexibility of thinking; the abilities to plan, organize, and form strategies for problem solving; and self-monitoring and self regulation. A minimum competency in these skills is necessary for an individual to understand what assistive technology is and to decide whether it is a desirable intervention. Advanced levels of executive abilities are necessary for the effective use of many assistive technology systems. For example, environmental control systems may be programmed to perform certain home control tasks automatically, but for an individual to use this feature effectively, he or she must be able to first develop an overall strategy for the ways in which appliances, lights, and thermostats should be manipulated over the course of a day. As a second example, some powered mobility systems provide a powered-recline feature that allows the individual independently to obtain pressure relief. For this to be beneficial, the individual must have sufficient self-discipline and self-monitoring ability. If the individual does not possess these abilities, the presence of the system could actually be harmful to him or her, because caregivers may assume that they need not assist with pressure relief.

EXAMPLES OF COGNITIVE AND PERCEPTUAL SKILLS NEEDED FOR THE OPERATION OF ASSISTIVE TECHNOLOGIES

The following examples provide generic descriptions of a few assistive technology techniques/systems together with an analysis of the cognitive and perceptual skills required to operate them. All of the techniques or systems described are embodied within one or more commercially available devices or systems; however, specific reference to these devices or systems has not been made so as to avoid possible misrepresentations. Most commercially available assistive technologies are not exclusively designed for persons with cognitive impairment, so conclusions regarding the general quality of design should be made cautiously based on an analysis of cognitive, perceptual, and motor requirements for operation.

Scanning communication systems

Many augmentative communication systems use a scanning interface that accepts input from a single switch (or multiple switches). Such systems can have a wide range of configurations. All of these systems require an evaluation of the user's motor abilities and a determination of switch type and placement for optimizing switch activation. One of the most common scanning interfaces consists of a two-dimensional array of letters, arranged so that the letters used most often require the least amount of time to select (Fig 1). In this configuration, each row of letters is highlighted sequentially until a switch activation occurs to select a particular row. Then, the individual letters of the row are highlighted sequentially until a second switch activation is made to select the particular letter of choice. Basic competency with this type of system requires that the user be able to

- understand the basic two-step selection strategy;
- respond appropriately to visual cues, under specified time constraints, with a switch activation;
- keep the message context, word, and specific letter in mind; and
- visually search the letter array and identify the location of the desired letter.

Development of a higher level of skill with this system requires the ability to memorize letter positions, so as to eliminate the necessity of visually searching for each selection.

An additional complexity of some scanning systems is that selection of an item may produce various combinations of text entry, branching to a new menu, voice generation, or other action. In this case, requirements for operation would include the ability to understand and memorize the relationship between the screen cues used for each item in the array (eg, color, character style, and icon semantics) and the actions that occur when the item is selected.

Another common characteristic of scanning systems is multiple levels of a scanning array, in which the contents of any particular location varies with the level selected. As levels are changed, the cues associated with

_	E	A	R	D	U
T	N	S	F	W	B
O	H	C	P	V	J
I	M	Y	K	Q	'
L	G	X	Z	.	,

Fig 1. Example of row-column letter matrix for a scanning communication system. Letters are placed in a frequency-based arrangement, so that the most frequently used letters can be selected most quickly.

each specific location may stay the same (static display) or change (dynamic display). Additional requirements (beyond those discussed above) for operation of multiple levels include the ability to remember, or determine from information provided by the system, the current level as well as methods for changing between levels. In the case of a static display, the user must be able to combine knowledge of the current level with the cues at a particular location to decide which of the possible location contents (or meanings) is currently available. For a dynamic display, the user must be able to visually search an array that changes its labels on the basis of the selected level.

It is important to note that individuals who have deficits in these areas of cognition may still be appropriate candidates for scanning systems, because some of these skills may be improved or developed through appropriate clinical intervention. For example, the relatively complex strategy required to select a row and then a column from a scanning matrix can be built by concentrating on its components. Simpler single-switch scanning with one-dimensional arrays or even computer games can facilitate the development of switch activation under specific time constraints. It may then be possible for an individual to use that skill to pick a single letter from a reduced set of options and gradually progress to the entire matrix. However, the ability to generalize such acquired skills may be limited in many cases. As a second example, for individuals who have trouble keeping track of the desired message or current level, training can focus on simple strategies enabling the user to utilize the available cues provided by the system on-screen.

Power wheelchair controls

Power wheelchairs employ a range of interfaces that are designed to accommodate a variety of motor impairments. Two basic approaches to power wheelchair operation are proportional and switch control. Most commonly, proportional interfaces employ a joystick: the direction in which the joystick is pushed signifies the direction of wheelchair travel, and the magnitude of joystick displacement represents the speed of the chair. This type of interface requires that the user have adequate general orientation, spatial orientation, vision, visual perception, simple reaction time, sustained and selective attention, and the perceptual and analytic abilities with which to associate joystick control with wheelchair movement.

For individuals with inadequate motor abilities to operate a proportional controller, multiple switch input is often used. The number of switches and the way in which they are activated can vary considerably with these systems. Modern electronic control systems automatically provide gradual accelerations and limitations on turn gains. This alleviates some of the increased cognitive and perceptual demands that might otherwise be imposed with switched control. However, there still remain increased demands that stem from the use of switch input for wheelchair control. The descriptions of switch control systems that follow are presented in order of decreasing motor and increasing cognitive requirements. A major source of this additional cognitive load is that, as motor requirements decrease, the mapping between the user's input and the wheelchair actions becomes less direct.[5]

The first option to be considered is a switched joystick control in which there are usually four or eight switches located around the joystick circumference. This type of system only allows movement in fixed directions at a preset speed and does not have as natural a relationship between joystick and wheelchair movement as does a proportional control system. A second option entails the use of multiple switches in a linear or semicircular array (eg, arm-slot switches). This method may require even greater cognitive and perceptual skills, in part because of the more indirect relationships between switch position and intended direction of travel.

Another common type of switch control, which is designed for people with severe motor limitations (who cannot operate the controller types previously described), is "sip-and-puff" control. In this type of system, pneumatic switches are activated through air pressure or a vacuum produced by oral movement. While meeting the needs of individuals with more severe motor limitations, this type of system imposes additional cognitive requirements. Sip-and-puff controls require a degree of encoding to be used effectively for wheelchair control. For example, a typical control set-up requires the user to produce two levels of sip and puff (ie, hard/soft sip, hard/soft puff), as depicted in Fig 2. In this configuration, a hard puff latches the chair in the forward direction, with a soft sip or soft puff used to turn left or right, respectively. Additional hard puffs are used to increase speed and a hard sip is used to stop the chair or move backwards from a stopped position. There are a number of potential variations on this scheme, which include such features as a nonlatching control for forward motion.

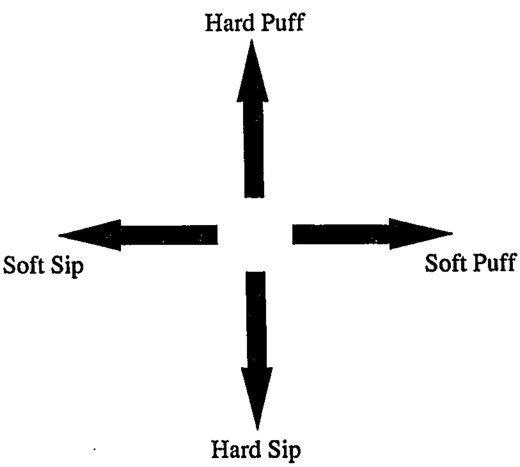

Fig 2. Mapping between user actions and direction of wheelchair movement for a pneumatic (sip-and-puff) power wheelchair control.

To achieve basic competency in the use of this type of system, the individual must understand the different levels of sips and puffs and how they relate to the speed and direction of the wheelchair. Because the mapping between user action and wheelchair movement is less direct than with a joystick control, it may be more difficult for the user to develop an expert skill level at which performance essentially is cognitively effortless ("automaticity"). If automaticity cannot be achieved by the user, it may require a much higher level of concentration during operation than would joystick control. This may represent a distraction in relation to tasks that must be performed simultaneously with switch input, such as perceiving and avoiding obstacles. A consideration with sip-and-puff control is that for users with disability stemming from injury or disease, there is considerable predisability experience in associating hand movement with directions and movements, whereas there is no experience in using a pneumatic mouth control. This poses a difficulty for many users but especially for individuals with brain injury whose ability to learn may be compromised. Such individuals may be assisted in mapping sip-and-puff inputs to wheelchair movements by placing a cue sheet (similar to Fig 2) in an appropriate location near the controller display.

Other types of power wheelchair controls also have increased cognitive and perceptual requirements as a result of compensating for limited motor capabilities. For example, scanning controllers for power wheelchair control may require only single-switch input but add requirements in terms of a user's ability to understand the association between a control interface display, planning of movements, and the anticipation required to perform actions within a limited time, in order to achieve the desired wheelchair movement.

Another aspect of wheelchair controllers is that many have several "channels," which can be used to control other things besides the wheelchair. One of the channels is allocated for the standard mode of wheelchair operation, but other channels can be assigned to functions such as the setting of wheelchair drive parameters (ie, maximum speed), power recline, remote control of electrical appliances, telephone operation, and so on. With a multiple-channel controller, the form of the input device remains constant, but its function may change with the channel selected. For example, a joystick may serve as a proportional controller for wheelchair operation but may serve as a four-switch joystick on the remote control channel. Effective use of such a system requires the executive ability to switch appropriately between channels according to the individual's current goals, the ability to identify the current channel from a visual display or auditory feedback, and to remember the appropriate method of control for that channel.

MODELING OF PERFORMANCE

The above examples demonstrate that the cognitive and perceptual requirements of assistive technologies can have a major impact on an individual's ability to learn and use a system. The next step is to begin to develop methods of understanding how great that impact is for a particular individual and a particular system. To this end, a simplified model of user performance with a common augmentative communication technique is presented.[6] This model illustrates how human performance with an assistive technology system can be analyzed and how an assessment can be made of the cognitive, perceptual, and motor skills required for its use. More specifically, it demonstrates an approach to assessing the trade-offs that are frequently involved, between improved motor efficiency in accessing the technology and increased cognitive and perceptual load. Assessment of cognitive and perceptual load is an important consideration, even for users with purely physical impairments, as increased load in these areas can lead to decreased performance. However, for users who experience cognitive impairment, the "performance costs" of methods that increase cognitive and perceptual load may be significantly higher, which makes accurate performance assessment of even greater importance.

Background

The augmentative communication technique to be examined here, called "word prediction," was described briefly in the introduction. While there are a number of different types of word prediction schemes.[7-10] the basic technique takes advantage of the recurrence of words in English to predict a set of words that are the most likely candidates for user entry. Word prediction choices are typically displayed in a short list and are refined as the user inputs additional letters. If the desired word is found in the list, it can be selected with one additional input, which eliminates the need to select each remaining letter individually.

As described earlier, a basic trade-off involved in word prediction is that decreasing the number of necessary character selections may increase the time required to make each selection by increasing the cognitive and perceptual requirements, thereby leading to unknown effects on overall performance.[1,11,12] A brief review of the literature on word prediction systems illustrates this. Theoretical and experimental studies show that required keystrokes can be reduced by 24% to 70%,[7-9,13] depending on the characteristics of the entered text and the word dictionary. Maximum efficiency has been estimated at 82%, under the assumption that every word could be selected with only one keystroke.[9] However, despite these significant reductions in motor requirements, overall performance does not universally improve. Experimental measurements in subjects with disabilities reveal a wide range of performance changes, from significant decreases in speed,[14] to modest or no improvement,[8,13] to substantial increases in speed.[14] At least one clinical study has confirmed that, while efficiency (number of characters selected/number of characters entered) may improve significantly, text entry speed may not.[15]

These results do not mean that word prediction *never* enhances rate. They merely point out that the claims that word prediction is time saving,[16] increases typing rate,[17] and provides quicker access[18] should be examined more closely to determine when they hold true and when they do not.

There are three main questions that should be answered to assess the trade-off between efficiency and selection time. These are:

- What are the factors that contribute to an increase in selection time?
- What are the time requirements associated with each of these factors?
- Can we integrate this information with the efficiency data to define a crossover point between rate enhancement and rate inhibition?

While the definitive answers to these questions require further research, there is a significant body of literature in the field of human-computer interaction (HCI) that can be applied today, as demonstrated below.

Factors affecting selection time

Use of a word prediction feature requires additional cognitive and perceptual processes, and these are the major contributors to the increase in selection time. Processes that are frequently cited include the visual search of the prediction list and the subsequent decision about whether the list contains the desired word.[1,12,15] The time required to determine whether the word is in the list will also be affected by memory abilities (the ability to remember if a word is there, rather than explicitly searching for it) and judgment abilities (the ability to develop a sense for the likelihood of a word's being there).

An often-overlooked source of cognitive load is the executive processing involved in planning use strategies and guiding overall activity.[19,20] For example, the user may spend time deciding whether to search the list at all. Not all users will employ this strategy, choosing instead either to search every time or not at all; however, many users may adjust their use of word prediction according to their perception of the recent success of the predictive algorithm.[15] As a second example, some users may exhibit noticeable delays if the word is not found in the list, which may correspond to the processing required to shift attention from a task of recognition to one of text generation.[15]

Associated time requirements

The times required for each of these component actions may vary widely between augmentative communication users and may be substantially affected by cognitive and perceptual impairment. However, many of these processes can be quantified by the experimental performance of able-bodied subjects to provide a "best-case" baseline. Such performance times can be expected to apply to augmentative communication system users who have cognitive and perceptual abilities within normal limits, while providing an upper limit for those with cognitive/perceptual limitations.

Several HCI studies[21,22] have been performed on the visual search of lists, in which subjects search for a given target word and make some motor response to choose the target. The response times reported, when corrected for the motor time, provide estimates of the time spent in visual search and target recognition. For short lists (around 5 items), ordered either alphabetically or by frequency of use, search times after some practice are 1.0 to 1.5 seconds[21,22] and may be expected to increase logarithmically if more items are added to the list.[21] With substantial practice, it may be possible to achieve search times of 0.5 seconds, although this estimate has not been validated empirically.[1]

The other cognitive processes discussed above are not as directly quantifiable, although relevant HCI work can supply approximations here as well. First, since the user of a word prediction system is faced with a choice of text-generation methods (either to search the list or ignore it), the times measured for choosing between methods in other domains indicate how long this decision might take. In a study of expert spreadsheet users, subjects consistently took an average of 1.76 seconds to choose whether to type or point to cells in entering a formula.[20] Another study has estimated that cognitive processing of this type takes 0.62 to 1.35 seconds.[19] Second, the amount of time required to shift attention from word recognition to text generation can be estimated by using an established model of human information processing.[19] While the details of the model are beyond the scope of this article, the cognitive shifting task can be considered to require one cycle of the "cognitive processor," or about 0.1 seconds, for a skilled user without cognitive deficits. These specific estimates are essentially informed guesses at this point. Nevertheless, the basic concept, that unobservable cognitive processes take measurable and sometimes lengthy amounts of time, has been well-validated in studies of HCI.[19,20,23]

Finding the crossover point

Crossover point refers to the point at which the decrease in time for motor actions is exactly the same as the increase in time for cognitive and perceptual tasks, resulting in no net improvement in performance. Once the crossover point is known, it is possible to determine whether a particular situation deviates from it, and in what direction. One approach to finding the crossover point is to gather more empirical data on users' speed with and without word prediction and to attempt to draw some general conclusions on the basis of the results. However, while this approach may successfully determine crossover points for specific user and system characteristics, it cannot make predictions about how changes in either the user or the system will affect the crossover point.

A more comprehensive approach attempts to create a model (analytical framework) that integrates system and user factors and supports the simulation of unlimited user-system combinations. The following analysis provides an example of a simple modeling approach using the timing parameters estimated above.

First, for a keyboard-based letters-only system, text entry speed can be estimated at $(5.7)(T_k)$ seconds per word, given 5.7 letters per word and T_k as the user's average key press time. If word prediction is added, with a keystroke savings of 50%, text entry speed becomes $(2.85)(T_{cp} + T_k)$, where T_{cp} is the time spent on cognition and perception for each selection. Assuming T_k is the same for both systems, the equations predict that the letters-only system will be faster when:

$$(5.7)(T_k) < (2.85)(T_{cp} + T_k) \text{ or } T_k < T_{cp}$$

By using best-case timing values, and assuming all processes occur in series,[19] T_{cp} is 1.22 seconds, which implies that word prediction with 50% keystroke savings will not enhance the rate for individuals whose key press time is less than 1.22 seconds.

To show the power of this approach, the model can now be used to analyze the crossover point for a word prediction system of any efficiency. For example, given a system that provides a 30% keystroke savings, the model predicts that the letters-only system will be faster when:

$(5.7)(T_k) < (4)(T_{cp} + T_k)$ *or* $T_k < (2.35)\ T_{cp}$

This implies that, with T_{cp} equal to 1.22 seconds and 30% keystroke savings, word prediction will not enhance the rate for individuals whose key press time is less than 2.88 seconds.

Note that these examples are only a theoretical illustration of the approach, and continued research is necessary before specific values can be applied in practice. Other types of analytical modeling techniques have provided similarly interesting results.[1,8,11]

DISCUSSION

The examples presented illustrate the general premise that, as an assistive technology interface is "enhanced" to accommodate motor impairment or increase system capability, there is usually an increase in cognitive and perceptual requirements that may negatively affect user performance. A major implication is the need to broaden the focus of assistive technology research to include a major effort geared towards understanding user-system interaction in addition to system development.[24] This implication, while generally applicable to all populations of assistive technology users, has especially important meaning for users with cognitive impairment. It is often very difficult to assess the trade-offs involved in using interface techniques for improved performance. The interplay of learning with user performance further complicates the issue, since a substantial amount of user experience may be required before performance can be assessed adequately.

The modeling example presented illustrates a potentially valuable approach to further understanding of user performance. Critical evaluation of such modeling approaches should be made, however, before any final conclusions are drawn. A specific evaluation of the word prediction model presented can be used to identify important considerations in this respect. Specific questions that need attention in this model include:

- Do users actually perform all the processes discussed above? If not, why not?
- How much time does each process really take? What is the individual variation?
- How do the times add up? Are processes performed serially, or partially in parallel?
- How well do model simulations predict actual performance?

Answers to these questions require a great deal of empirical measurement and observation. The key point is that, in addition to measuring the overall performance, we assess the individual contributions of the component actions that produce that performance, in order to build a foundation for general analytic and modeling techniques.

Although much research remains to be done, these ideals have practical implications today. For clinicians and users, an awareness of the cognitive and perceptual costs that may be introduced with an assistive technology interface provides an important balance to manufacturers' claims and can help the user make a more informed decision. For system developers, application of the ideas within the relevant HCI literature can result in significant design improvements.

An important limitation of the model presented is that, while its primary focus is one aspect of performance (ie, text entry rate), there are numerous additional factors that determine the ultimate success of an augmentative communication system or, similarly, any assistive technology system. For example, users may express preference for a word prediction system because it helps their spelling, regardless of its effects on sheer speed.[14,15] Moreover, improving physical efficiency may reduce fatigue for some users, allowing them to work longer or more comfortably. The optimal mix of text accuracy, user fatigue, and communication speed depends greatly on the specific goals and abilities of the user, and achieving this optimal mix requires a combined effort by clinician and user. However, a framework that provides an understanding of the factors that determine text entry speed and predicts the speed that may be accomplished with practice provides a significant contribution to this effort.

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More generally, there is a great need for improved understanding and prediction of performance outcomes with assistive technology systems. This need is perhaps greatest for users with cognitive impairment for whom the performance trade-offs of increasing cognitive and perceptual requirements are most difficult to assess. To satisfy this need, analytic approaches must be combined with empirical measurement in order to make substantial advancement in our understanding. The results of such research will be a better understanding by both technology developers and clinicians of the issues surrounding optimization of performance with assistive technologies.

REFERENCES

1. Horstmann HM, Levine SP. Modeling of user performance with computer access and augmentative communication systems for handicapped people. *Augment Altern Commun.* 1990;6(4):231-241.
2. Cole E, Dehdashti P. A multi-functional computer-based cognitive orthosis for a traumatic brain injured individual with cognitive deficits. *Proceedings of 13th Annual RESNA Conference,* Washington, DC: RESNA; 1990:387-388.
3. Kirsch NL, Levine SP, Fallon-Krueger M, Jaros LA. The microcomputer as an "orthotic" device for patient with cognitive deficits. *J Head Trauma Rehabil.* 1987;2(4):77-86.
4. Chute DL, Conn G, Dipasquale MC, Hoag M. Prosthesis ware: a new class of software supporting the activities of daily living. *Neuropsychology.* 1988;2:41-57.
5. Hutchins EL, Hollan JD, Norman DA. Direct manipulation interfaces. *Human-Comput Interact.* 1985;1:311-338.
6. Horstmann HM, Levine SP. The effectiveness of word prediction. *Proceedings of 14th Annual RESNA Conference,* Washington, DC: RESNA; 1991:100-102.
7. Bentrup JA. Exploiting word frequencies and their sequential dependencies. *Proceedings of 10th Annual RESNA Conference,* Washington, DC: RESNA; 1987:121-123.
8. Gibler CD, Childress DS. Language anticipation with a computer-based scanning communication aid. *Proceedings of the IEEE Computer Society Workshop on Computing to Aid the Handicapped,* New York, NY: IEEE; 1982:11-15.
9. Swiffin AL, Arnott JL, Pickering JA, Newell AF. Adaptive and predictive techniques in a communication prosthesis. *Augment Altern Commun.* 1987;3(4): 181-191.
10. Yang G, McCoy K, Demasco P. Word prediction using a systematic adjoining grammar. *Proceedings of 13th Annual RESNA Conference,* Washington, DC: RESNA; 1990:185-186.
11. Goodenough-Trepagnier C, Rosen MJ. Predictive assessment for communication aid prescription: motor-determined maximum communication rate. In: Bernstein L, ed. *The Vocally Impaired.* Philadelphia, Penn: Grune & Stratton; 1988.
12. Soede M, Foulds RA. Dilemma of prediction in communication aids and mental load. *Proceedings of 9th Annual RESNA Conference,* Washington, DC: RESNA; 1986:357-359.
13. Scull J, Hill L. A computerized communication message preparation program that "learns" the user's vocabulary. *Augment Altern Commun.* 1988;4(1):40-44.
14. Newell AF, Booth L, Beattie W. Predictive text entry with PAL and children with learning difficulties. *Br J Educ Technol.* 1991;22(1):23-40.
15. Treviranus J, Norris L. Predictive programs: writing tools for severely physically disabled students. *Proceedings of 10th Annual RESNA Conference,* Washington, DC: RESNA; 1987:130-132.
16. Gorgens RA, Bergler PM, Gorgens DC. HandiWARE.

Proceedings of RESNA 13th Conference, Washington, DC: RESNA; 1990:43-44.

17. Gunderson J, Vanderheiden G. One-screen multiplexed keyboard for transparent access to standard IBM PC software. *Proceedings of ICAART 88*, Washington, DC: RESNA; 1988:378-379.
18. Rowley BA. Interfacing the disabled to computer software through virtual interfaces. *Proceedings of ICAART 88*, Washington, DC: RESNA; 1988:380-381.
19. Card S, Moran T, Newell A. *The Psychology of Human-Computer Interaction*. Hillsdale, NJ: Lawrence Erlbaum Associates; 1983.
20. Olson JR, Nilsen E. Analysis of the cognition involved in spreadsheet software interaction. *Human-Computer Interact.* 1988;3(4):309-350.
21. Landauer TK, Nachbar DW. Selection from alphabetic and numeric menu trees using a touch screen: breadth, depth, and width. *Proceedings of CHI '85*, New York, NY: ACM; 1985:73-78.
22. Somberg BL. A comparison of rule-based and positionally constant arrangements of computer menu items. *Proceedings of CHI+GI '87*, New York, NY: ACM; 1987:255-260.
23. Olson JR, Olson GM. The growth of cognitive modeling in human-computer interaction since GOMS. *Human-Comput Interact.* 1990;5:221-265.
24. Rosen MJ. Editorial. *Assist Technol.* 1989;1:79-80.